Sixth Workshop on the Hydraulics of River Ice
Lord Elgin Hotel
Ottawa, Ontario, Canada
October 23-25, 1991

A Strategy for Studying Ice Jamming on the Upper Niagara River

by:

Randy Crissman
New York Power Authority
Niagara Power Project
P. O. Box 277
Niagara Falls, New York 14302
Tel: (716) 285-3211

Robert Gerard
Department of Civil Engineering
University of Alberta
Edmonton, Alberta T6G 2G7
Canada
Tel: (403) 492-2066

Robert Ettema
Iowa Inst. of Hydraulic Research
College of Engineering
University of Iowa
Iowa City, Iowa 52242
Tel: (319) 335-5224

David Andres
Alberta Research Council
P. O. Box 8330, Postal Station F
Edmonton, Alberta T6H 5X2
Canada
Tel: (403) 450-5279

Abstract

The New York Power Authority (Authority) is upgrading its hydroelectric generating facilities at its Niagara Power Project, located on the Niagara River, to provide additional peaking capacity. As part of this undertaking, the Federal Energy Regulatory Commission (FERC), which issued and maintains the operating license for the Niagara Power Project, requested the Authority to conduct studies aimed at evaluating the relationship between the project's design, its operation, and the formation of ice jams and stoppages in the upper Niagara River. The studies are intended to assess the impacts of ice on power generation losses and shoreline flooding and to evaluate possible improvement measures for reducing the frequency and severity of ice stoppages and jams in the river.

A plan of study (Plan) was developed by the Authority, which outlines the strategy, specifications, implementation plan, and schedule for the studies. Several integrated studies are prescribed in the Plan to determine the relationship between hydropower operations and the formation of ice jams, to evaluate methods for reducing the likelihood that ice jams will occur, and to develop strategies for limiting the negative impacts of ice jams. The studies focus on the concurrent use of physical and numerical models such that the results can be used to assess and lessen the limitations inherent in physical and numerical modeling of river ice processes. The modeling will be supported by analyses of historical data and a field data collection program. Most of the prescribed studies were or will be initiated in 1991 and are to be concluded in 1993.

Key Words

Niagara River, ice jams, hydroelectric power, flooding, numerical modeling, physical modeling, river ice, Lake Erie, lake ice, ice booms

Introduction

The Authority's Niagara Power Project, situated on the Niagara River in Lewiston, Niagara County, New York, has a generation capacity of 2,400 megawatts. It is the largest power plant among the Authority's facilities with about 35% of the Authority's total installed generating capacity. Water for the Niagara Power Project and the Sir Adam Beck Generating Stations, operated by Ontario Hydro, is diverted from the Grass Island Pool of the upper Niagara River, just upstream of Niagara Falls (Figure 1). The combined generating capacity of the U.S. and Canadian stations[1] is about 4,500 megawatts. Diversions for hydropower production are made in accordance with the terms of the "1950 Treaty Between the U.S. and Canada Concerning the Uses of the Waters of the Niagara River," which requires that flows over Niagara Falls be not less than 100,000 cfs (2,832 m^3/sec) during tourist hours and not less than 50,000 cfs (1,416 m^3/sec) during non-tourist hours. All of the water not used to satisfy the Falls flow requirement of the 1950 Treaty is available for hydroelectric power generation.

The operation of the Niagara Power Project and the Canadian generating stations has at times been hampered during winter by ice generated in the river or transported into the river from Lake Erie. On occasion, severe ice conditions have led to ice jams and subsequent flooding of the low-lying areas along the upper Niagara River. Ice has also caused generation losses, because water is needed as required by the 1950 treaty, to pass ice over Niagara Falls. These losses, which are shared equally by the Authority and Ontario Hydro,[2] have averaged about 66,000 megawatt-hours annually over the last ten years (International Niagara Working Committee, 1980-1990).

---

1. Including the Ontario Power and Canadian Niagara generating stations located in the cascades section of the river just upstream of Niagara Falls.
2. The Authority and Ontario Hydro jointly dispatch water from the Grass Island Pool to the generating stations and the Falls. They are jointly responsible for meeting the water level regulations applicable to the Grass Island Pool and the Falls flow requirement in the treaty.

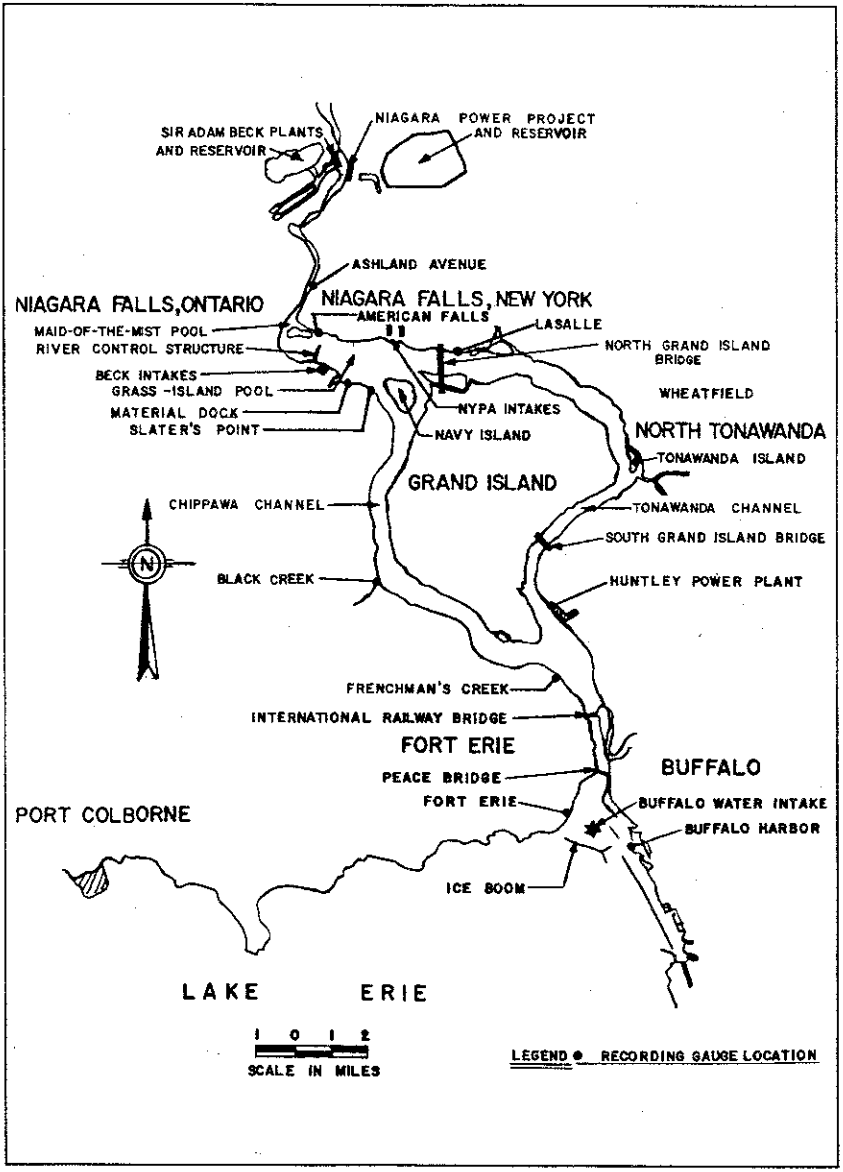

Figure 1: Map of the Upper Niagara River.

At a replacement power cost of $30 per megawatt-hour (1988 $ U.S.), the lost benefits to the residents of New York State and Ontario amount to about two million dollars per year (1988 $ U.S.).

The Authority is upgrading its hydroelectric generating facilities at the Niagara Project to provide additional peaking generation capacity. This undertaking involved the Authority's applying for an amendment of its operating license issued by the Federal Energy Regulatory Commission (FERC). The application for the amendment was approved by the FERC, but included several conditions. The FERC required the Authority to develop and implement a study plan (Plan) aimed at evaluating the relationship between project design and operations and formation of ice jams in the upper Niagara River as it impacts on power generation losses and shoreline flooding.

Specifically, the Authority was required to "undertake an ice model study, either mathematical or physical, of the upper Niagara River." In addition, the FERC required the Authority to "retain a board of qualified, independent, engineering consultants (Board) experienced in ice engineering, physical modeling, and mathematical modeling to assess the potential for the possible solution to ice jam conditions on the upper Niagara River, as such conditions affect the operations of the project and shoreline flooding." The Board assisted the Authority in developing the Plan and will review the progress and results of its implementation, analyze them, and develop conclusions and recommendations, if any, for remedial measures. Lastly, the Authority was required to "survey the scientific community regarding the practicality of developing a physical ice model for the upper Niagara River." Over 30 responses to the survey were received.

General Strategy for the Plan

The objectives of the Plan are: 1) to determine whether and/or how the Authority's intake and its appurtenant structures or physical features affect ice transport, ice jam initiation, and ice jam development in the upper Niagara River, 2) to investigate whether there are measures, either physical, structural, and/or operational that will significantly reduce the likelihood of ice jam formation and resulting flooding and power generation losses, and 3) to investigate whether there are measures that will ensure that intake operation will not exacerbate the problems related to ice jam progression once a jam is initiated in the vicinity of, downstream of, or upstream of the intake.

After reviewing the background material, it was concluded that appropriate physical and numerical modeling, and careful interpretation of the modeling results, could be used to address these three objectives with the understanding that the first objective is a necessary, diagnostic precursor to the second and third objectives. It was also concluded that it is not possible to completely eliminate the occurrence of ice jams in the river, especially in the complicated Grass Island Pool reach. There are potential combinations of hydraulic and hydrometeorologic conditions that will produce ice discharges of such severity that jams will develop irrespective of any action taken by man.

Mitigation Schemes

Following a review and synthesis of the background material, three principal mitigation schemes were identified for investigation to address the second and third objectives of the Plan. However, before the three schemes can be investigated, several baseline studies need to be conducted pursuant to the first objective of the Plan. Baseline information[3] is needed for assessing the effectiveness of the measures identified for evaluation in the three schemes. Five types of studies are prescribed, including technology assessments, historical data analyses, field observation and measurement programs, numerical modeling and physical modeling.

The first mitigation scheme to be investigated is the implementation of structural, physical, or operational changes that might increase the ice discharge capacity of the Grass Island Pool in the vicinity of the Authority's intake. The second scheme is the reduction of ice discharges into the upper Niagara River or, at least, into the Tonawanda Channel.[4] The third scheme, largely operational in nature, is the improvement of ice transport conditions within the river. All three ice-jam mitigation schemes are to be investigated using physical and numerical models.

A rather large physical model of a portion of the Grass Island Pool will be used as the primary tool in evaluating the first mitigation scheme. Concurrent numerical modeling of the ice processes in the Grass Island Pool will also be conducted to compensate for shortcomings in the physical modeling and to evaluate impacts on the remainder of the river. These models will also be used to assess any potential impacts on operations and/or ice jamming potential in the Grass Island Pool from any measures evaluated under the second mitigation scheme.

The second mitigation scheme to be investigated has two aspects. One is the improvement in the design of the Lake Erie - Niagara River ice boom to further reduce the frequency and severity of lake ice runs. The second is diversion of ice from the Tonawanda Channel to the Chippawa Channel.

---

3. Studies to establish a set of data and observations for use in comparing against cases involving changes to the existing condition.

4. Most ice that enters the upper Niagara River from Lake Erie drifts into the Tonawanda Channel due to the prevailing winds and currents.

The goal of the latter is to alter the temporal and spatial distributions of ice in the river system to improve ice transport past the hydropower intakes in the Grass Island Pool. It would also encourage utilization of the full ice discharge capacity of the river, rather than just that of the Tonawanda Channel.

The evaluation of potential improvements in the Lake Erie - Niagara River ice boom may involve three phases of study. Current ice boom technology will be assessed to determine if any alternative designs appear to be applicable to the situation. If so, laboratory (physical) modeling of the prospective designs and the current design may be done to assess performance. If an alternative design demonstrates superior performance, then one or two test sections may be installed and monitored during one or two winter seasons. If successful, a new boom may replace the existing boom.

The feasibility of diverting ice from the Tonawanda Channel will be investigated initially by using a numerical model of flow and ice drift in a portion of the river upstream of Grand Island. Use of a physical model will also be considered, if numerical modeling indicates that structural measures may reduce ice discharge into the Tonawanda Channel. The design of the physical model would be guided by the outcome of the numerical modeling, primarily because it is not practical to physically model the large general area in which a structural measure might be located.

The third mitigation scheme requires analysis of the use of operational procedures in response to particular combinations of hydraulic, ice, and meteorological conditions. As in the two other schemes, operational procedures for mitigating ice jamming conditions will need to be evaluated by a combination of physical and numerical modeling. Operational procedures may be identified through sensitivity analyses of a wide range of hydraulic and ice conditions, as well as operational actions. Operational actions which may be determined to yield potentially successful mitigation strategies for particular combinations of hydraulic and ice conditions may be adopted as procedures for winter operations.

Feasibility of Improvements

Several potential improvements, at least on initial consideration, hold promise for reducing the possibility of ice jamming in the upper Niagara River. The improvements can be categorized as being of three primary types; physical, structural or operational. Potential improvements applicable to specific areas of the river are listed in Table 1. Those identified as having a medium to high priority are included in the Plan; the highest priority measures will be studied first. The priority is based on preliminary practical and economic considerations, as well as the likelihood of success. If the studies reveal that they will not be practical, further consideration of lower priority improvements may be needed.

There are no obvious simple improvements, or "solutions," that will significantly reduce the likelihood of ice jamming in the upper Niagara River. Moreover, there are no simple modeling methods to determine with assurance that potential improvements will be effective. Though the three mitigation schemes are straightforward, and a sizable list of alternative mitigation measures can be identified (Table 1), the complexity of the system and the number of different interests involved require that any improvement or combination of improvements be carefully evaluated.

Methods of Evaluation

Five methods for evaluating the three ice jam mitigation schemes (technology assessment, historical data analysis, field measurements and study, physical modeling, and numerical modeling) have been identified.

Table 1

Potential Improvements That May Reduce the Frequency and Severity of Ice Stoppages and/or Ice Jams in the Upper Niagara River

Grass Island Pool		
Type of Change	**Description**	**Priority for Consideration**
Physical	Deepen and extend excavation in front of Authority's intake	Medium
Physical	Excavate to redirect portion of flow from the Chippawa Channel to the Authority's intake	Medium
Physical	Excavate portions of the Grass Island Pool to decrease size of ice island	High
Physical	Modify ice escape channel	Medium
Structural	Modify or remove the Buckhorn Dikes	High
Structural	Install ice deflector structures or ice booms in the Grass Island Pool	Medium
Structural	Modify the Authority's intake	Low
Structural	Relocate the Authority's intake	Low
Structural	Modify the International Control Structure	Low
Operational[5]	Revise diversion procedures	High
Operational	Increase icebreaker operations and number of icebreakers[6]	High
Operational	Modify Grass Island Pool water level limits[7]	High
Operational	Modify International Control Structure operation	High
Operational/ Structural	Install temporary, removable structures, such as ice booms or barges	Medium

5. Operational changes may involve improvements in criteria for implementation, as well as modes of operation. The success of operational changes would be predicated on accurate monitoring of hydraulic, ice, and meteorological conditions.
6. The Authority and Ontario Hydro currently use up to three icebreakers in winter operations on the upper Niagara River (Crissman and Hollmer, 1991).
7. Water levels in the Grass Island Pool are regulated pursuant to a 1973 directive of the International Niagara Board of Control.

Table 1 (continued)

Potential Improvements That May Reduce the Frequency and Severity of Ice Stoppages and/or Ice Jams in the Upper Niagara River

Upstream of Grand Island		
Type of Change	Description	Priority for Consideration
Physical	Excavate to increase proportion of flow into Tonawanda Channel	Low
Physical	Excavate to decrease proportion of the ice discharge into the Tonawanda Channel	Low
Structural	Install a permanent ice retention structure in Lake Erie	Low
Structural	Increase ice-retention performance and capacity of the Lake Erie - Niagara River ice boom	Medium
Structural	Install permanent ice-deflector structure in the river upstream of Grand Island to deflect ice into the Chippawa Channel	Medium
Operational/ Structural	Use temporary ice-deflector structure in the river upstream of Grand Island to deflect ice into the Chippawa Channel, e.g. ice booms or barges	High

Tonawanda Channel		
Type of Change	Description	Priority for Consideration
Physical	Excavate to reduce the potential for hydraulic thickening of ice covers that raise water levels	Low

---

The technology assessment, historical data analysis, and field work are needed to provide input into the physical and numerical modeling tasks. Neither physical modeling nor numerical modeling alone is adequate for assessing any of the schemes. Moreover, both physical and numerical modeling are constrained by important limitations, and both need to be supported by information obtained from analysis of historical information and field studies.

Technology Assessment: The objective is to examine the current state of the technology in two main areas: 1) ice boom design and performance; and 2) instrumentation for field measurements of ice and hydraulic parameters. The former ties into the objective of evaluating measures that could be implemented to reduce the discharge of ice into the Niagara River. The main effort will be to survey current trends in ice boom design and assess the potential for improving the Lake Erie - Niagara River ice boom. The review of instrumentation is needed to assess the best methods for obtaining information for calibrating and testing the physical and numerical models and for monitoring and forecasting for operations.

Analysis of Historical Information: A substantial body of historical information concerning past ice jams and stoppages has been gathered and documented by the Authority and other organizations. Much of it is well collated and provides considerable insight into events surrounding past ice jams. That insight can be used for two purposes. One is to perform diagnostic reconstructions of events leading, and consequent, to past ice jams. The other is to provide information for calibration of physical and numerical models and verification of the results they produce.

Field Measurements and Observations: Some of the hydraulic and ice processes can neither be modeled adequately nor understood from past information. Additionally, modeling activities have to be calibrated and, if possible, verified against field measurements and observations. The purpose of the field measurements and observations is to obtain information on ice and flow conditions in the upper Niagara River that is critical for developing an acceptable degree of confidence in the modeling results, which then can be translated into recommendations for remedial action.

Unfortunately, it is no easy matter to collect some of the information required. Since the nature, magnitude, duration, and timing of ice runs on the upper Niagara River are random, it is difficult to develop a field measurement program that will be effective in responding to a particular event. For example, many significant ice events, ones that would provide the most useful data for the purposes of this study, occur during storms with high winds, blowing snow and cold temperatures. At least half of the events occur during darkness. Many occur within a period of several hours, which makes it difficult to mobilize a field crew in time to obtain the needed measurements.

Physical Modeling: Physical modeling will be used because ice transport and accumulation in the local areas of concern, e.g. the area in the vicinity of the Authority's intake, involve complicated, three-dimensional flows and related dynamic processes which cannot be adequately investigated by means of numerical modeling alone. However, there are several important constraints on physical modeling. First, there is a lack of well-stated requirements to ensure dynamic similitude between the model and the prototype and the lack of model-ice material(s) to meet these requirements. Indeed, complete similitude cannot be satisfied even for single-phase flows. The modeling problem is further complicated by the absence of criteria, and adequate means, for scaling the thermal behavior of ice (ice growth and dissipation) and the dependency on temperature of the mechanical properties of ice, which themselves are not well understood and less well formulated.

Nonetheless, to arrive at any design decisions involving potentially expensive and complex constructed works, there is little recourse other than to use physical modeling. Consequently, as in practically any modeling situation, it is necessary to determine what processes are really important and what forces dominate them, and then to scale the model and model material properties so as to maintain the same ratios between these forces in the model and the prototype for at least these important processes. In the present case, it will not be possible to accurately model even some of the important processes such as the thermal and mechanical behavior. Nevertheless, it is expected that very useful results can be obtained from astute operation of the physical models and careful interpretation of the results. The goal is to correctly model the submerged weight and the general dimensions of ice, with the aim of adequately reproducing the hydrostatic and hydrodynamic forces exerted against ice either as individual pieces and/or as contiguous accumulations. Considerations of the mechanical and thermal behavior of ice have to be set aside, although, to the extent possible, their effects will be taken into account either experimentally or analytically.

Numerical Modeling: Numerical modeling will be used for several reasons. To begin with, areas of the upper Niagara River which may potentially either be affected by, or affect, hydropower operation and/or flooding potential extend over large distances, and occur over long periods of time. One of the attributes of numerical modeling is that it facilitates modeling of the entire river, or large portions of it, over long time periods, which would not be feasible for a physical model. In this regard, a numerical model probably would be at least as useful as a physical model for the purpose of investigating how jams, once initiated, develop in a long channel like the Tonawanda Channel. To model this phenomenon physically would require a long physical model and a large volume of model ice.

A further reason for using numerical models is that flow of water and ice, and ice accumulation, are subject to unsteady processes which may not be satisfactorily reproduced in a physical model. For example, the unsteady nature of water and ice flow from Lake Erie during wind-set-up conditions affect flow and ice transport throughout the entire river in ways that numerical modeling can best illuminate. Also, unsteady effects on flow patterns and ice transport, resulting from variations in the diversion discharge at either the Authority's or Ontario Hydro's intakes, are better determined, visualized, and documented with a numerical model.

Hydrometeorologic effects, such as wind and low air temperatures, on ice transport and accumulation can be investigated with greater accuracy and ease using a numerical model than is possible with a physical model, though both methods have limitations.

Specifications for Studies

With a strategy in place, the scope and specifications for the studies to address the objectives were developed. The list of studies, though extensive, is focused on the mitigation schemes. The studies and short descriptions of them are summarized in Table 2.

The first overall objective of the studies is to determine whether and how the Authority's intake, together with the appurtenant structures for ice management, affect ice transport and jamming in the Grass Island Pool and lower reaches of the Tonawanda Channel. The second and third overall objectives are to determine what improvements, if any, might best fulfill the requirements of the three ice-jam mitigation schemes.

The first mitigation scheme will be addressed through Studies H1, H2, P1.1, N1, and N2 (refer to Table 2). If they reveal practicable improvements that would significantly increase the ice-discharge capacity of the Grass Island Pool in the vicinity of the intake, then Studies N3 and P1.2 will be implemented. If improvements are confirmed from these studies, a near-field model of the intake may be required to assess the effects of the improvements on the intake's hydraulic performance.

Studies T1, H3, N4, P2, and P3 (refer to Table 2) are designed to evaluate measures for reducing ice discharge into the upper Niagara River and/or the Tonawanda Channel. These studies address the second mitigation scheme and will be done more or less concurrently with Studies H1, H2, P1.1, N1,

Table 2

Proposed Studies
Hydropower and Ice on the Upper Niagara River

Technology Assessment Studies

Study	Description
Study T1	Assessment of ice boom technology applicable to possible Lake Erie - Niagara River ice boom improvements.
Study T2	Assessment of instrumentation for use in measuring ice characteristics for use in forecasting models.

Analyses of Historical Information

Study	Description
Study H1	Compilation of historical data required to perform analyses and to calibrate physical and numerical models.
Study H2	Analysis of historical data to develop better understanding of cause and effect relationships between ice jam occurrence, hydraulics, meteorology, and project operation.
Study H3	Analysis of historical data to assess performance of Lake Erie - Niagara River ice boom.

Field Observations and Measurements

Study	Description
Study F1	Aerial photographs of ice conditions in the 1990-1991 and 1991-1992 winters.
Study F2	Estimate ice discharge into the Niagara River from Lake Erie and split into Tonawanda and Chippawa channels during the 1990-1991 and 1991-1992 winters.
Study F3	Measure ice thicknesses in the upper Niagara River during the 1990-1991 and 1991-1992 winters, if appropriate.
Study F4	Measure ice jam water level and thickness profiles in the Tonawanda Channel in the 1990-1991 and the 1991-1992 winters, if an ice jam occurs.
Study F5	Acquire standard operational ice observations and water temperature measurements in the 1990-1991 and the 1991-1992 winters.
Study F6	Acquire discharge and velocity measurements in the 1990-1991 and the 1991-1992 winters.

Table 2 (continued)

Proposed Studies
Hydropower and Ice on the Upper Niagara River

Numerical Model Studies

Study	Description
Study N1	Model ice drift in the Grass Island Pool to assess effect of project operations and proposed structural and/or physical measures.
Study N2	Model ice jam stability and progression in the Tonawanda Channel.
Study N3	One-dimensional, dynamic ice transport modeling of the Tonawanda and Chippawa channels.
Study N4	Numerical model of structure upstream of Grand Island to deflect ice from Lake Erie from the Tonawanda Channel to the Chippawa Channel.
Study N5	Development of flow and ice transport forecasting models for operations.

Physical Model Studies

Study	Description
Study P1.1	Physical modeling of ice transport and accumulation processes in the Grass Island Pool area of the upper Niagara River under existing conditions and with possible mitigating measures (Phase I).
Study P1.2	Physical modeling of impacts of possible mitigating measures on operation of power plants (Phase II).
Study P2	Physical model studies of improved Lake Erie - Niagara River ice boom design and performance comparison.
Study P3	Physical model studies of structure to deflect ice from the Tonawanda Channel to the Chippawa Channel.

---

and N2. If they indicate that improvements are practicable, then Studies N3 and P1.2 will be implemented.

All of the previously mentioned studies will be supported with efforts to obtain field measurements and observations which can be used for calibration and verification. The required measurements and observations are specified in Studies F1 - F6. These studies can only be done on an opportunity basis; i.e., when conditions are appropriate, during the winters of 1990-1991 and 1991-1992.

Studies T2 and N5 are aimed at assessing alternative techniques for monitoring and forecasting flow and ice conditions. They are long-term and on-going studies to integrate the most recent technologies and methods for monitoring and simulation so that operational responses to ice conditions become as effective as possible. Since these studies are independent of the other studies in the Plan and are long-term, they were assigned a lower immediate priority than the modeling tasks.

Status of Studies

The Plan described above was approved by the FERC in March 1991 and is currently being implemented. The status of the studies prescribed in the Plan is briefly summarized below:

Historical Data Analyses: These studies are being conducted by Authority staff and include an assessment of the performance of the Lake Erie - Niagara River ice boom, development and analysis of possible stage-fall relationships that could be used to improve the accuracy of discharge estimates into the river, and multivariate statistical analyses of ice stoppage and ice jam occurrences.

Field Observations and Measurements: Relatively few field measurements of ice conditions were obtained in 1991 due to a mild winter, but plans are in place to obtain further measurements in 1992. Open-water flow velocity and discharge measurements required for physical and numerical model calibration were collected by the U.S. Army Corps of Engineers (Detroit) and Water Survey of Canada (Ontario Region) under an agreement with the Authority in 1990 and 1991.

Technology Assessment Studies: The studies to assess recent technological developments in ice boom design and instrumentation have not yet been initiated.

Physical Model Studies: Proposals for Study P1 were received in July 1991 and are currently being evaluated with the intention of awarding a contract in early November 1991. The P1 physical model will encompass the area depicted in Figure 2 and will be built at a horizontal scale of 1:120 and a vertical scale of 1:50. This study is to be completed within 18 months of the contract award date.

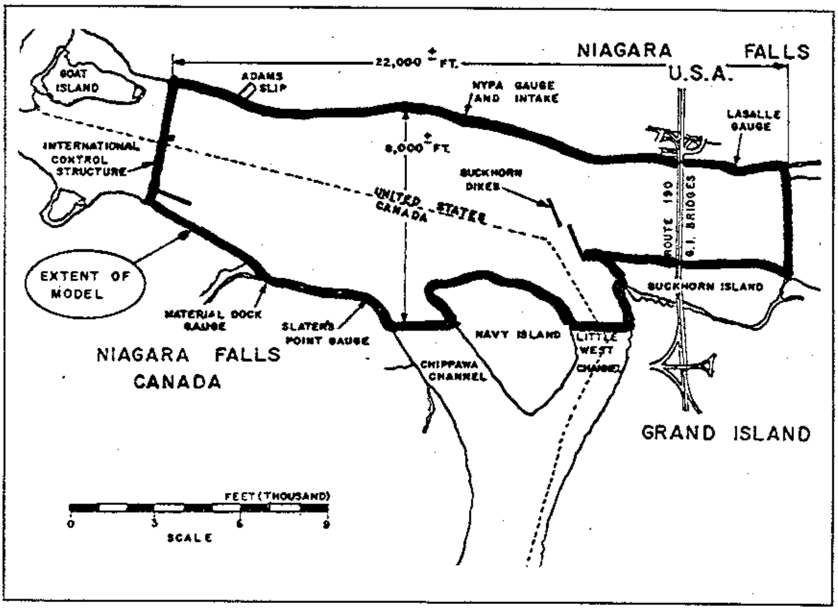

Figure 2: Area of the Upper Niagara River to be Modeled in the P1 Study.

Numerical Model Studies: The numerical modeling tasks prescribed in the Plan (Studies N1, N2, N3, and N4) are to be performed by Dr. H. T. Shen and his associates at Clarkson University under a previously existing agreement with the Authority, and were begun in August 1991. The Authority has been working with Dr. Shen since 1988 to develop an ice dynamics simulation model that can be applied to the upper Niagara River (Wake and Xiao, 1989; Lal and Shen, 1989; Shen et al., 1991). The models developed by Dr. Shen for the Authority, as well as other models developed for other applications, are applicable to the studies prescribed in the Plan.

Conclusion

A general strategy for studying and, hopefully, mitigating the processes that can lead to the occurrences of ice stoppages and ice jams on the upper Niagara River has been developed and set forth in a comprehensive plan of study and is being implemented. The principal intent of the strategy and plan is to determine whether or not there are practicable measures to reduce the frequency and severity of such occurrences on the upper Niagara River. The authors believe that the studies prescribed in the plan of study will lead to advances in the state-of-the-art of understanding and modeling of river ice hydraulics.

References

Crissman, R. D. and Hollmer, A., 1991, "A Shallow-Draft Icebreaker for the Upper Niagara River," Proceedings of the Sixth International Cold Regions Engineering Specialty Conference, American Society of Civil Engineers, Hanover, New Hampshire, February 26-28, 1991, pp. 396-405.

International Niagara Working Committee, 1980 to 1990, Operation of the Lake Erie - Niagara River Ice Boom. Annual reports prepared by the International Niagara Working Committee for the International Niagara Board of Control.

References (continued)

Lal, A. M. W. and Shen H. T., 1989, An Unsteady Flow Model for the Upper Niagara River, Report No. 89-12, Department of Civil and Environmental Engineering, Clarkson University, Potsdam, New York, August 1989.

New York Power Authority, 1991, Hydropower and Ice on the Upper Niagara River: A Study Plan.

Shen, H. T., Chen, Y. C., Wake, A., and Crissman, R. D., 1991, "A Two-Dimensional Surface Drift Model for River Ice," Proceedings of the Sixth International Cold Regions Engineering Specialty Conference, American Society of Civil Engineers, Hanover, New Hampshire, February 26-28, 1991, pp. 355-362.

Wake, A. and Xiao, Q., 1989, Hydrodynamic Simulation of the Grass Island Pool, Phase I: Upper Niagara River Ice Dynamics Simulation, New York Power Authority, June 1989.