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# DEVELOPMENT OF A COMPREHENSIVE NUMERICAL RIVER ICE MODEL

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for
"Task Force on Numerical Modeling of River Ice Conditions"*

## ABSTRACT

The NRCC Sub-Committee on the Hydraulics of Ice Covered Rivers formed the above mentioned Task Force in June 1986. Since then, the Task Force has concluded that the development of a comprehensive numerical river ice model was needed and economically justified because of a relatively large number of important future applications in Canada and other nordic countries. Furthermore its development was judged to be feasible from a technical, administrative and financial points of view.

As a result a proposal to carry out the model development work was prepared and supported by a number agencies. Its global objective is to produce a well designed, tested and documented numerical river ice model. It would be non-proprietary and would be used by a relatively large number of users. The work should be completed within a duration of 3 years.

The paper presents an outline of proposal including the objectives of the project, the capabilities of the proposed model, the expected future applications of the model, and outlines the 11 phases of the proposed work.

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This paper is an updated version of a similar paper presented at the "Hydro Operations and Maintenance: Winter Operation - Ice Problems" Workshop, August 26-28, 1987, Montréal

## 1.0 IMPORTANCE OF NUMERICAL MODELING

### 1.1 General

The evaluation of ice conditions is often a very important though difficult task in the planning, design, construction and operation of river development projects. There are three basic methods of predicting ice conditions in rivers; as outlined below:

1) Analytical Methods: Simple backwater calculations, combined with approximate ice cover stability limits can be used to estimate upper and lower bounds of an ice regime in a river. Hand calculations or simple programs on micro-computer are normally used to carry out these computations. For example, the critál depths of ice jams can be used to estimate the upper limit of water levels for a given discharge under certain ice jam conditions (references (1) and (2)).

2) Numerical Modeling Method: Detailed computer programs are used to evaluate the ice regime as a function of discharge, bathymetry of the river and ice characteristics. Normally, the overall objective of the simulation is to determine the evolution of ice regime with time as a function of discharge and meteorological conditions. The evolution in ice characteristics with time are either input by the user or evaluated by the model.

   Typically the numerical modeling studies are required to calculate the ice regime for normal and severe ice conditions. The severe conditions are usually of most interest and are normally much more severe than those already observed.

3) Physical Modeling Method: Physical models are normally used on important projects to verify the results obtained from numerical models and to simulate certain two and three dimensional effects which are very difficult or impossible to simulate on a computer.

The selection of which of the above methods should be used on a given project normally depends the nature and the precision of required results for a given study. This is true for the evaluation of ice conditions as well as for the evaluation of other complex hydraulic conditions such as dispersion of polutants in rivers and estuaries.

## 1.2 Application of Numerical Models by Hydro-Electric Utilities

Hydro-electric utilities are one of the main users of numerical river ice models. The most common and important application is to compute predicted backwater conditions in a river under a variety of possible ice conditions. The river conditions of most interest are typically a profile of water levels, flow velocities, and ice cover thicknesses. In order to compute these and other variables, such as water temperatures, the model (s) must simulate one or more of the following ice processes: water cooling, ice generation and transport, ice cover formation, thickening, shoving, eroding, melting, and break-up. Figure 1 illustrates the ice conditions which are typically encountered downstream of hydro-electric plants.

Numerical models which simulate one or more of the above mentioned ice processes, are used for the following types of studies.

1) Engineering Design Studies: Important hydro-electric projects normally progress through about four phases of study before a final design is adopted for construction. Typically ice simulations are carried out to evaluate the normal and extreme water levels and other hydraulic conditions for a range of future possible winter conditions. Like other hydraulic studies, the detail of required field data increases as the detail of analysis increases for successive project phases.

Numerical simulations of ice conditions should normally be carried out in all stages of design of hydro-electric works, as discussed in section 1.3.

2) Hydro-Electric Operation Studies: Increasingly hydro-electric plants are being called upon to meet the peaking loads occuring seasonnally, weekly, daily or even hourly. For alternative generation patterns the utilities are interested in knowing the ice effects on generation efficiencies (head losses), and what generation constraints should be imposed to avoid unacceptable ice conditions (ice jams, high water levels, erosion, etc.). The nature of studies, requiring accurate numerical simulation of ice conditions under a range of possible hydro-meteorologic conditions, are as follows:

- long term power operation strategy studies for future hydro-electric works. The results of these studies may significantly affect the final design of the works;

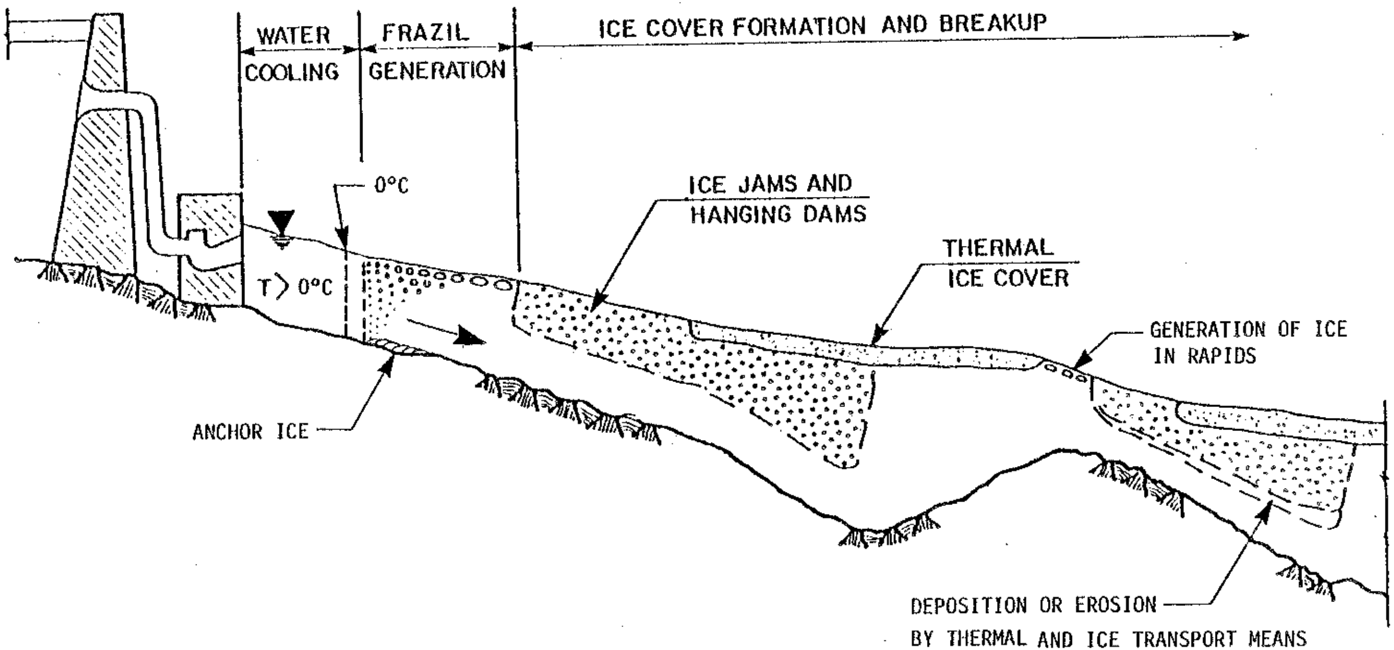



FIGURE 1.: TYPICAL ICE CONDITIONS TO BE SIMULATED BY A NUMERICAL MODEL

- long term power operation studies for existing hydro-electric works to evaluate ice effects on plant efficiency and to define operating constraints;

- short, intermediate, and long term real time power planning and management studies. Ideally one will be able to predict the optimum current and predicted power production pattern as a function of current previous, and predicted ice conditions.

3) Environmental Impact Assessment Studies: The impacts on the environment caused by the construction and operation of hydro-electric works require adequate knowledge of the thermal, hydrodynamic, and ice regimes. In order to do this, simulation tools must be used to adequately define the existing regimes and to predict the future regimes following harnessing of a river, or a complex of rivers with reservoirs, canals, etc.

Numerical modeling is applied in what may be summarized as a two-step process of environmental impact evaluation. The first step consists of calculating the ice regimes (with and without hydro-electric works) by numerical simulation. This is normally carried out under the supervision of an experienced ice engineer who directs the simulation work, validates the obtained results and seeks important input from environmentalists.

The second step consists of evaluating the environmental impacts by environmentalists who use the results furnished by the model. Among the many impacts of ice on the environment is the example of its effects on fish which was recently well described by Walsh and Calkins (4).

## 1.3 Relationship of Numerical Modeling Work and Field Observations and Mesurements

Hydro-electric design studies normally progress through about four different phases of study before a final decision is made to proceed with construction of the project. These stages are preliminary, pre-feasibility, feasibility, and detailed design. Numerical modeling studies are important because they should be used to advantage at all four stages of study. Like other hydraulic engineering studies, the detail of required field data and detail of analysis increases as the project moves through different phases of study. Also, it is very important to carry out a numerical modeling study after each series of ice observations. The numerical modeling study, even though approximate initially, will give additional details on the river's flow conditions and ice regime which, in turn, will be very useful in improving the effectivenes of the next ice observation program.

The simulation results will help to identify the most critical reaches in the river where additional ice observations and bathymetric data may be necessary and where existing data is sufficient. In this way the risk of gathering relatively costly data from non-essential reaches of the river are reduced. Figure 2 on the following page illustrates the role of numerical modeling in a river development project where the evaluation of ice conditions is an important consideration.

## 2.0 BACKGROUND AND STATUS OF EXISTING MODELS

Table 1 gives a current list of known models and associated persons who are developers and/or users of numerical river ice models. Reference (3) gives a description of most of these models.

In general the numerical models have been developed for engineering studies on specific rivers. Also each model was initially designed to solve a particular problem associated with one or more ice processes such as: freeze-up jams, hanging dams, spring break-up and ice jams, and/or unexpected ice conditions occuring during a winter flood. The most complete numerical ice models have been developed and used by consulting engineers who have developed and modified the models as the need arose. Often the time for development work and documentation was limited to meet the technical objectives of the engineering project (s), and to accomodate its corresponding schedule.

As a result of the above described background of development, there are severe limitations to existing models. This is particularly evident when one compares their capabilities with the state of the art knowledge on river ice, and with the power of computer software and hardware available in almost all engineering offices. All the models use rules of thumb, simplified ice theory, and/or calculation procedures. The application of these models can result in important calculation errors leading to substantially greater additional costs in construction and operation of hydro-electric works, and other river projects.

In addition most of the models are proprietary and their documentation is often poor or non-existant. As a result, modification of the models is difficult and is

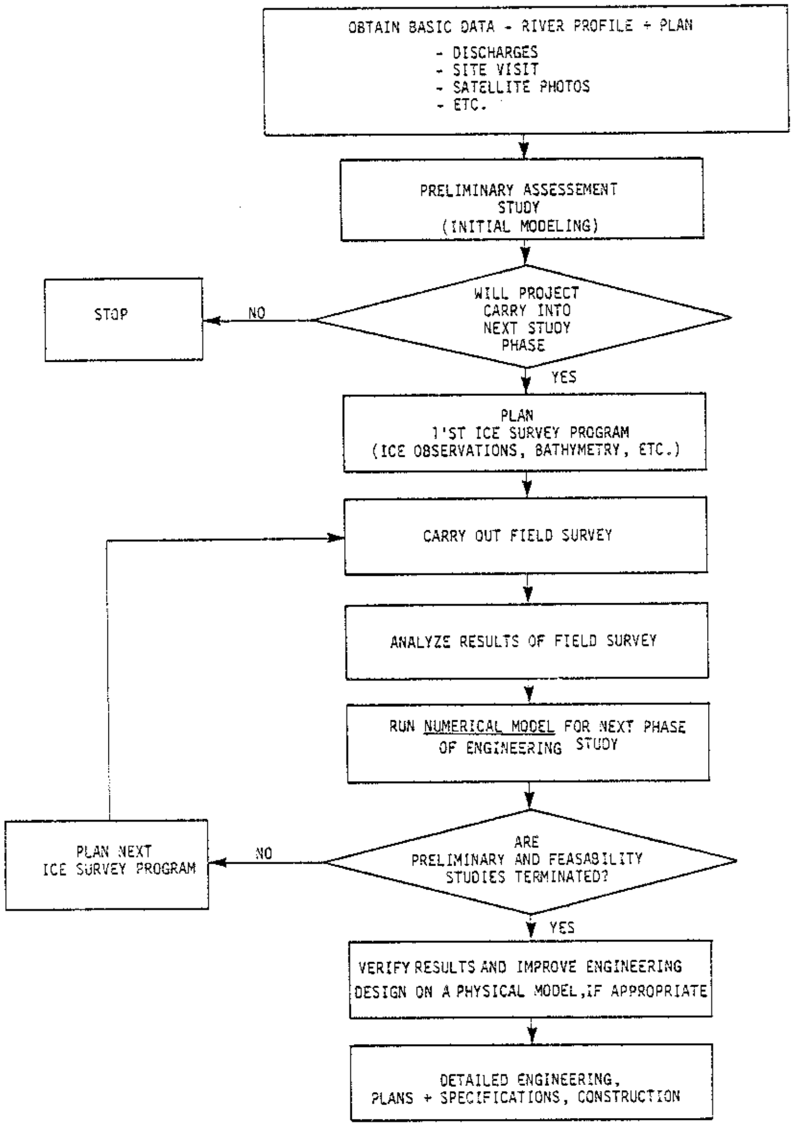



FIGURE 2: ROLE OF NUMERICAL MODELING IN A RIVER DEVELOPMENT PROJECT

TABLE 1

LIST OF KNOWN NUMERICAL RIVER ICE MODELS

| | | |
|---|---|---|
| 1. | SIMGLACE | Sylvester Petryk<br>Tecsult |
| 2. | ICESIM | Rick Carson/Jim Anderson<br>ACRES |
| 3. | HEC-ICE | Darryl Calkins<br>CRREL |
| 4. | Ottaquechee River | Same as above |
| 5. | Rivière des Milles Iles and rivers in the NBR Complex | Pierre R. Tremblay<br>TECSULT |
| 6. | Rivers in Quebec and other parts of Canada | R. Hausser/F. Parkinson<br>LaSalle Hydraulic Lab (LHL) |
| 7. | RIVHER | Numa Marcotte<br>HYDRO-QUEBEC or<br>R. Hausser/F. Parkinson/<br>J.P. Saucet<br>LHL |
| 8. | Small Rivers | Harold Belore<br>CUMMING-COCKBURN & ASSOC. |
| 9. | Liard River and Peace River | Bijou Kartha<br>B.C. HYDRO |
| 10. | Burntwood River and others in Manitoba | W.C. Girling<br>MANITOBA HYDRO |
| 11. | St.Lawrence River | H.T. Shen<br>CLARKSON UNIVERSITY |
| 12. | University of Iowa Model | Robert Ettema<br>UNIVERSITY OF IOWA |
| 13. | Ministère de l'Environnement du Québec (MENVIQ) | J.M. Tanguy/A.R. Tremblay/<br>Claude Pesant, MENVIQ |
| 14. | Hanging Dams | B. Michel<br>UNIVERSITY OF LAVAL |
| 15. | Ice Forecasting Model | Doug Hodgins<br>MacLaren Plansearch (Lavalin) |
| 16. | Finish River Model | M. Huokuna<br>Reiter Ltd, - Helsinki |

normally carried out by the conceptor of the model. Often, the logic in the model is complicated, due to a long history of modifications which evolved as a result of the particular needs of each model application.

Consequently, extensive experience exists with numerical river ice models which have been used on engineering projects for more than 20 years. However this experience has not been adequately documented and the existing numerical models are not easily accessible to new users.

## 3.0 TASK FORCE ON NUMERICAL MODELING OF RIVER ICE CONDITIONS

Recognizing the practical importance of numerical modeling of ice to Canada and other nordic countries, and the need to establish a coordinated effort in this field, the NRCC Sub-Committee on the Hydraulics of Ice Covered Rivers formed the "Task Force on Numerical Modeling of River Ice Conditions" at its June 18, 1986 meeting. Following the first meeting of the Task Force in September, 1986, it became evident that there was an urgent need to develop a comprehensive non-proprietary numerical model, and that this model development was feasible from technical, financial and administrative points of view.

As a result a Joint Venture of Consultants (Tecsult, Acres, LaSalle Hydraulics Laboratory, and MacLaren PlanSearch (Lavalin)) have formulated an unsolicited proposal for the development of a non-proprietary numerical river ice model. They were assisted by the Task Force.

The following two sections describe the technical objectives of the proposed model and the methodology for carrying out the proposed work.

## 4.0 OBJECTIVES OF PROPOSED MODEL

The proposed numerical river ice model would be designed to simulate the complex phenomena of water cooling, ice generation, transport, ice cover formation, thickening, shoving, eroding, melting and break-up. The model would be principally based on existing state of the art knowledge on river ice. In addition every effort will be made to introduce important new concepts. For example, important work is foreseen on the modeling of ice conditions subject to hydraulic transients, even though this has rarely been tried before on engineering projects. The modeling of these transients is required for the proper evaluation of hydraulic conditions and corresponding effects on the ice cover.

The model will be composed of semi-independent modules, i.e. the user will have the option of using all the modules of the model or only certain modules required for the simulation of the particular conditions being studied.

A preliminary list of modules with their functions is presented below to illustrate the planned simulation capabilities and requirements of the model.

1) Input data system.

2) Hydraulic Modeling Module. This module would carry out the hydraulic calculations while interacting with the ice regime modules mentioned below. It will mainly consist of a time varied flow model which would be capable of calculating steady state conditions, as well as calculating an ice regime which is subject to transient flow conditions. These transients are typically caused by operation of hydraulic works and/or break-up of ice covers and the subsequent relatively rapid formation/release of ice jams. The model would be quasi-two-dimensional, being able to predict the average velocity distribution across the channels (with the composite section method). Flow around islands and grounding of ice jams will be included.

   A significant research and development effort will be undertaken to determine the feasibility of modeling hydraulic surges from break-up of solid ice covers, from sudden release of ice jams and from certain peaking power plants. If feasible, a separate surge module will be included in the model.

3) Heat balance in a river reach:

   a) water-atmosphere
   b) ice-atmosphere
   c) water-ice cover
   d) other sources - tributaries
                    - power plants
   e) lateral dispersion of heat.

4) Border ice - growth
              - destruction.

5) Open water ice generation - frazil
- floating ice covers
- anchor ice.

6) Ice transport balance.

7) Initiation of ice cover:

- bridging of river (surface concentration effects, etc.);

- geomorphic effects - islands
  - bends
  - spacial changes in bathymetry. (laterally and longitudinally along the channel)

8) Ice cover progression and thickness changes:

- juxtaposition
- crushing
- freezing and melting of ice covers
- thickening and erosion by transport of ice particles
- melting.

9) Ice cover break-up: - accumulation covers
- hanging dams
- static ice covers.

10) Ice cover strength:

- accumulation cover - cohesion effects

- static ice cover - effects of water level fluctuations, rise in water level, solar radiation, degree-days of melting.

11) Output data system - variables
- tables
- graphics
- report generator type of output, designed for direct insertion simulated results in engineering reports.

At the end of the proposed project, a non-proprietary numerical river ice model would be available and would be used by a relatively large number of users. This will encourage its application on a large number of rivers and will provide a common forum for exchange of future modeling experience. In turn, this should help to encourage further improvements in our numerical modeling capabilities. (It is expected that this proposed river ice model will be at least as successful and useful as the development of the open-water backwater HEC-2 model whose first version was completed in the early 1960's by the Hydrologic Engineering Center in California).

## 5.0 PROPOSED METHODOLOGY

### 5.1 Project Participants

The model development project will be carried out by a Project Group consisting of the Joint Venture of Consultants working with a relatively large number of in-house participants. The Joint Venture will be primarily responsible for designing, testing and documenting the model and the simulation results obtained from several Canadian rivers. The Inland Waters/ Lands Directorate (WPMB and NWRI) will handle the programming, and help in the testing and documentation. The main in-house participants, furnishing field data and providing numerical modeling and river ice expertise related to their particular experiences, will include 12 agencies as follows: IWLD, B.C. Hydro, Manitoba Hydro, Ontario Hydro, New York Power Authority, Hydro-Québec, Alberta Environment, Ministère de l'Environnement du Québec, Ontario Ministry of Natural Resources, N.B. Department of Municipal Affairs and Environment, Department of Fisheries and Oceans and U.S. Cold Regions Research and Engineering Laboratory. The Alberta Research Council, Trans Alta Utilities, and the Government of Northwest Territories (Department of Public Works) have offered interesting river ice data for this project. Finally, the NRCC Sub-Committee on the Hydraulics of Ice-Covered Rivers will function in an advisory role and maintain liaison between the Project Group and a relatively large number of Corresponding Members. (A corresponding Member is a person who has ice expertise, is interested in the proposed model, and should provide valuable feedback to the Project Group and Sponsors).

## 5.2 Project Phases

The proposed project is subdivided into 11 phases as follows, and should be completed within a period of 3 years.

Global Design of Model

Phase 1 - Preparation of a detailed simulation requirements and capabilities.

Phase II - Identification and priority ranking of modules.

Phase III - Preparation of heirarchial flow chart and detailed description of interrelationships between modules.

Design of Modules

Phase IV - Definition of technical criteria and computation procedures.

Phase V - Preparation of detailed flow charts for modules, and programming instructions.

Programming by IWLD

Preliminary Testing and Model Improvements

Phase VI - Evaluation of the performance of each module (individually and linked with others modules).

- Testing of the preliminary version of the model, and carrying out revisions.

Phase VII - Release of the preliminary version of model to users with ice expertise.

Phase VIII- Monitoring of simulation results and description of recommended improvements to the model.

Phase IX - Carrying out model improvements.

Final Testing and Documentation

Phase X - Testing final version of model on a number of rivers.

Phase XI - Preparation of final documentation, and publication of model and simulation results.

## 6.0 A LONG TERM PERSPECTIVE OF FUTURE IMPROVEMENTS

In the past, the following three groups have contributed most to our numerical modeling capabilities.

- Persons responsible for river ice surveys and observation.
- Project engineers responsible for the evaluation of the ice regime in a river by means of numerical models.
- Researchers working on improvements in the theory on the hydraulics of river ice.

It is evident that future improvements, as shown in Figure 3, will also come from these three groups of people. However, to date, researchers have seldom applied numerical models to improve their research results. They have normally studied a particular subject in a given reach of river.

In the future, it is hoped that researchers will use and further develop the proposed model. For example they could use it to evaluate the river's ice regime upstream and downstream of the particular point (s) of study, and in this way, have a much better understanding of the background and the reasons for the observed local ice conditions. This will encourage the feedback of results between the above mentioned three groups, particularly between the project engineers and researchers, and should lead to more rapid improvement of our numerical modeling capabilities in the long term.

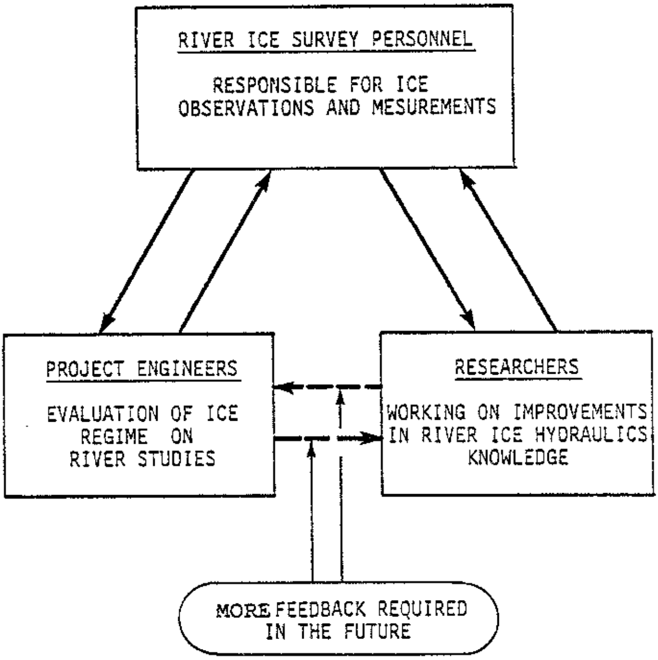
## 7.0 SELECTED REFERENCES


1) Michel, B. (1987), "The Maximum Stage of an Ice Jam", IAHS Workshop on River Ice, Vancouver, B.C.

2) Pariset, E., R. Hausser and A. Gagnon (1966), "Formation of Ice Covers and Ice Jams in Rivers", ASCE Journal of Hydraulics Div., Vol. 92, HY6, p.1

3) Petryk, S. (1986), "Numerical Modeling of Ice in Rivers" Short Course on "Ice Engineering", Ecole Polytechnique de Montréal, Montréal.

4) Walsh, M. and D. Calkins (1986) "River Ice and Salmonids" 4th Workshop on Hydraulics of River Ice, Montreal.




CONCLUSION: FUTURE IMPROVEMENTS IN NUMERICAL MODELING CAPABILITIES WILL COME FROM:

- RIVER ICE SURVEY PERSONNEL
- R + D PERSONNEL
- PROJECT ENGINEERS

FIGURE 3

FUTURE IMPROVEMENTS IN

NUMERICAL MODELING OF RIVER ICE

5th ICE WORKSHOP

DISCUSSION FORM

PAPER: Mathematical Modeling of Ice Jams

AUTHOR: Sylvester Petryk

QUESTION BY: K.S. Davar

QUESTION/COMMENT:

Every river eventually reaches its estuary; has any consideration been given to providing a linkage with a subsequent estuarine model?

REPLY:

The model being developed is pseudo two-dimensional for time varied flow conditions in rivers. It could be used to model certain estuary flow conditions which are subject to negligible or very low tides. To model a wide range of estuary conditions, it is preferable to have a true 2 - dimensional model. Research at École Polytechnique and Concordia University is being conducted for the development of such models. However their wide application to engineering projects are not expected for a number of years.

5th ICE WORKSHOP

DISCUSSION FORM

PAPER: Mathematical Modeling of Ice Jams

AUTHOR: Sylvester Petryk

QUESTION BY: Les Sawatsky, W-E-R Engineering

QUESTION/COMMENT:

Numerical models are often misused by users who are not as familiar with the physical processes and model formulation as the originator. This is particularly true for the larger and more complex models. Since the proposed ice jam numerical model will be very large, very complex, and supposedly widely used, are you not concerned that your model will be subject to very much misuse, possibly leading to even more confusion than presently exists?

REPLY:

Numerical models in general are used to evaluate processes, which can not be evaluated by simple analytical/empirical relationships. This numerical model, like models in other fields, is designed to help experienced ice engineers evaluate ice regimes much more accurately and rapidly than they are capable with existing simplified models. Typically the experienced engineer will plan, direct, and validate the work of less experienced engineers and technicians. Therefore if an engineering office uses results obtained from a user, which is "not familiar with the physical processes and model formulation", then that office is behaving irresponsibly. As an absolute minimum, such results should be reviewed by an experienced ice engineer in order to validate the results and to obtain a second opinion.

5th ICE WORKSHOP

DISCUSSION FORM

PAPER: Status and Needs of Numerical Modeling of River Ice

AUTHOR: Sylvester Petryk

QUESTION BY: Gordon D. Fonstad, Alberta Environment

QUESTION:

This model is being developed/tested on a CRAY computer. What are the plans of the Task Force in terms of the computer size (mainframe, PC) that this model will be able to run upon?

REPLY:

As we all know, the "PC" computers are becomming very powerful. In three years, when the project is completed, we are projecting that all engineering offices, who will be doing river ice modeling, will have powerful PC's such as the "386" series. Therefore, we are planning to have a version that will run on such a powerful PC.

5th ICE WORKSHOP

DISCUSSION FORM

PAPER: Status and Needs of Numerical Modeling of River Ice

AUTHOR: Sylvester Petryk

QUESTION BY: Greg Snyder, WMS Associates Lld, Filon, NB

QUESTION:

Who will have "control" of the model to incorporate new methods as they develop, or will the model again diverge as each group of users has their own experience with it? Will there be an obligation to forward charges and experience or will these become proprietary. Do not forget the importance of estuaries for future incorporation in the model.

REPLY:

The Inland Waters Directorate of Environment Canada will be the custodian of the model, and will handle distribution, coordinate future changes, and encourage exchange of modeling experience in the form of workshops and other means.

In regard to the possibility of using the model for estuaries, please refer to the above author's reply to the discussion by K. Davar.

5th ICE WORKSHOP

DISCUSSION FORM

PAPER: Status and Needs of Numerical Modeling of River Ice

AUTHOR: Sylvester Petryk

QUESTION BY: P.M. Pelletier, WRB, IWD, Environment Canada

QUESTION:

1) How will you ensure that the future proposed numerical river ice model is fully structured; that the modules are independent; that the user is not allowed to modify the computer programs and that updates/additions are easy to incorporate into the model?

2) I would suggest to use in expert system(ES) approach for the development of the proposed model. An ES is a computer program that is designed to help solve complex, but very specific, real-world problems. They are interactive programs incorporating judgment, experience rules of thumb, intuition, and other expertise to provide knowledgeable advice.

REPLY:

- Model structure, independence of modules, and facility of making future modification:

This depends on the experience of the model designers and computer personnel. We have very experienced personnel in the project group from the consultants and in-house users. In addition comments are being encouraged from "Corresponding Members" of the project, as described in the paper. Anyone interested in becoming a corresponding member is requested to contact the author or any other member of the project group.

- Future modifications:

As mentioned in the previous discussion, the Inland Waters Directorate will coördinate future changes to the model. In addition, since the program is non-proprietary, each user may make his own modifications to the program since the program listing will be available.

- Possibility of using an expert system:

This is an excellent suggestion which was also previously mentioned by Hydro-Quebec. We will definitely consider using it.

5th ICE WORKSHOP

DISCUSSION FORM

PAPER: Development of Mathematical Modeling for Prediction of River Cooling, and Frazil and Anchor Ice Formation

AUTHOR: G. Tsang

QUESTION BY: Sylvester Petryk

QUESTION/COMMENT:

The author should be congratuated for his excellent presentation on frazil ice formation and dynamics, its effect on anchor ice, and how an operational computer model can be developed and applied by Hydro-Electric utilities. There is also on urgent need to develop and test an associted design simulation model which would predict anchor ice growth, decay, and uplift as a function of meteorlogic and hydraulic conditions.

For Hydro-Electric projects, two design criteria are normally retained:

1) The prediction of <u>average expected</u> onchor ice effects.

2) The prediction of <u>maximum expected/maximum possible</u> anchor ice effects under severe ice conditions.

The hydraulic effects of anchor ice can be considered to have two components which affects the conveyance of channels:

- an equivalent ice thickness on the bottom of the channel;
- a change in roughness of the bottom of the channel.

To help develop the above mentioned design simulation model, further research is required on the mechanics of uplift of anchor ice. The fundemental question is under what <u>history</u> of conditions and under what <u>current</u> conditions will frazil ice uplift from the river bottom. This is expected to be a function of following parameters:

- river bed formations and their heat conduction properties;
- ground water flow conditions under the river bed;
- solar radiation and the basic heat transfer mechanisms which transmit this radiation heat to the river bottom;
- water temperature (super-cooled, zero, or above zero).

Theoretical studies (such as that carried out by the author), field studies, and laboratory studies in cold rooms should be encouraged to help solve this problem.

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In conclusion, the Task Force thanks the above discussors; we appreciate the interest you have shown in this project, and we look forward to your continued input in the future.