from the Tonawanda Channel. In the second case, ice first enters the GIP from the Chippawa Channel via the Little West Channel. In the third case, ice enters the GIP simultaneously from the Tonawanda and Little West Channels. The eventual pattern depends on the wind and ice conditions during the ice run, but the first case is the most common.

(vii) Formation of Grounded Ice Accumulations in the Grass Island Pool. There are shallow areas in the GIP that become covered with grounded ice accumulations during lake ice runs, as depicted in Fig. 4. The most significant of these is the "ice island," which forms in the center of the GIP and can cover up to 20% of the surface area of the GIP. The ice island can grow to its maximum size within a few hours after a lake ice run begins to enter the GIP. In many cases, ice entering the GIP from the Little West Channel goes into building the ice island. The ice island is a significant obstruction to ice transport through the GIP.

(viii) Movement of Ice Past the NYPA Intakes. The main goal of NYPA's and OH's efforts to minimize the impacts of ice on power generation is to keep ice moving past the NYPA intakes. This is difficult to accomplish in severe ice runs, because ice entering the GIP from the Tonawanda Channel naturally prefers to move along the US shore through the ice escape channel. One of the more effective strategies to achieve this goal has been to reduce the NYPA diversion to provide more water to transport ice through the ice escape channel. This is an effective strategy when the ice discharge entering the GIP from the Tonawanda Channel does not exceed the ice transport capacity of the ice escape channel. However, in high ice discharge events, the capacity of the ice escape channel to convey ice and water limits the effectiveness of this strategy, especially after the ice island has formed. As a consequence, flows from diversion reductions that exceed the discharge capacity of the ice escape channel are shifted into a narrow sinuous channel still open between the ice island and the Buckhorn Dikes.

Fig. 4. Ice island of grounded ice formed in the upper Niagara River a short distance above the Falls.

(ix) Final Movement of Ice Through Grass Island Pool. Ice from the Tonawanda Channel can be transported into the GIP through the sinuous channel when the sum of the NYPA diversion and the discharge capacity of the ice escape channel is less than the flow in the Tonawanda Channel. Since the water discharge in the Tonawanda Channel is affected by the accumulation of ice within the GIP, and since the NYPA diversion flow can be changed, the ice discharge capacity of the sinous channel can vary significantly with time. Furthermore, once an ice stoppage occurs at the NYPA intake, ice entering the GIP from the Tonawanda Channel is forced to move through the sinuous channel. If the ice discharge capacity of this channel is not exceeded or the ice does not thicken enough to ground, ice transport into the GIP continues. Otherwise an ice jam forms in the Tonawanda Channel, as illustrated in Fig. 5.

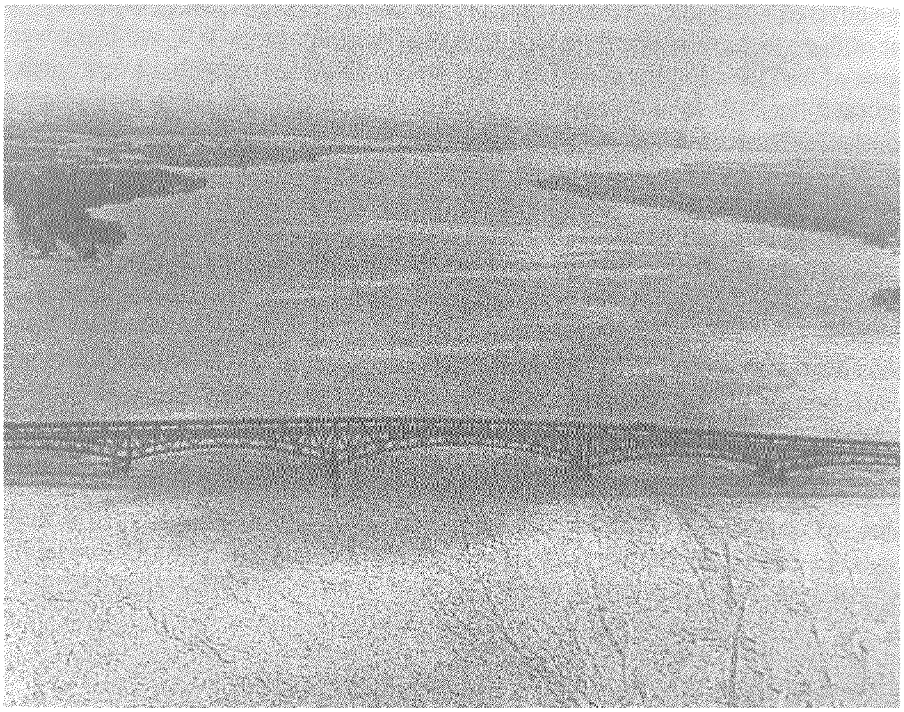

Fig. 5. Ice jam in the upper Niagara River. View up the Tonawanda Channel from the NYPA Intake.

FLOOD WARNING PLAN

The Flood Warning Plan, which was prepared by NYPA and approved by FERC, describes the organizational structure required to implement responses to flooding emergencies (NYPA, 1996). It designates general areas of responsibility, includes instructions to NYPA's operating personnel, and details notification procedures. The Plan also contains appendices describing the physical characteristics of the hydropower facilities using the river, a summary of floodable areas, plans for training and review, and documentation of consultations with Federal, State, and local agencies. Copies of the Plan are made publicly available.

TYPES OF FLOOD ALERT CONDITIONS

The Plan addresses two types of flood alert conditions:

(i) *Flood Watch*, in which ice jamming could occur and water levels could rise rapidly to cause flooding. At any gauge, the following conditions may exist: water levels are within 0.15 m of the gauge's zero-damage level; the water level is 0.15 m above the openwater level for the same river discharge; the duration of the ice-affected flow exceeds 30 hours. All of these criteria should be met simultaneously before notification of this condition is issued. The amount of time to react to this condition varies. Typically, once a Flood Watch notification is given, a major ice jam could develop within about 6 hours. Jam occurrence need not immediately cause flooding, however. Therefore, the alerting agencies are encouraged to maintain a close watch on developments. In some cases, flooding could develop very shortly after this condition is recognized, and the warning time could be less than 1 hour.

(ii) *Flood Warning*, in which flooding is imminent or is occurring. The water surface level at any of the stage gauges equals or exceeds the gauge's zero damage level. The alerting agencies begin public notifications immediately.

The two conditions are differentiated on the basis of results of a flood damage study conducted by the US Army Corps of Engineers (1986). In that study, zero-damage-elevations (defined as the elevation at which water begins to flood residential, commercial, and industrial properties resulting in structural and/or content damage and/or damage to gas and electric services) were established at locations of each water-level gauge on the East Channel. The Plan sets forth surveillance procedures for monitoring the river, during conditions (i.e., in winter and early spring) when the river is prone to ice-jam formation, and operational procedures for dealing with imminent or actual flood conditions.

RIVER AND WEATHER SURVEILLANCE

NYPA and OH staff at the River Control Centre continuously (over 24 hours) monitor the Niagara River and Lake Erie, track weather conditions, and compute the appropriate diversions for hydropower generation. The River Control Supervisor at the Centre is responsible for recognizing the development of an emergency from the extensive surveillance and monitoring network deployed along the river. As ice conditions in Lake Erie are of prime concern, water temperature and ice conditions in the lake are monitored during winter. In addition, marine radar and low-light-level cameras installed on the NYPA intake gate structures both sides of the GIP enable the Center to observe ice entering the GIP. The radar is intended for use during night and inclement weather conditions. The radar is especially useful, because most major ice problems occur during severe storms at night.

Augmenting the visual surveillance program is a water-level and flow-monitoring network. It is incorporated into a computerized "On-Line Early Warning and Operational Information System for Ice-Affected Flows" (OEWS) to help the operators track and identify indicators for the potential occurrence of ice jams that may lead to flooding. The data-processing and user system is illustrated in Fig. 6. Early warning indicators are built into OEWS, which also includes a computer model for estimating flow stages at gauges. If the estimated water level at any time is lower than the measured water level, the flow is considered "ice-affected." The early warning indicators detect the period and extent when water level is ice-affected, extent of water-level elevation, and the rate of change in river flow. Thresholds for these indicators have been set from analyses of historical ice-affected flow events. A warning message appears when the thresholds are exceeded, whereupon the River Control Supervisor, if appropriate, sets in motion the flood warning plan.

NOTIFICATION

An important part of the Plan is a notification flowchart for use in the event of a flood condition. The flow chart, shown herein as Fig. 7, summarizes who is to be notified and who is responsible for notifying public officials having jurisdiction for public safety. In the event of a flooding condition, the River Control Supervisor initiates the Plan. There is a hierarchy of notification established in regularly scheduled meetings with the alerting agencies.

EMERGENCY OPERATING PROCEDURES

When the River Control Supervisor has determined that an emergency situation is developing or has occurred, he has three operational responses: adjusting hydropower diversions, adjusting the Control Structure; and, deploying two icebreakers. These responses can be effective in dealing with small or moderate quantities of ice. When large quantities of ice enter the river, the responses can be overwhelmed.

(i). Diversion Adjustment. On recognition of a developing problem, the hydropower diversions are reduced to provide more water to convey ice to the Falls. Typically, the diversion flow is reduced about thirty percent by adjusting flow through the powerhouse six kilometers from the river (Fig. 1). Once a jam forms, the diversions may be increased to draw down water levels in the vicinity of the jam. This procedure requires careful observation of water levels and ice conditions.

(ii). Control Structure Operation. The gates on the International Control Structure can be manipulated to lower the GIP level and increase water velocities or to raise the level to inhibit grounding of ice. In some cases, attempts are made to loosen grounded or stopped ice by means of rapid opening and closing of the gates.

(iii). Icebreaker Operation. NYPA and OH operate at least two icebreakers to keep ice moving past the hydropower intakes and to help remove ice jams. The icebreakers begin operating as soon as a severe ice situation is recognized. They continue operating around the clock until the potential for ice jamming dissipates. The icebreakers are needed to open a flow path through a jam after it occurs, reducing resistance to flow and lowering flow stage.

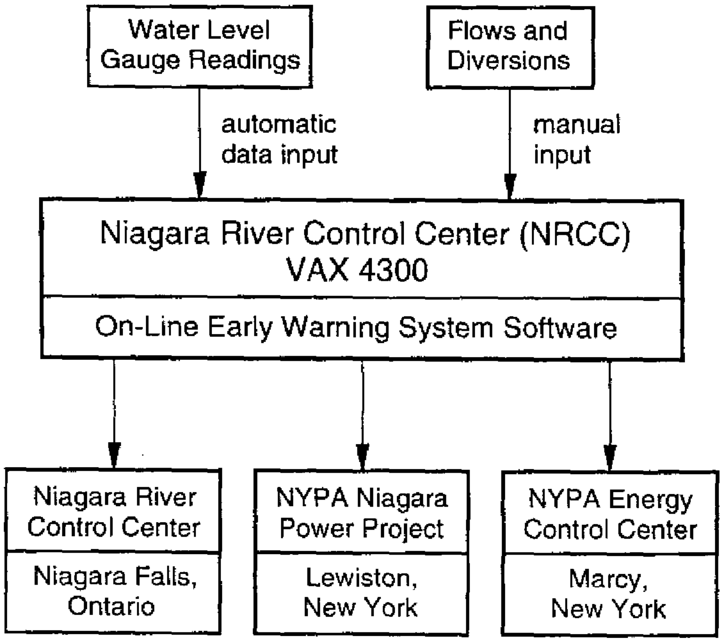

Fig. 6. Data-processing and user network for the "On-Line Early Warning and Operational Information System For Ice-Affected Flows."

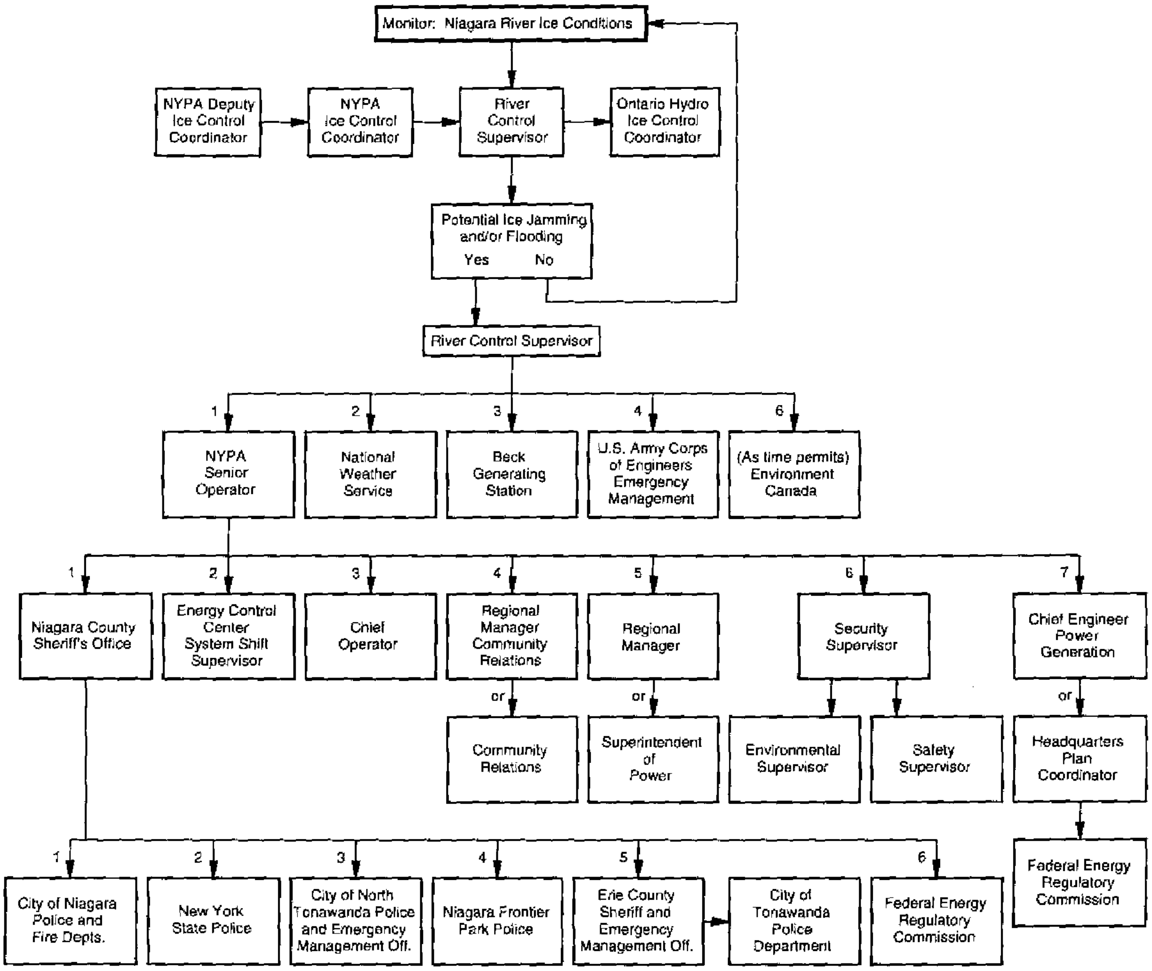

Fig. 7. Flood warning notification flowchart

CONCLUDING COMMENT

The Flood Warning Plan was activated for the first time in response to a potential for flooding of shoreline property that resulted during an ice jam that occurred in late January 1992. Notification of a Flood Warning condition was issued at 00:00 hours on January 25, with less than 1 hour being needed to notify all the personnel indicated in the notification flowchart. Serious flooding was averted, due, in large part, to implementation of the emergency operating procedures. The situation was downgraded to a Flood Watch condition at 14:00 hours on January 25. This condition persisted until February In overall terms, all the agencies involved concluded that the Plan worked well, providing a practicable means for managing flood risks along the river. However, the agencies also recognized a need to improve understanding the mechanisms whereby the ice jams develop and to find means to mitigate their development. They also recognized the importance of on-going training to keep organization personnel adequately informed about the Plan's procedures.

EPILOGUE

Recently, a comprehensive study was completed to determine whether there are measures, physical or operational, that will further significantly reduce the likelihood of ice jam formation and its adverse consequences, flooding and power generation losses, in the upper Niagara River. The study, which was administered by NYPA at the request of FERC, is unusual for its breadth of scope and integration of the methods used to attain its aims.

It was clear at the outset of the study that no simple improvements, or quick fixes, will significantly reduce the incidence of ice jams in the upper Niagara River. Moreover, it was clear that there are no simple ways to determine with assurance that potential modifications will prove effective. The hydraulic characteristics of the upper Niagara River are complex. The interests of numerous concerned parties have to be addressed. Besides, Lake Erie can grow lots of ice. As it may not be practicable to completely eliminate the occurrence of jams in the river, the following three concepts were identified for reducing the incidence of ice jams: retain more ice in Lake Erie; optimize the distribution of ice passing though the river's channel system; and, increase the ice-conveyance capacity of the river at its most congested reach, the GIP. The most attractive concept would seem to be to retain ice in Lake Erie. However, structural and environmental concerns diminish the feasibility of that concept. Redistribution of ice passing through the river's bifurcated channels upstream of Grand Island looks promising, but the engineering details for so doing need further study. The ice-conveyance capacity of the GIP can be increased, but only moderately and at enormous cost, and probably not without raising an environmental ruckus.

Five methods were used to conduct the study: historic-data analyses, field investigations, physical modeling, numerical modeling, and technology assessment. The historic and field investigations were conducted to perform diagnostic re-constructions of events leading, and consequent, to past and recent ice jams, and to provide the data needed to calibrate and verify the physical and numerical models. Considerable effort was spent to identify the instrumentation necessary to provide on-going monitoring of water and ice movement in the river. A central part of the study is a large physical model of the GIP reach. The model was needed because ice transport and ice accumulation processes in that reach involved complicated three-dimensional flows and related nonlinear dynamic processes which could not be adequately investigated with numerical models. It was recognized that physical modeling generally is hindered by several constraints. The dynamic similitude requirements for ice accumulation are deficient, especially similitude requirements and means for scaling the thermal behavior of ice, and the dependency of ice properties on temperature. Additionally, the important influences of unsteady flow and wind could be readily taken into account. Nonetheless, to arrive at any decisions involving potentially expensive and complex constructed works for the river, there was little recourse other than physical modeling.

To circumvent physical modeling limitations, a suite of numerical models was developed to examine water flow, ice conveyance and ice in the river. An innovative aspect of the numerical modeling was its use of the GIP physical model to calibrate and aid formulation of a detailed numerical model of the GIP, particularly in forecasting the effects of channel modifications on flow and ice movement The numerical model, once calibrated and validated, extended the physical model results for a greater range of flow conditions and included the influences of wind and air temperature. Other numerical models examined water and ice movement in the entire upper Niagara River, and the ice-retention performance of ice booms in Lake Erie. The study led to significant advances in physical and numerical modeling of ice transport and accumulation processes for situations similar to those in the upper Niagara River

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