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FLOOD WARNING PLAN
FOR ICE-AFFECTED FLOODING OF THE NIAGARA RIVER

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INTRODUCTION

This paper describes a Plan developed by the New York Power Authority (NYPA), under the oversight of the Federal Energy Regulatory Commission (FERC), as an early warning program for inhabitants and water-related facilities along the upper Niagara River. The river is an important source of hydroelectric energy for the United States and Canada. NYPA's Niagara Power Project and Ontario Hydro's (OH) Sir Adam Beck (SAB) Stations use the enormous flow of the river and its drop over the Falls to produce approximately 4,500 megaWatts of relatively cheap electric power However, the upper Niagara River is prone to sudden flooding caused by ice jams during winter and early spring. The jams may form rapidly, occasionally producing floods that have somewhat of a flash-flood character Concerns for potential flooding of the fairly densely inhabited and industrialized land along extensive portions of the upper Niagara River, coupled with a desire to maximize hydropower production, have required that the river be closely monitored and that well-defined procedures be prepared for responding to imminent and actual flooding.

An interesting feature of flood-risk management on the Niagara River is that a hydropower corporation, NYPA, has been assigned the lead responsibility for flood-risk management, issuing flood warnings, and implementing and funding flood-control measures for a major river The governmental agencies (e g , the US Army Corps of Engineers) who usually have these responsibilities play a secondary role.

The FERC license for operating the Niagara Power Project encumbers on NYPA a responsibility for flood-risk management of the upper Niagara River. This responsibility has required that NYPA prepare a flood warning notification plan (Plan) for use in the event of ice-affected flooding. The Plan contains guidelines typically developed for emergency action plans for the failure of hydropower dams licensed by FERC. Under this arrangement, NYPA does not usurp the overall responsibility of statutory governmental agencies for warning and evacuation of people. The Plan obligates NYPA to identify potential flooding situations through surveillance, to notify the alerting agencies whose jurisdictions may be affected, and to undertake ice-jam flood-mitigation measures. As the upper Niagara River is used jointly by the United States and Canada, implementation of the Plan also requires the participation of OH.

ICE-JAMMING OF THE UPPER NIAGARA RIVER

Hydraulically, the upper Niagara River is a complicated river Its relatively short channel contains complex bathymetry and nominally half of its flow is diverted to off-channel hydropower facilities that involve sophisticated pump-storage operations Hydrologically, the river is relatively simple; flooding along the river is attributable primarily to ice jams. The large size of the Great Lakes watershed drained by the river dampens flow peaks created by individual rain-storm events. Descriptions ensue of the river, its hydropower facilities, and the typical stages of ice-jamming on it

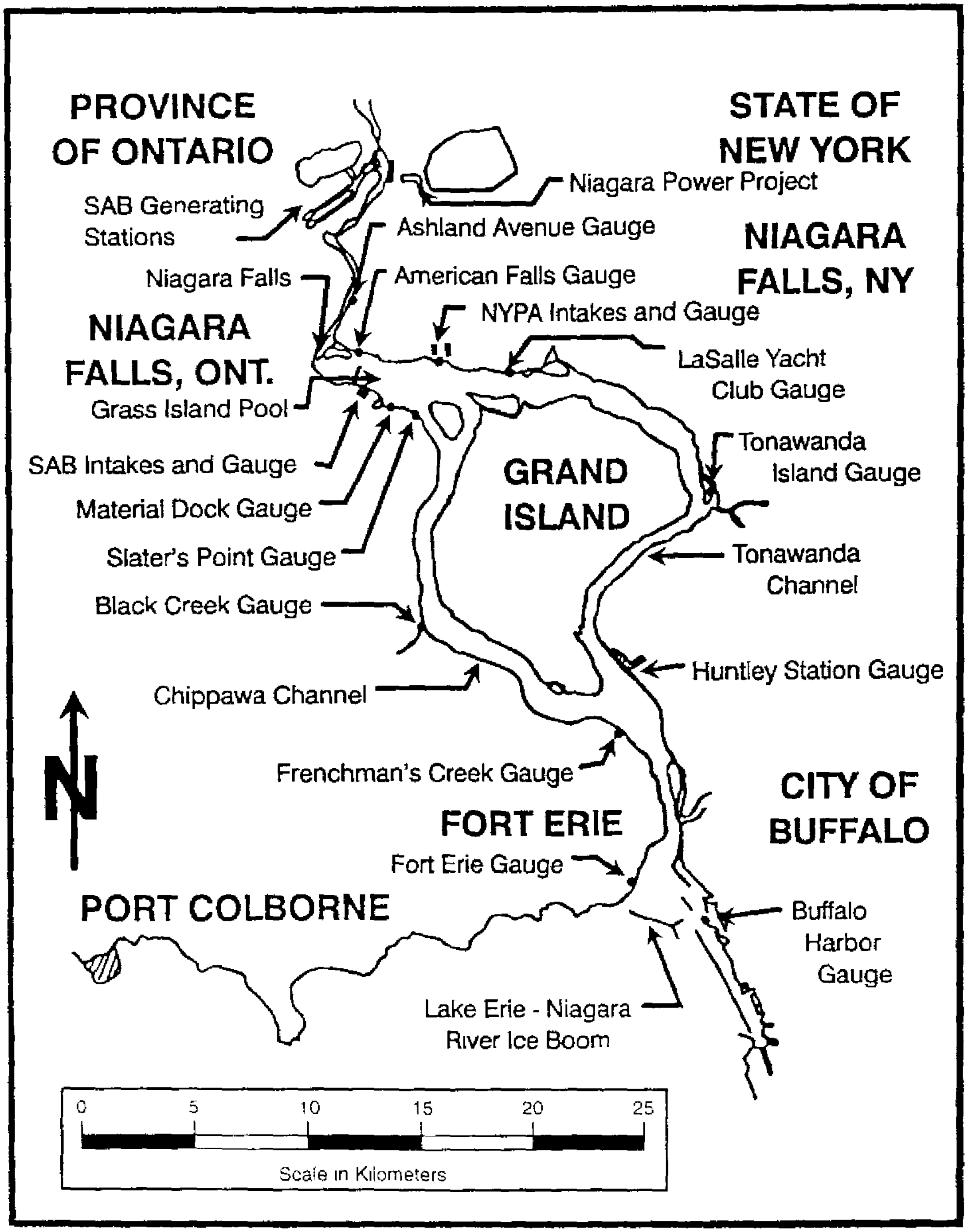

Fig. 1 Map of the upper Niagara River, showing locations of gauges and hydropower facilities

THE UPPER NIAGARA RIVER

The 58-km-long upper Niagara River connects Lake Erie with Lake Ontario, as shown in Fig. 1. The difference in elevation between the two lakes is about 100 m, about half of which occurs at Niagara Falls. The river drains an area of approximately 684,000 km^2. Its average annual flow is approximately 5,700 m^3/s, though its monthly mean flow has been as low as 2,800 m^3/s and as high as 7,350 m^3/s. At Grand Island, the river divides into two channels, the Chippawa and the Tonawanda. The Chippawa Channel is approximately 18 km long, whereas the Tonawanda Channel is approximately 24 km long. During periods when the flow is not affected by weed growth or ice, the Chippawa and Tonawanda Channels carry about 58% and 42%, respectively, of the total river flow. At the downstream end of Grand Island, the channels unite to form a wide and shallow reach called the Grass Island Pool (GIP), whose main features are shown in Fig. 2.

Flow into the river is controlled by the water elevation at the outlet of Lake Erie, but it can be restricted, by up to 1,400 m^3/s, due to backwater effects caused by ice accumulations in the river. Hourly and daily flow variations occur during wind setup events on Lake Erie resulting from sustained southwesterly winds. Lake Erie elevations at Fort Erie can increase by as much as 2.5 m and flows into the Niagara River can increase concomitantly by as much as 2,800 m^3/s during those events The high flows associated with wind setup reach the GIP in about two hours. Ice entering the river from Lake Erie, though, takes about 12 hours to drift to the GIP, provided it does not jam. Water levels on the upper Niagara River are measured at ten gauges upstream of a flow-stage regulation structure, called the International Control Structure (ICS), in the GIP. The gauges are monitored and recorded in real-time to provide information for hydropower operations and early warning of flooding events

HYDROPOWER FACILITIES

NYPA's Niagara Power Project, situated on the Niagara River at Lewiston, New York, was built in the early 1960s and has a generating capacity of 2,400 megaWatts. Water for the Niagara Power Project and OH's Beck Generating Stations, which were built between 1920 and 1960, is diverted from the GIP just upstream of Niagara Falls (Fig. 1). The combined generating capacity of the NYPA and OH stations is about 4,500 megaWatts. Diversions for hydropower production are made in accordance with the terms of the 1950 Treaty Between the US and Canada Concerning the Uses of the Waters of the Niagara River The Treaty had two primary objectives. to permit the development of substantial low-cost power generation from the waters of the Niagara River, and, to preserve and enhance the scenic beauty of Niagara Falls. To meet these objectives and to reduce the impacts of ice on power generation, both structural and non-structural measures were implemented by NYPA and OH (including an ice boom, a flow-control structure and the Buckhorn Dikes indicated Figs 1 and 2) Auxiliary non-structural procedures for minimizing ice effects include the use of icebreakers and an ice monitoring program. The procedures and program are described subsequently

The treaty requires that flows over Niagara Falls exceed 2,832 m^3/s during tourist hours and 1,416 m^3/s during non-tourist hours. Tourist hours are from 8 a.m. to 10 p.m between April 1 and September 15 and from 8 a m. to 8 p m between September 15 and October 31. During the tourist season, water levels in the GIP and the hydropower diversions fluctuate, within regulatory limits, on a daily basis to meet the Falls flow requirements and maximize diversions for power production During the non-tourist season, between November 1 and March 31, the daily level of the GIP and diversion-flow fluctuations are typically less All of the water not used to satisfy the Falls flow requirement of the 1950 Treaty is available for hydroelectric power generation.

NYPA's Niagara Power Project diverts water from the GIP through two intakes located about 4 km upstream of Niagara Falls (Fig 2). The upper sill of each intake is submerged about 5.5 m below the surface of the GIP, is aligned parallel to the north bank of the GIP, and is about 180 m long. Each intake

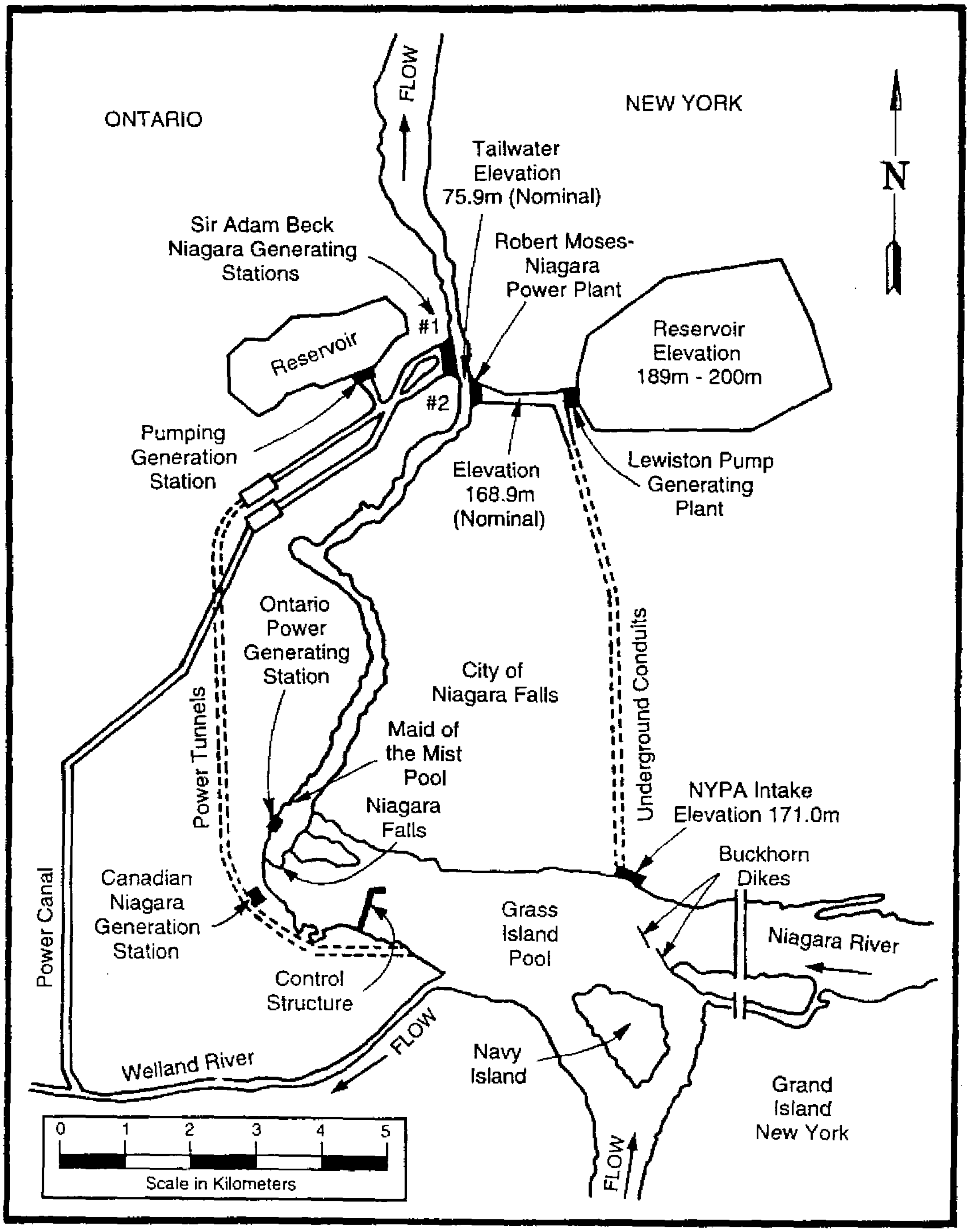

Fig. 2. Layout of hydropower facilities on the Niagara River

has evenly spaced, vaned openings that decrease in height with distance downstream, from a maximum height of about 8 m to about 4 m. The hydraulic capacity of the two conduits that deliver the water to the Niagara Power Project is about 2,800 m^3/s. OH's hydropower diversions for its Beck (SAB) generating stations are made through intakes located on the Canadian shore of the GIP and upstream of the International Control Structure (ICS). The combined capacity of the OH intakes is about 1,900 m^3/s.

The ICS is located about 1 6 km upstream from the Niagara Falls. It extends from the Canadian shore over one-half the distance across the river. It has eighteen 30m-wide movable gates to control water levels in the GIP. When the gates of the ICS are fully closed and, if the GIP is at normal levels and flows are not affected by weeds or ice, then about 1,400 m^3/s flows around the ends of the ICS toward Niagara Falls.

Ice escape channels, excavated on both sides of the river when the power projects were built, reduce the potential for ice grounding and maintain ice movement past the intakes (Fig. 2). The ice escape channel near the NYPA intakes was excavated to a minimum depth of 2.5 m. The ice escape channel on the US shore has a minimum depth of about 3 m in the first 150 m extending from the US shore and just downstream of the NYPA intakes and a minimum depth of about 1.8 m in the other areas. Two guidebanks, with overall length of 640 m, called the Buckhorn Dikes, are located at the northern tip of Grand Island to constrict the flow, thereby increasing water velocities to enable ice to drift more easily past the NYPA intakes. They were constructed at the time the NYPA intakes were built.

Every year since 1964, NYPA and OH have installed an ice boom at the head of the Niagara River (Fig 1) to reduce the volume of ice that may enter the Niagara River from Lake Erie. The ice boom hastens the formation and stabilization of an ice arch that normally forms every winter near the head of the river. Once the ice arch forms upstream of the ice boom it transfers, to the lake shore, water and wind drag loads exerted on the ice. On occasion, storms may destabilize the ice arch and drive large masses of ice against the boom. When this happens, the boom is designed to submerge rather than fail under the high loads to which it is subjected, and ice overrides it until the load is relieved.

ICE-JAM FLOODING

Since inception of the Niagara Power Project and Beck generating stations, NYPA and OH have collected valuable information on the ice, hydraulic, and meteorological conditions during lake ice runs This information and the years of operating experience have been used to develop winter operating procedures aimed at minimizing the impacts of ice on power generation.

Ice jamming in the upper Niagara River occurs in nine chronologically ordered stages:

(i) Ice Formation on Lake Erie. The shallowest and smallest in volume of the Great Lakes, Lake Erie typically generates the most ice relative to its surface area. Ice thickness in the lake can be roughly related to the accumulated freezing degree-days after the water temperature reaches 0° C throughout the lake. The typical mid-winter ice cover thickness is 0.30 to 0.40 m. However, the thickness of ice in the lake can vary substantially due to thermal and mechanical processes.

(ii) Storms and Wind Setup on Lake Erie. Lake ice is susceptible to being fractured, rafted, ridged, and moved about, particularly in the early winter. This typically occurs when cold fronts, having wind speeds of 50 to 80 km/hr, move across the lake. The winds, typically aligned with the major axis of the lake (SW to WSW direction), also generate wind setups on the lake before the cover is consolidated that can raise the water level at Buffalo by 2.0 m or more. The increase in water level increases the discharge into the upper Niagara River by 50% or more. The passages of the cold fronts are also normally accompanied by 10° to 15° C declines in the air temperature.

(iii) Ice Transport Past the Lake Erie - Niagara River Ice Boom. Under the right combination of weather and ice conditions, lake ice can enter the upper Niagara River, as shown in Fig 3, at rates and in quantities large enough to cause ice jamming in the GIP and the Tonawanda Channel In almost all of these cases, the ice runs occur with the ice boom in place. They can be classified as either early freeze-up, late freeze-up, early break-up, or late break-up, depending on the accumulated freezing degree-days between the day the lake water temperature reaches 0° C and the day on which the ice run occurs.

(iv) Discharge Variation During Lake Ice Runs. The discharge in the upper Niagara River is highly unsteady during lake ice runs leading to ice jams. It normally increases to a maximum above the calm lake level flow within 12 hours and, more important, declines to below the calm lake level flow within 12 to 24 hours of the peak discharge, because ice in the river can restrict flow out of Lake Erie. Ice in the river also affects the distribution of flow around Grand Island. About 42% of the total flow is carried by the Tonawanda Channel in open water. During severe ice conditions, however, the channel may carry only 20% of the total flow. A one-dimensional, unsteady model of flow in the upper Niagara River was used to assess the impacts of ice on the distribution of flow around Grand Island for the five historical lake ice runs (Crissman et al. 1993). The model's Kalman filtering technique provided feedback, from water level measurements during the events, that was used to adjust the resistance coefficients to account for the presence of ice in the river. The discharge restriction in the Tonawanda Channel is important, because it reduces the ice transport capacity of the channel.

(v) Transport of Lake Ice Within the Upper Niagara River. It has been observed that the ice hugs the downwind bank as it moves downstream. Since ice runs occur when the winds are from the SW or WSW, most of the ice in a lake ice run enters the Tonawanda Channel. The ice discharge capacity of the upstream end of the Tonawanda Channel varies with time. When the ice discharge capacity is exceeded, ice transport will be shifted into the Chippawa Channel. Typically, it takes about 10 to 12 hours for the leading edge of an ice run to enter the GIP by way of the Tonawanda Channel. Ice that enters the GIP by way of the Chippawa Channel and the Little West Channel enters the GIP about 8 to 10 hours after leaving Lake Erie. The actual travel times are related to the severity of the wind, the magnitude of the river flow, and the ice conditions.

Fig. 3. Ice enters the upper Niagara River at Buffalo, New York.

(vi) Initial Movement of Ice Into the Grass Island Pool. The patterns of ice inflow into the GIP are quite variable, but fall into three cases based on the first arrival of ice. In the first case, ice first enters the GIP