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Modification of Great Lakes Regulation Plans for Simulation of Maximum Lake Ontario Outflows

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ABSTRACT. *Nearly 50,000 years of Lake Ontario outflows were simulated and analyzed as a part of the Hydro-Québec Beauharnois-Les Cèdres spillway rehabilitation study. Historical Lake Ontario outflows could not be used for the study because of anthropogenic effects reflected in the data, the statistically short record length, and autocorrelation of the data. Stochastically generated Great Lakes net basin supplies were used in a Great Lakes hydrologic response model to obtain Lake Ontario levels and outflows. A significant problem was the lack of robustness in the Lake Superior and Lake Ontario regulation plans during simulations with extreme water supplies. The regulation plans were modified consistent with the International Joint Commission's regulation criteria and past operational actions to give reasonable results under these conditions. The simulated Lake Ontario levels and flows had a greater range than those resulting from historical water supplies. The maximum simulated Lake Ontario quarter-monthly level was 76.41 m (IGLD 55), and the maximum simulated quarter-monthly outflow was 14,160* m^3s^{-1}. *The maximum-flow limitation of Lake Ontario's regulation plan, 8,780* m^3s^{-1}, *was exceeded 0.27% of the time. The upper lake-level regulation limit, 75.22 m, was exceeded 0.15% of the time. It was found that some of the regulation criteria cannot be met simultaneously under extreme conditions. Historical water supplies, the current standard for the design and evaluation of modifications to the operational regulation plans, should no longer be the sole test of the plans.*

INDEX WORDS: *Lake Ontario, water levels, water supplies, flows, regulation, frequency analysis.*

INTRODUCTION

Hydro-Québec recently undertook a study of the spillway adequacy of the Beauharnois-Les Cèdres control structures located in the St. Lawrence River, upstream of Montreal, Québec. One approach used to determine the design flood was the stochastic generation and frequency analysis of St. Lawrence River flows. This required the simulation of Lake Ontario outflows which constitute the major portion of the St. Lawrence River flows at the Beauharnois-Les Cèdres complex. Recorded Lake Ontario outflows, although one of the longest time series of hydrologic data in North America (1860-present), could not be used to determine the design flood because anthropogenic changes, such as lake regulation, diversions, and connecting channel dredging, are reflected in the recorded data. In addition, the record length is statistically short, and autocorrelation is present in the data.

Simulation can create a long series of Lake Ontario outflows under a consistent hydraulic and hydrologic regime sufficient for frequency analysis. This approach, however, is not without difficulties. First, the hydrologic response of the entire Great Lakes system must be simulated because the outflows of Lake Ontario are a function of the inflow received from the upper lakes. Second, in simulating the hydrologic response of the lakes, water supplies are required as inputs to the regulation and routing models to determine outflows. These supplies must replicate the spatial and temporal characteristics of the observed data. And third, the Lake Superior and Lake Ontario regulation plans have been designed based on historical sequences of water supplies and were found to lack robustness during simulations with more extreme conditions. These problems were addressed by Hydro-Québec for the simulation of nearly 50,000 years of Lake Ontario outflows. The modification of the regulation plans for extreme conditions is reported here along with a summary of the simulation of Great Lakes water supplies (reported in detail by Rassam *et al.* 1992). The results of the simulated Lake Ontario levels and outflows are presented.

THE STUDY AREA

The area of interest for this study is the Great Lakes drainage basin above Lake Ontario's control structures, located in the St. Lawrence River between Massena, New York and Cornwall, Ontario. Figure 1 illustrates the basin geography. Lake Superior is also regulated; its control structures are located in the St. Marys River between the twin cities of Sault Ste. Marie, Michigan and Ontario. The regulation of Lake Superior and Lake Ontario is conducted under the auspices of the International Joint Commission (IJC) and its Boards of Control. The criteria, or guidelines, for the regulation of these two lakes (summarized in Appendices I & II) are set forth in Orders and Supplementary Orders of Approval issued by the IJC. Regulation plans which strive to satisfy these criteria have been developed and are incorporated in hydrologic routing models maintained by the U.S. Army Corps of Engineers and Environment Canada.

The middle lakes (Michigan, Huron, and Erie) are naturally controlled by the hydraulics of their outlet channels. Lake Michigan and Lake Huron are connected by the deep Straits of Mackinac and act as one lake hydraulically. Lake Erie exerts a backwater effect on Lakes Michigan-Huron via the St. Clair River-Lake St. Clair-Detroit River system. The Niagara River connects Lake Erie with Lake Ontario.

Three diversions exist which link the Great Lakes drainage basin to other major basins. The Long Lac and Ogoki Diversions transport water from the Hudson Bay watershed to Lake Superior. The Chicago Diversion links Lakes Michigan-Huron with the Mississippi River Basin. One intra-basin diversion exists, the Welland Canal, which diverts water from Lake Erie to Lake Ontario.

MODIFICATION OF THE LAKE SUPERIOR AND LAKE ONTARIO REGULATION PLANS

The Lake Superior and Lake Ontario regulation plans have been developed based on historical sequences of water supplies. Because of this, the plans lack robustness during simulations with water supply sequences more extreme (higher or lower and of longer duration) than those observed. Specifically, with low supply sequences, the minimum outflows called for by the plans are greater than the water supplies to the lakes. As a result, the lake levels fall below the lakes' lower regulation limits. With high supply scenarios, water supplies exceed the plans' maximum outflows and result in lake levels much higher than the upper regulation limits. In actual practice, when extreme conditions are experienced, the flow limitations are relaxed (as downstream conditions permit), and the regulatory works are operated under the direction of the IJC and its Boards of Control to best meet the needs of the various interests.

The regulation plans' responses to an extreme high supply scenario and an extreme low supply scenario are illustrated in Table 1. The 5-year supply scenarios are based upon a Great Lakes precipitation index for 1860 to 1988 (Quinn 1991). For the high supply scenario, the 5 wettest years were selected and arranged in ascending order. Modeled or recorded values of monthly basin runoff and recorded precipitation for these years were combined with an extreme low sequence of stochastically generated values of lake evaporation to obtain the sequence of net basin supplies. The low supply scenario was developed in the same manner using the 5 driest years arranged in descending order and an extreme high sequence of lake evaporation. Levels and flows were then calculated using the supply scenarios with the regulation plans and middle lakes routing models obtained from Environment Canada. Note that these models reference water levels to the International Great Lakes Datum of 1955 (IGLD 55), and their results have been converted to metric from English units. In the following paragraphs, the regulation limitations are shown in metric units and in English units to provide continuity in references to the Orders of Approval, summarized in Appendices I & II.

With respect to the high supply scenario, Lake Superior's end-of-month level reaches a maximum of 184.82 m (Table 1), but the monthly outflow associated with this level is 1,560 m^3s^{-1} (55,000 cfs), the minimum flow limitation. In an effort to main-

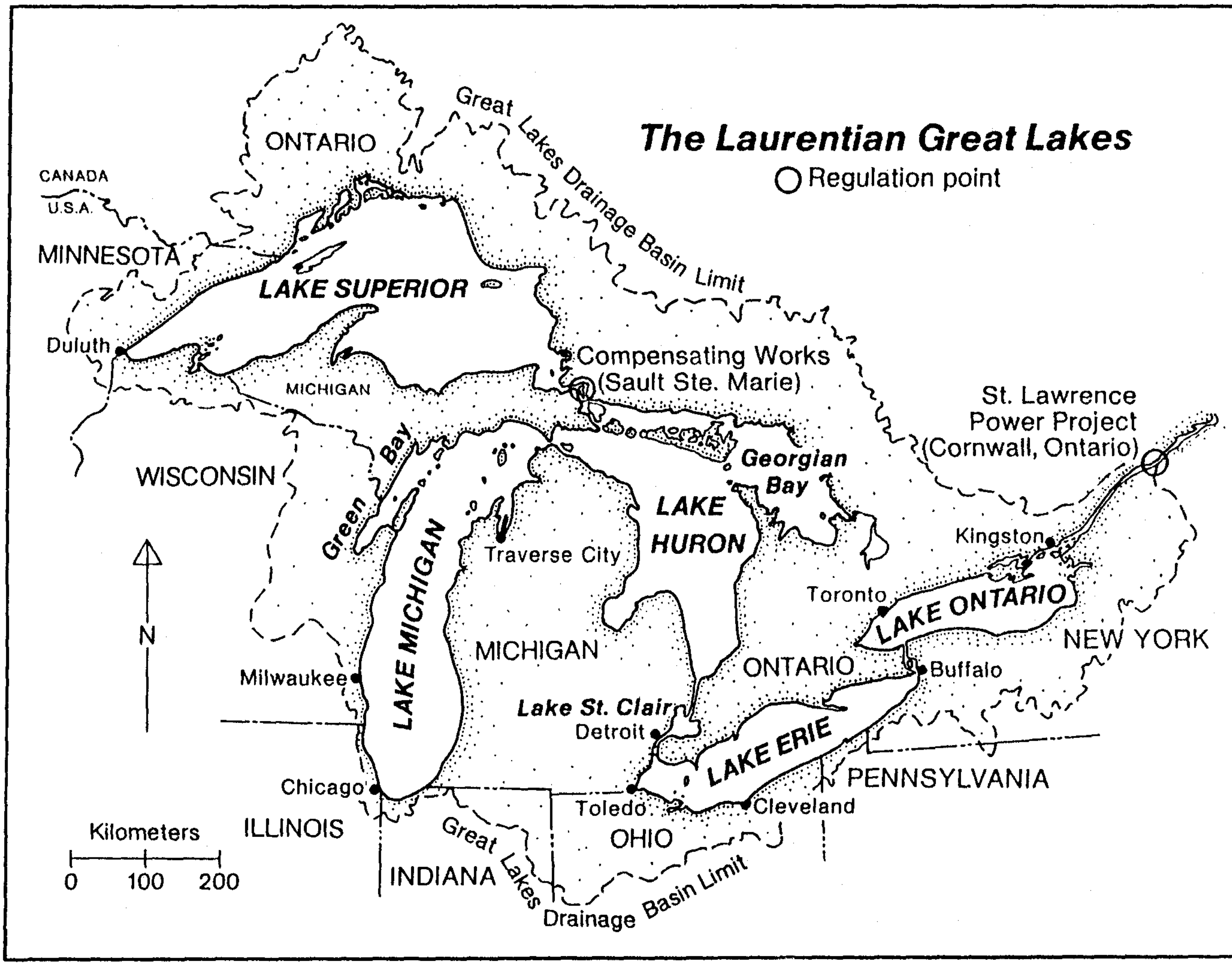

FIG. 1. Great Lakes-St. Lawrence River system.

TABLE 1. Levels and associated outflows obtained with extreme high and low five year water supply scenarios with unmodified regulation plans.

	High Supply Scenario		Low Supply Scenario	
Lake	Max. Level (m)	Outflow (m^3s^{-1})	Min. Level (m)	Outflow (m^3s^{-1})
Lake Superior[1]	184.82	1,560	182.01	1,560
Lakes Michigan-Huron[1]	177.76	7,450	174.29	3,090
Lake Erie[1]	175.24	8,840	172.48	3,260
Lake Ontario[2]	80.92	8,780	69.15	5,470

[1]End-of-month levels and monthly outflows
[2]End-of-quarter-month levels and quarter-monthly outflows

tain levels downstream of the control structures under 177.67 m (582.9 ft—an aspect of Criterion (b), refer to Appendix I) the plan reduced outflows to the minimum flow limitation. But as Lakes Michigan-Huron's level also increased, the level below the Lake Superior control structures could not be maintained below 177.67 m due to the backwater effect transmitted via the lower St. Marys River. For this scenario, portions of the control structures would be overtopped (overtopping is estimated to occur at 184.71 m). The operation of the control structures in this manner would be unlikely in actual practice and is inconsistent with previous actions taken by the IJC to alleviate Lake Superior levels above 183.49 m (602.0 ft) (International Lake Superior Board of Control 1985). Likewise, with the extreme high scenario, Lake Ontario's end-of-quarter-month levels rise to 80.92 m with the plan specifying a quarter-monthly outflow of 8,780 m^3s^{-1} (310,000 cfs), the maximum outflow limitation. As recently as May, 1993, the St. Lawrence River Board of Control increased outflows above 8,780 m^3s^{-1}, to as high as 10,900 m^3s^{-1} when lake levels exceeded 75.22 m (246.77 ft), the upper level limitation (International St. Lawrence River Board of Control 1993). During this period, Lake Ontario levels reached 75.50 m (Fay, Great Lakes-St. Lawrence Regulation Office, Environment Canada, personal communication, 1994).

Results are also shown in Table 1 for the regulation plans' response to the extreme low water supply scenario. Lake Superior and Lake Ontario water levels fall below their lower regulation limits of 182.39 m (598.4 ft) and 74.00 m (242.77 ft), respectively. Lake Ontario's response to the low supply scenario is particularly dramatic, with a minimum end-of-quarter-month level of 69.15 m. In both cases, the low levels result from prolonged periods of supplies lower than the minimum outflow limitations specified in the regulation plans.

However, for the successful simulation of water levels and outflows from a long series of stochastically generated supplies, some operational rules must be derived for extreme conditions and incorporated within the regulation programs. Thus, the primary goal here was to implement simple rules of operation for extreme conditions which were consistent with the IJC's regulation criteria and past operational actions.

Lake Superior Regulation Plan Modifications

Lake Superior's current regulation plan, Plan 1977-A, was implemented in June, 1990 by the Lake Superior Board of Control (International Lake Superior Board of Control 1990). The plan was designed and tested based on water supplies to the Great Lakes experienced from 1900 through 1986. The plan's main objective is to specify an outflow from Lake Superior for the coming month which balances the positions of Lake Superior and Lakes Michigan-Huron levels relative to their long-term monthly mean levels. The plan strives to maintain Lake Superior levels between 182.39 m (598.4 ft) and 183.49 m (602.0 ft) in accordance with Criterion (a) of the Orders of Approval and to prevent the St. Marys River level below the control structures from rising above 177.67 m (582.9 ft) in accordance with Criterion (b).

To make the plan more robust under low supply conditions, the regulation plan was modified consistent with Criterion (c) (Appendix I). Criterion (c) requires that when Lake Superior's level falls below 183.03 m (600.5 ft), the regulated outflow can be no greater than what it would have been under the discharge conditions which existed prior to 1887. These conditions are often referred to as "pre-project" conditions and have traditionally been represented by the single stage-discharge relationship:

$$Q_S = 823\ (L_M - 180.96)^{1.5} \tag{1}$$

where Q_s is the Lake Superior outflow (m^3s^{-1}), and L_M is the level of Lake Superior (m, IGLD 55) at Marquette, Michigan. Thus, when Lake Superior's level falls below 183.03 m (600.5 ft), the "pre-project" flow is specified if it is less than the plan's flow, even if it is below the minimum flow limitation of 1,560 m^3s^{-1} (55,000 cfs). In the operational regulation of Lake Superior, Criterion (c) has been applied by a manual check of the conditions after the results of the regulation program were obtained.

The pre-project stage-discharge relationship that was used for this study differs slightly from that given in Equation 1. Southam and Larsen (1990) have shown that this relationship can only be applied for the period 1860-1887 for which it was developed, due to the impact of crustal movement over time at the Marquette gage location. Southam and Larsen (1990) have proposed a pre-project stage-discharge relationship based on the original equation, adjusted to the Pt. Iroquois gage. The effect of crustal movement relative to the lake's outlet is small at this site in comparison to the Marquette site. Differences between lake-wide average conditions and levels recorded at Pt. Iroquois have been shown to be small (generally less than 1 cm) and change little over time (Lee and Southam 1994). Southam and Larsen's (1990) findings are supported by those of Quinn (1978). The relationship used here is that proposed by Southam and Larsen (1990):

$$Q_S = 823\ (L_P - 181.05)^{1.5} \tag{2}$$

where Q_S is the Lake Superior outflow (m^3s^{-1}), and L_P is the level (m, IGLD 55) of Lake Superior at Pt. Iroquois, Michigan. Beginning in 1993, and subsequent to the completion of the study reported here, the International Lake Superior Board of Control adopted Equation 2 for computing outflows under Criterion (c).

To make the plan more robust under conditions of high supplies, Plan 1977-A was modified such that above 183.49 m (602.0 ft), the regulated outflow is that which would have occurred under pre-project conditions, using Equation 2. This modification was added to prevent unreasonably high Lake Superior levels during simultaneous conditions of high Lake Superior and Lakes Michigan-Huron levels as illustrated earlier. Criterion (b) indicates that only *excess* flow above pre-project flows are to be restricted in order to maintain levels below the control structures less than 177.67 m (582.9 ft). Thus, when conditions are such that Criterion (b) cannot be satisfied due to backwater effects from Lake Michigan-Huron, it seems reasonable to specify pre-project flows.

Provisions were also made within the regulation plan in the unlikely event that supplies and levels were so extreme that overtopping of the locks, dikes, and other structures associated with the control works would occur even with the above modification. A stage-discharge relationship was estimated based on the momentum principle applied to flow over a broad crested weir (Chow 1959) and the length of the crest line of the locks, dikes, and associated structures (U.S. Army Corps of Engineers 1991):

$$Q'_S = 3{,}803\,(L_S - 184.71)^{1.5} \qquad (3)$$

where Q'_S is the flow overtopping the dikes, locks, and associated structures in m^3s^{-1}, L_S is the Lake Superior level in m (IGLD 55). In the event of overtopping, the flow computed by Equation 3 is then added to that of the capacity of the control structures.

The effect of the modified plan on levels and flows with the extreme high and low supply scenarios is shown in Table 2. With respect to the high supply scenario, Lake Superior's maximum end-of-month level is reduced by almost 0.9 m with the modified plan when compared to that of the unmodified plan (Table 1). The reduction in Lake Superior levels results in a corresponding rise of about 0.4 m and 0.3 m in Lakes Michigan-Huron and Lake Erie's maximum end-of-month levels, respectively.

TABLE 2. Levels and associated outflows obtained with extreme high and low five year water supply scenarios with modified regulation plans.

Lake	High Supply Scenario		Low Supply Scenario	
	Max. Level (m)	Outflow (m^3s^{-1})	Min. Level (m)	Outflow (m^3s^{-1})
Lake Superior[1]	183.94	3,680	182.14	1,020
Lakes Michigan-Huron[1]	178.17	8,130	174.21	3,000
Lake Erie[1]	175.51	9,570	172.44	3,140
Lake Ontario[2]	76.27	14,160	72.86	3,620

[1]End-of-month levels and monthly outflows
[2]End-of-quarter-month levels and quarter-monthly outflows

Lake Ontario Regulation Plan Modifications

Lake Ontario's current regulation plan, Plan 1958-D, was implemented in 1963. The plan was designed and tested based on water supplies to the Great Lakes experienced from 1860 through 1954. The plan's objective is to control levels and outflows such that the criteria in the Orders of Approval (Appendix II) are satisfied and to protect or provide advantages to the various interests (International St. Lawrence River Board of Control 1963). The interests include upstream and downstream riparians, hydropower, and navigation. The plan strives to maintain lake levels between 74.00 m (242.77 ft) and 75.22 m (246.77 ft), and limits outflows to an annual range of 5,320 m^3s^{-1} (188,000 cfs) to 8,780 m^3s^{-1} (310,000 cfs).

To improve the plan's robustness for conditions of low supply, a rule similar to that employed for Lake Superior was implemented. Below Lake Ontario levels of 74.00 m (242.77 ft), the minimum flow limitations were waived and a Lake Ontario pre-project discharge relationship was used to determine the regulated outflow. The level of 74.00 m (242.77) was selected because Criterion (j) of the Orders of Approval (Appendix II) specifies that the lake shall be maintained at or above this elevation during the majority of the year (April through November). The pre-project relationship (Dumont and Fay 1990), corrected for isostatic rebound at Oswego, New York relative to the lake's outlet for 1903 to 1992, is:

$$Q_O = 578\,(L_O - 69.48)^{1.5} \qquad (4)$$

where Q_O is the Lake Ontario outflow (m^3s^{-1}), and L_O is the level (m, IGLD 55) of Lake Ontario.

To increase the plan's robustness for conditions of high supply, the Lake Ontario regulation plan was modified considering past operational actions taken by the St. Lawrence River Board of Control during 1974-1989, a period during which high supplies and lake levels dominated. Deviations from the regulation plan made by the Board are reflected in the recorded levels and flows for this period. In making a decision to deviate from the plan, the Board takes into consideration many factors including expected total supplies, river ice cover stability, and potential upstream and downstream damages. Because this complex decision process cannot presently be incorporated into the existing regulation plan, various modifications of the plan were made such that simulated monthly levels and flows for 1974-1989 matched as closely as possible the recorded levels and flows. The evaluation of the modified plans was based on comparisons of monthly statistics (correlation and root mean squared error) of the simulated levels and flows versus those recorded. Initially, three approaches were considered to explore possible plan modifications. Figure 2 illustrates the concepts of these approaches.

With the first approach, when lake levels rose above 75.22 m (246.77 ft), the outflows necessary to maintain that level were specified without consideration of the plan's flow limitations. This approach essentially ignored several criterion of the Orders of Approval which were established to protect downstream interests from flows more extreme than would have occurred prior to the project. To preserve physical channel contraints on the outflow, the outflow was limited by the channel capacity, given by the following relationship:

$$Q_O' = 747\,(L_O - 68.94)^{1.47} \qquad (5)$$

where Q_O' is the maximum possible Lake Ontario outflow (m^3s^{-1}) for Lake Ontario level L_O (m). The channel capacity curve was developed based on data from a steady-state model of the International Rapids Section of the St. Lawrence River, calibrated for high flows (Sparks 1992). Nonlinear regression was used to fit the data to the standard form of a stage-discharge relationship. It represents the maximum flow which could be evacuated with all gates open at the Long-Sault Dam with no flow through the Moses-Saunders power station (worst case scenario).

With the second approach, when levels rose above 75.22 m (246.77 ft), outflows were specified by the plan's rule curves. The rule curves specify outflows as a function of lake levels and the previous months' trend in water supplies, and adjusted for the appropriate season. The rule curves were originally designed to maintain flows below chan-

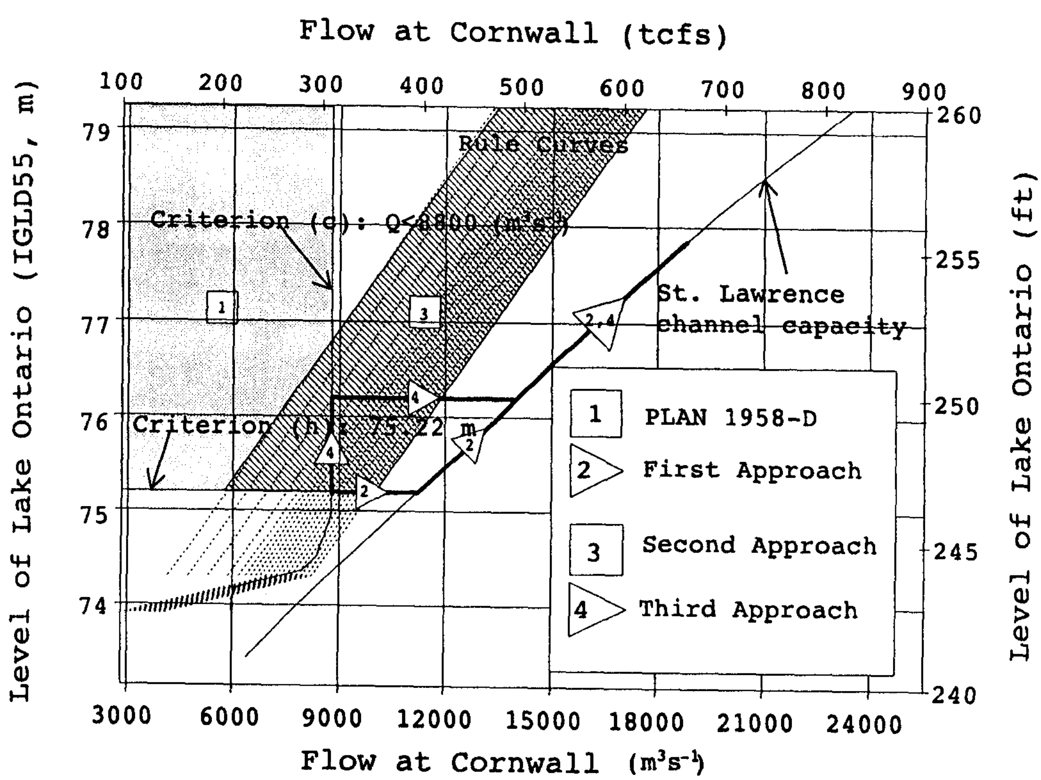

FIG. 2. Proposed Lake Ontario simulation schemes for extreme conditions (Sparks 1992).

nel capacity, thus the channel capacity constraint was not applied to this approach.

With the third approach, storage of excess inflow up to a threshold lake elevation of 76.20 m (250.00 ft) to avoid downstream damages was implemented. Thus, Plan 1958-D specified the outflows when levels were below 76.20 m. Above this elevation, the outflows required to maintain that level were specified, and were only constrained by the channel capacity.

Simulations using the modified plans were conducted with the conditions summarized in Table 3 and recorded water supplies. Inflows to Lake Ontario from the upper lakes were computed using the modified Lake Superior regulation plan and the middle lakes routing. The results of the three approaches were useful in that they provided insight into the tradeoffs required in balancing levels and outflows. However, none of these initial modifications satisfactorily reproduced the recorded 1974-1989 flows.

Subsequent variations of the three approaches were undertaken. In all, thirteen modified plans were evaluated. The best modified plan was a combination of the second and third approaches, and modified outflow limitations. The modified plan operated in the following manner. Below lake levels of 74.00 m (242.77 ft), Lake Ontario outflows were specified by pre-project outflows (Equation 4), as described previously. Between elevations 74.00 m (242.77 ft) and 76.20 m (250.00 ft), Plan 1958-D specified the outflows, subject to modified outflow limitations. Above 76.20 m, outflows were determined by the rule curve flow plus the flow needed to reduce any storage above 76.20 m. Figure 3 illustrates the selected simulation scheme.

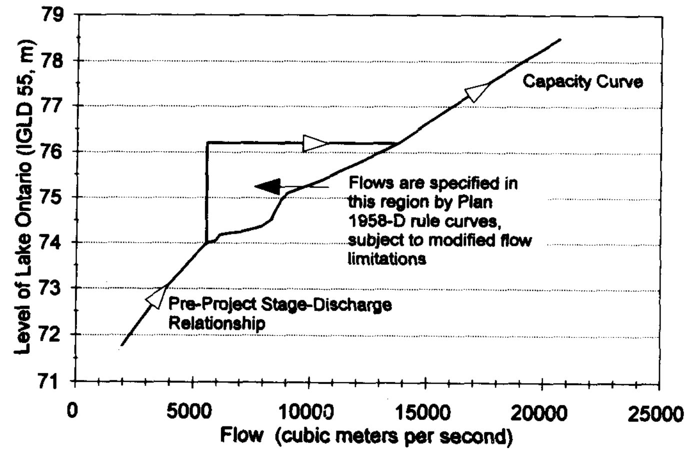

FIG. 3. Selected Lake Ontario simulation scheme for extreme conditions.

The plan's flow limitations were modified as follows. In order to increase winter flows, the maximum winter "L" limitations were increased from 6,230 m^3s^{-1} (220,000 cfs) to 6,680 m^3s^{-1} (236,000 cfs) for the last three quarters of January, from 6,800 m^3s^{-1} (240,000 cfs) to 7,930 m^3s^{-1} (280,000 cfs) for February, and 7,930 m^3s^{-1} to 8,500 m^3s^{-1} (300,000 cfs) for March. The "L" limitations were originally developed based on permissible limiting depths and velocities for navigation and the development of ice cover. However, winter conditions often permit the release of flows greater than the plan's limitations. These modifications were originally proposed during the Lake Erie Water Level Study (International Lake Erie Regulation Study Board 1981). The April to December "L" limitations were also increased. Above 74.97 m (245.96

TABLE 3. Conditions of the hydraulic regime.

Item		Conditions
diversion rates	1)	a constant Chicago diversion of 91 m^3s^{-1} out of Lake Michigan
	2)	a constant Long Lac and Ogoki diversion of 153 m^3s^{-1} into Lake Superior, the average of recorded monthly flows from 1944 to 1989
	3)	monthly mean values of the Welland Canal diversion from Lake Erie into Lake Ontario based on the recorded monthly flows from March 1973 to December 1989
outlet conditions	1)	Lake Superior outflows determined in accordance with Plan 1977-A as modified
	2)	Lake Ontario outflows determined in accordance with Plan 1958-D as modified
	3)	Lake Huron and Lake St. Clair channel conditions since the completion of the 8 m navigation channel dredging in 1962
	4)	Niagara River channel conditions representative of the period 1974-1986
ice and weed retardation	1)	St. Clair River and Detroit River monthly median retardation values based on computed retardation from 1962 to 1989
	2)	Niagara River monthly average values of weed retardation computed for 1974 through 1989 and median ice retardation values as computed from 1974 through 1989

ft) and 8,780 m^{3}s^{-1} (310,000 cfs), the flow limitation curve was extended to where it intersected the capacity curve at 76.20 m (250.00 ft) - 13,760 m^{3}s^{-1} (486,000 cfs). Above 76.20 m, the capacity curve became the April to December "L" limitation. The original "L" limitations are shown in Figure 4a, and the modified limitations are shown in Figure 4b.

The "P" limit (designed to limit the deviation of the regulated flows from pre-project flows) was waived when the elevation 75.22 m (246.77 ft) was exceeded or the rule curve flow exceeded 8,780 m^{3}s^{-1} (310,000 cfs). The "I" limitation was also waived. This limitation was originally incorporated for the development of a stable ice cover at a structure which was to be located below Montreal. This structure was never built, and in practice, the "I" limit is ignored. The "J" limitation, which restricts flow changes to plus or minus 565 m^{3}s^{-1} (20,000 cfs), was modified such that when the lake level was greater than 76.20 m (250.00 ft) or the rule curve flow was greater than 8,780 m^{3}s^{-1} (310,000 cfs), flow changes of plus or minus 1,130 m^{3}s^{-1} (40,000 cfs) were allowed.

The monthly flows simulated with the selected modified plan were generally comparable to the recorded monthly flows for 1974-1989 as shown in Figure 5. The outflows calculated by the unmodified plan are also shown for comparison. Simulated flows during the winter months did not match actual flows as well as during the remainder of the year because the modified flow limitations were still smaller than the actual flows released.

The correlation and root mean squared error be-

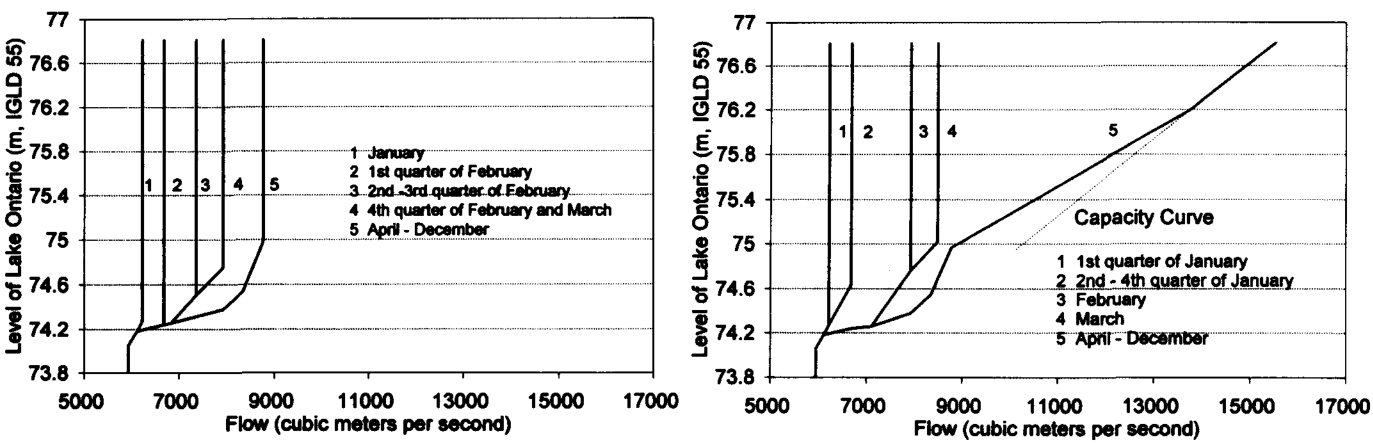

FIG. 4. (left–a) Original Lake Ontario "L" limitations and (right–b) modified Lake Ontario "L" limitations.

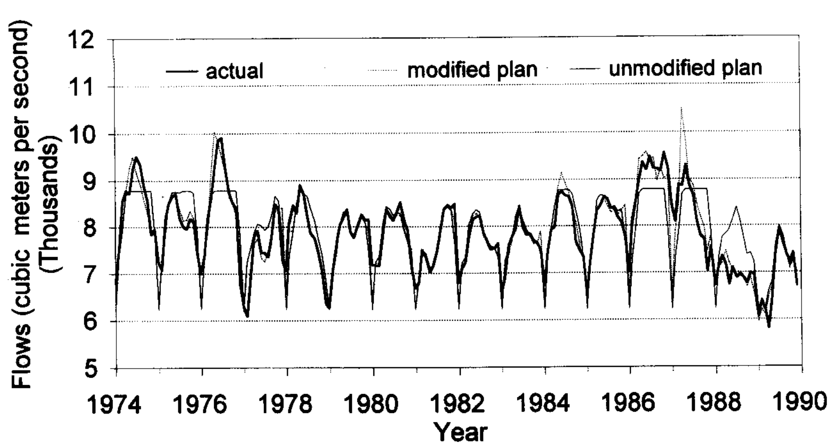

FIG. 5. Lake Ontario actual and simulated outflows, 1974–1990.

tween the simulated monthly levels and flows and recorded data are given in Table 4 for the modified and unmodified regulation plans. From this table, it can be seen that the statistics of the modified plan were greatly improved over those of the unmodified plan.

To complete the evaluation, levels and flows were calculated using the extreme high and low supply scenarios presented earlier. Comparing results shown in Tables 1 and 2, it can be seen that the modified plan significantly lowered the maximum Lake Ontario level resulting from the high supply scenario, with a corresponding increase in Lake Ontario outflows. Similarly, the modified plan significantly increased the minimum Lake Ontario level resulting from the low supply scenario, with a decrease in the associated outflow.

WATER SUPPLY SIMULATION

A time series of 49,950 years of net basin supplies (Rassam *et al.* 1992) was used as input to the modified regulation plans and middle lakes routing model for the simulation of lake levels and outflows. The length of the simulated time series was selected so that the sample size would be sufficient to obtain a 1 in 10,000 year Lake Ontario outflow after the data were resampled allowing for sufficient lag-time between maximum events to remove the effects of autocorrelation. The supplies were simulated using a shifting-level multivariate autoregressive (SL/AR(1)) model (Salas and Boes 1980) based upon the 1900-1989 historical water supplies to the individual Great Lakes. The model was designed to preserve on an annual basis, the spatial cross correlation of order zero between lakes, the annual serial correlation, shifts in the historical supply series, and the means and standard deviations. In addition, it was designed to preserve the monthly means and standard deviations of the net basin supplies. The model was tested by generating 11 time series of monthly water supplies of 90-year duration and routing them through the system. The results of the simulations were judged relative to those of the 1900-1989 base period using 16 evaluation statistics (Rassam *et al.* 1992). The model satisfactorily reproduced both annual and monthly net basin supply and water level statistics. A comparison of the maximum Lake Ontario levels and flows using the test model supplies and those of the historical scenario are shown in Table 5.

The 49,950-year net basin supply sequence was routed through the system as one consecutive series with the conditions as summarized in Table 3. For each year of the simulation, the annual maximum, minimum, and mean of the net total supplies (the net basin supply plus the connecting channel inflow), outflows, and lake levels were preserved. These data are on a monthly basis for the upper lakes, and on a quarter-monthly basis for Lake Ontario.

RESULTS AND DISCUSSION

Figure 6 shows the mean, maximum, and minimum simulated quarter-monthly outflows from

TABLE 4. Evaluation statistics of simulated Lake Ontario levels and outflows versus recorded data for 1974-1989.

	Monthly Outflows, m^3s^{-1}				Monthly Levels, m			
	Correlation		RMSE		Correlation		RMSE	
Month	unmodified plan	modified plan	unmodified plan	modified plan	unmodified plan	modified plan	unmodified plan	modified plan
Jan	0.00	0.68	807	634	0.46	0.86	0.58	0.12
Feb	0.59	0.95	450	167	0.59	0.89	0.61	0.12
Mar	0.85	0.97	411	252	0.55	0.86	0.64	0.15
Apr	0.96	0.89	320	513	0.55	0.91	0.64	0.12
May	0.91	0.97	408	320	0.40	0.89	0.64	0.09
Jun	0.85	0.99	439	167	0.30	0.85	0.67	0.09
Jul	0.69	0.97	583	178	0.32	0.85	0.67	0.09
Aug	0.71	0.97	496	173	0.27	0.85	0.67	0.09
Sep	0.73	0.96	442	173	0.23	0.84	0.64	0.06
Oct	0.80	0.96	416	173	0.42	0.94	0.61	0.06
Nov	0.60	0.95	603	212	0.42	0.94	0.55	0.06
Dec	0.57	0.82	580	453	0.53	0.95	0.52	0.09

TABLE 5. Exploratory simulation results.

Supply Series	Maximum Quarter-Monthly Outflow (m^3s^{-1})	# of Quarter-Monthly Outflows over 8,780 (m^3s^{-1})	Maximum Quarter-Monthly Level (m)	# of Quarter-Monthly Levels over 75.22 (m)
1	9,880	10	75.30	5
2	9,970	12	75.33	6
3	13,880	14	76.26	11
4	9,710	2	75.32	2
5	10,020	9	75.42	5
6	10,420	12	75.37	6
7	12,540	20	76.04	13
8	11,240	26	75.58	13
9	11,980	15	75.85	9
10	9,510	12	75.26	3
11	11,300	14	75.60	8
Maximum	13,880	26	76.26	13
Average	10,950	13.3	75.58	7.4
Minimum	9,510	2	75.26	2
Historical Supply Series	10,930	13	75.51	8

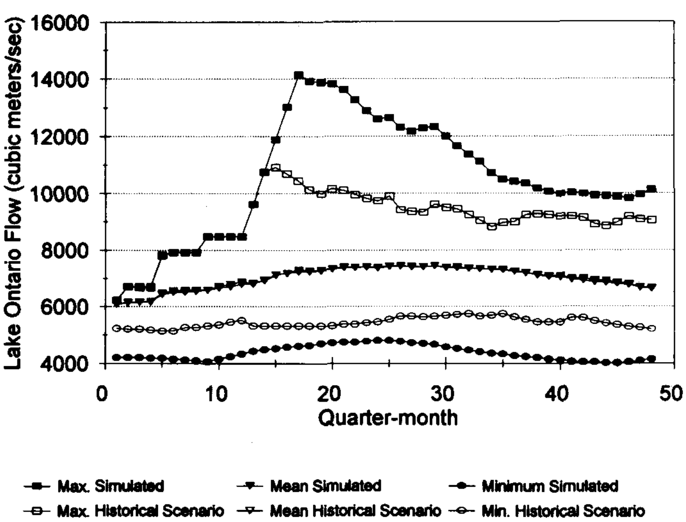

FIG. 6. Maximum, minimum, and mean simulated and historical supply scenario Lake Ontario outflows.

Lake Ontario along with those of the historical supply series. The simulated quarter-monthly means replicate those of the historical scenario. The maximum quarter-monthly outflows of the simulated series for the first 14 quarter-months are also identical to those of the historical scenario. This similarity is due to the constraints on winter outflows of the "L" limitations. For the remaining quarter-months, the simulated maximum outflows are significantly higher than those of the historical net basin suppply scenario. The maximum simulated quarter-monthly outflow is 14,160 m^3s^{-1}. The maximum-flow limitation of Plan 1958-D, 8,780 m^3s^{-1} (310,000 cfs), is exceeded 0.27% of the time (6,491 occurrences out of 2,397,600 quarter-months). The simulated minimum quarter-monthly levels are significantly lower than those of the historical scenario, with a minimum flow of 4,020 m^3s^{-1}.

Figure 7 shows similar statistics as in Figure 6 for the Lake Ontario quarter-monthly levels. As with the outflows, the means of the quarter-monthly levels replicate those of the historical scenario and the maximum and minimum levels have a wider range. The maximum quarter-monthly simulated level is 76.41 m, and the upper lake-level regulation limit, 75.22 m (246.77 ft), is exceeded 0.15% of the time. The minimum simulated quarter-monthly level is 73.12 m.

Figures 8 and 9 show the cumulative frequency plots of the annual maximum quarter-monthly outflows and levels, respectively, on a logarithmic return period scale. Although the simulated frequency curves lie below the historical scenario frequency curves, the difference is less than 3% for the outflows, and less than 0.10 m for the levels.

The results of the simulated annual maximum,

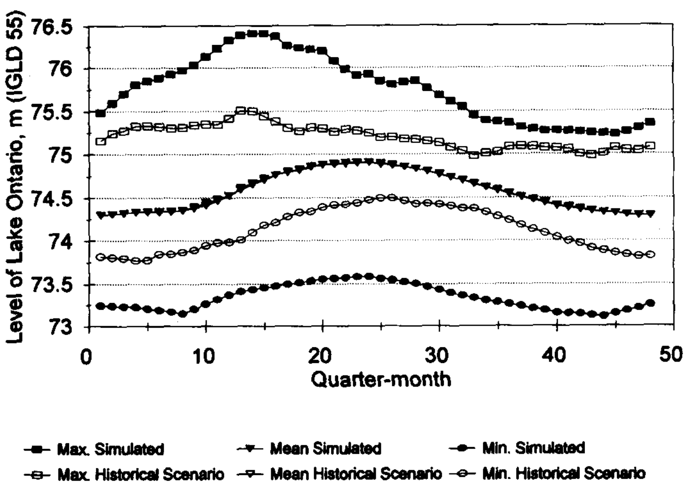

FIG. 7. Maximum, minimum, and mean simulated and historical supply scenario Lake Ontario levels

minimum, and mean levels and outflows for the upper lakes compared to those of the historical water supply scenario are shown in Table 6. Here again, it can be seen that the means are preserved, but the range in levels and flows is greater than those of the historical scenario. It is interesting to note that the maximum simulated Lake Superior level is 184.01 m, more than 0.6 m below the level at which its control structures are estimated to be overtopped. Thus, the modification made to the regulation plan which accounted for overtopping was not used.

CONCLUSIONS

A long series of lake levels and outflows have been successfully simulated for the Hydro-Québec Beauharnois-Les Cèdres spillway design study. Modified Lake Superior and Lake Ontario regulation plans yielded more reasonable levels and outflows for extreme high and low supply conditions. The frequency analysis of the simulated Lake Ontario levels and flows replicated those based on the historical water supply scenario within acceptable margins while extending the frequency curves; making it possible to assign probabilities of occurrence to more extreme levels and flows.

The results show a wider range of levels and flows than those resulting from the historical sequence of water supplies, as expected. Those concerned with Great Lakes water levels and flows must consider this in planning, design, and resource management.

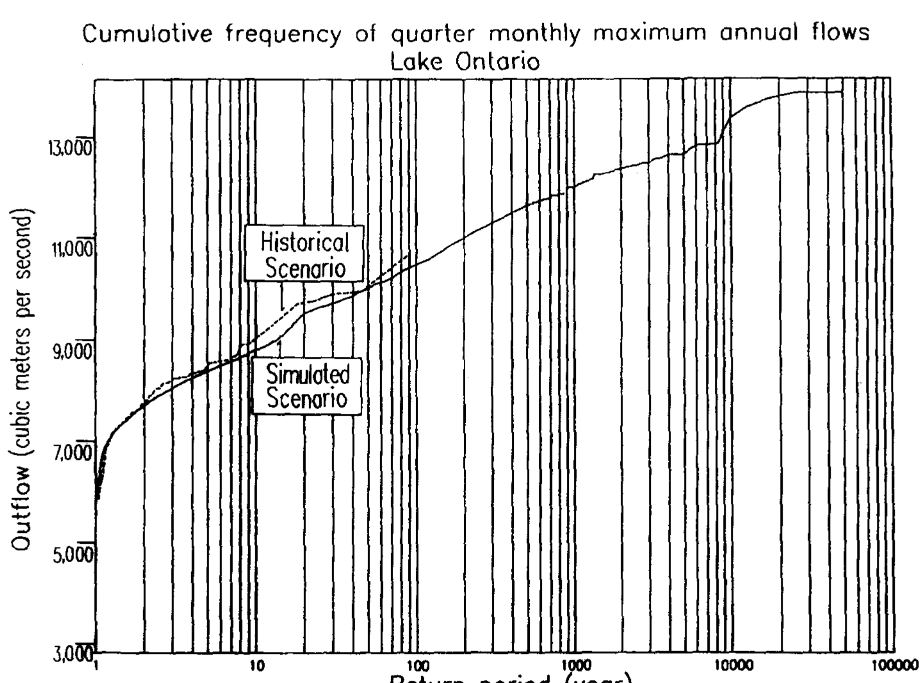

FIG. 8. Frequency of quarter-monthly maximum annual Lake Ontario outflows.

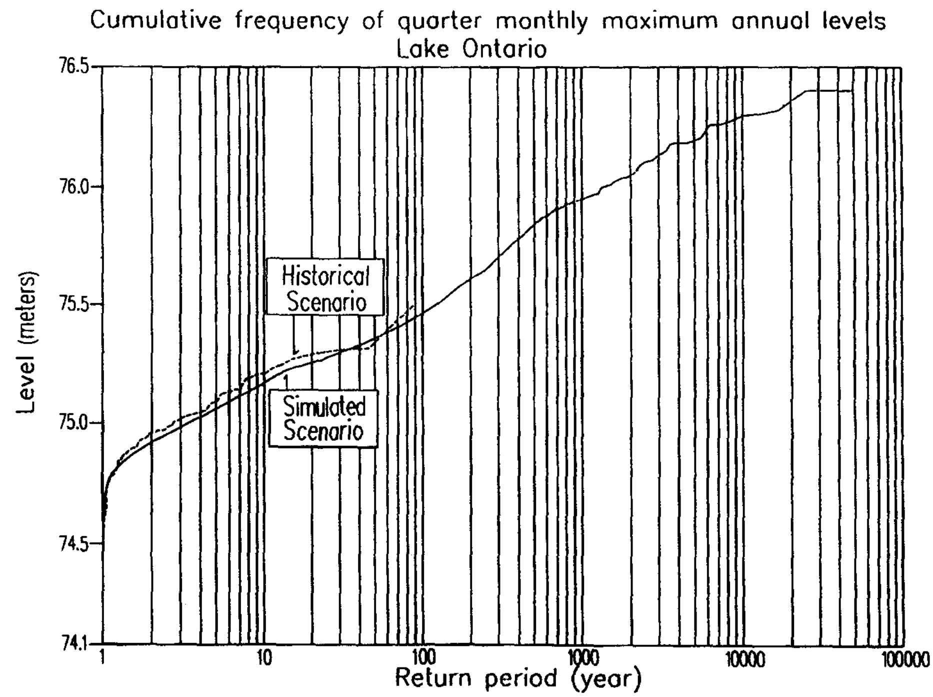

FIG. 9. Frequency of quarter-monthly maximum annual Lake Ontario levels.

TABLE 6. Upper Great Lakes statistics of the 49,950 simulated years and the historical scenario.

	Superior		Michigan-Huron		Erie	
	Historical Scenario	Simulated	Historical Scenario	Simulated	Historical Scenario	Simulated
			Monthly Lake Outflows (m^3s^{-1})			
Maximum	3,840	4,240	6,810	7,940	7,870	8,960
Minimum	1,400	960	3,750	3,010	4,320	3,450
Mean	2,210	2,220	5,300	5,320	5,980	6,000
			Monthly Lake Levels (m)			
Maximum	183.45	184.01	177.27	177.94	174.84	175.32
Minimum	182.48	182.17	175.30	174.64	173.13	172.62
Mean	183.03	183.04	176.25	176.27	174.00	174.01

The Lake Superior and Lake Ontario regulation plans are shown to lack robustness when used in simulations with extreme sequences of water supplies; some of the regulation criteria cannot be met simultaneously under extreme conditions. The simulation of Great Lakes water supplies provides a means by which revisions to the plans can be tested and evaluated. Historical water supplies, the current standard for design and evaluation, should no longer be the sole test of the plans.

ACKNOWLEDGMENTS

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APPENDIX I. IJC Orders of Approval Criteria for the Regulation of Lake Superior (IJC 1979).

a. The level of Lake Superior shall be maintained within its recorded range of stage when tested with supplies of the past as adjusted. The regulated monthly mean level of Lake Superior shall not exceed elevation 602.0 (IGLD 55) or fall below elevation 598.4 (IGLD 55) under these conditions.
b. To guard against unduly high stages of water in the lower St. Marys River, the excess discharge at any time over and above that which would have occurred at a like stage of Lake Superior prior to 1887 shall be restricted so that the elevation of the water surface immediately below the locks shall not be greater than 582.9 (IGLD 55).
c. To guard against unduly low levels in Lake Superior, the outflow from Lake Superior shall be reduced whenever, in the opinion of the Board, such reductions are necessary in order to prevent unduly low stages of water in Lake Superior; provided, that whenever the monthly mean level of the Lake is less than 600.5 (IGLD 55), the total discharge permitted shall be no greater than that which it would have been at the prevailing stage and under the discharge conditions which obtained prior to 1887.

APPENDIX II. IJC Orders of Approval Criteria for the Regulation of Lake Ontario (ISLRBC 1963).

a. The regulated outflow from Lake Ontario from 1 April to 15 December shall be such as not to reduce the minimum level of Montreal Harbour below that which would have occurred in the past with the supplies to Lake Ontario since 1860 adjusted to a condition assuming a continuous diversion out of the Great Lakes Basin of 3,100 cubic feet per second at Chicago and a continuous diversion into the Great Lakes Basin of 5,000 cubic feet per second from the Albany River Basin.
b. The regulated winter outflows from Lake Ontario from 15 December to 31 March shall be as large as feasible and shall be maintained so that the difficulties of winter operation are minimized.
c. The regulated outflow from Lake Ontario during the annual spring break-up in Montreal Harbour and in the river downstream shall not be greater than would have occurred assuming supplies of the past as adjusted.
d. The regulated outflow from Lake Ontario during the annual flood discharge from the Ottawa River shall not be greater than would have occurred assuming supplies of the past as adjusted.
e. Consistent with other requirements, the minimum regulated outflows from Lake Ontario shall be such as to secure the maximum dependable flow for power.
f. Consistent with other requirements, the maximum regulated outflow from Lake Ontario shall be maintained as low as possible to reduce channel excavation to a minimum.
g. Consistent with other requirements, the levels of Lake Ontario shall be regulated for the benefit of property owners on the shores of Lake Ontario in the United States and Canada so as to reduce the extremes of stage which have been experienced.
h. The regulated monthly mean level of Lake Ontario shall not exceed elevation 246.77 ft (IGLD 55) with the supplies of the past as adjusted.
i. Under regulation, the frequency of occurrences of monthly mean elevations of approximately 245.77 ft (IGLD 55) and higher on Lake Ontario shall be less than would have occurred in the past with the supplies of the past as adjusted and with present channel conditions in the Galop Rapids Section of the St. Lawrence.
j. The regulated level of Lake Ontario on 1 April shall not be lower than elevation 242.77 ft (IGLD 55). The regulated monthly mean level of the lake from 1 April to 30 November shall be maintained at or above elevation 242.77 ft (IGLD 55).
k. In the event of supplies in excess of the supplies of the past as adjusted, the works in the International Rapids Section shall be operated to provide all possible relief to the riparian owners upstream and downstream. In the event of supplies less than the supplies of the past as adjusted, the works in the International Rapids Section shall be operated to provide all possible relief to navigation and power interests.

Supplementary Order: The project works shall be operated in such a manner as to provide no less protection for navigation and riparian interest downstream than would have occurred under pre-project conditions and with supplies of the past as adjusted.

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