Impacts of Alternative Great Lakes Regulation Plans on Hydropower Production

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Hydropower production is evaluated for two alternative regulation measures developed under the recent International Joint Commission Great Lakes Water Levels Reference. Measure 1.18 included a new control structure to regulate outflows from Lake Erie, while measure 1.21 was a revision of the current regulation plans for lakes Superior and Ontario. A negative impact to the entire hydropower system was calculated to range between US$11.9 and US$20.9 million/year under measure 1.18, while measure 1.21 had a positive impact in the range of US$1 to US$3 million/year. Considering the impacts to all interests, the Reference Study Board recommended no further consideration be given to measure 1.18, but that a measure similar to 1.21 should be implemented.

La production d'énergie hydraulique fait l'objet d'une évaluation par rapport à deux mesures de régulation développées sous la récente Référence des niveaux des Grands Lacs de la Commission mixte internationale. La Mesure 1.18 comprenait un nouvel ouvrage de dérivation destiné à réguler les débits sortants du Lac Érié tandis que la Mesure 1.21 portait sur une révision des projets de régulation actuels concernant les Lacs Supérieur et Ontario. On a calculé que la mesure 1.18 aurait un impact négatif sur l'ensemble du système d'énergie hydraulique qui coûterait entre US$11.9 et US$20.9 millions par an. La mesure 1.21, en revanche, aurait un impact positif qui se situerait entre US$1 et US$3 millions par an. Prenant en compte les répercussions pour tous les partis, le Conseil d'étude des références a recommandé l'abandon de la mesure 1.18 au profit de la mise en oeuvre d'une mesure similaire à la mesure 1.21.

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1. Introduction

The Laurentian Great Lakes (Figure 1) is the largest freshwater system in the world, containing some 23,000 km^3 of water and representing approximately 18% of the world's surface freshwater supply (Botts and Krushelniski, 1987; Botkin and Keller, 1995). The Great Lakes-St. Lawrence River watershed is home to more than 39 million people, who have a wide variety of uses for the waters. Approximately 220 million tons (200 million metric tonnes) of international and interlake cargo are transported through the Great Lakes-St. Lawrence Seaway each year (US Army Corps of Engineers, 1991). Iron ore, coal, limestone, and grain accounted for 85% of all shipments across the lakes and in 1990, the commercial fleet on the lakes numbered 185 vessels (117 Canadian and 68 US registry) (Waxmonsky, 1992). Even though the importance of heavy industry has declined in the basin over the past two decades (Stokoe and Trott, 1993), Great Lakes waters still service industries ranging from iron and steel, to pulp and paper, petroleum and chemical refining (International Joint Commission, 1989). Hydropower facilities located on the St. Marys, Niagara, and St. Lawrence rivers have a total installed capacity of 8,300 megawatts (MW), which is enough

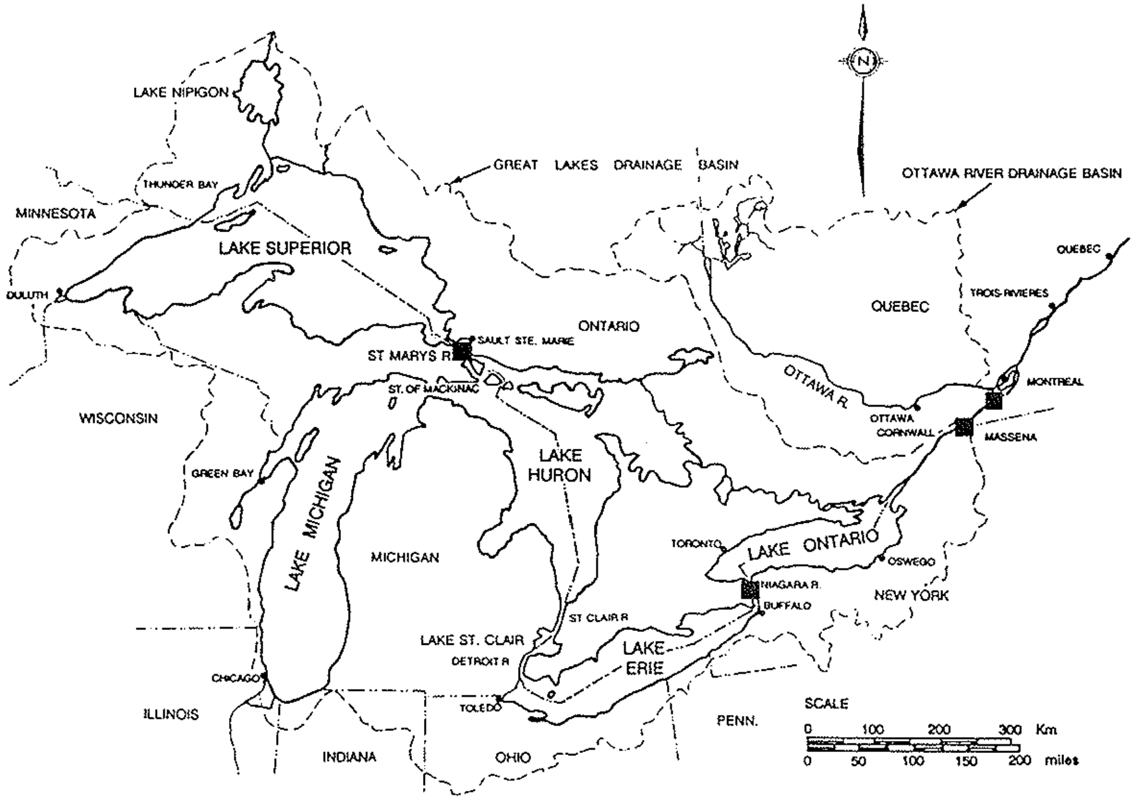

Figure 1: Great Lakes - St. Lawrence River Basin, with Locations (■) of Major Hydropower Projects (After Yee et al., 1990)

power to service residential peak demand for a population more than four times greater than the island of Montreal (*c.f.* Hydro-Quebec, 1992). Thermal power plants (coal, oil, and nuclear) obtain fuel via commercial shipping and use the water for cooling purposes (Irvine *et al.*, 1990). Sport fishing thrives throughout the basin (*e.g.*, Dawson and Voiland, 1988; Siemer and Brown, 1994) and one estimate indicated that the Great Lakes provided 110,341,000 angler-days in 1983 (Botts and Krushelniski, 1987). Although commercial fishing has declined on the lakes, the Ontario waters of Lake Erie, for example, still produced 35.5 million tons (32.2 million metric tonnes) of fish (primarily smelt, walleye, white and yellow perch) worth Cdn$27.5 million in 1994 (Ontario Ministry of Natural Resources, 1995). Great Lakes-St. Lawrence River waters are used for recreational purposes, including swimming and boating (Bergmann-Baker *et al.*, 1995). Slightly more than 100,000 residential (*i.e.*, riparian) properties and 40 Native North American communities line the shores (International Joint Commission, 1993a).

Water levels on the lakes fluctuate at different temporal scales (several years, seasonally, short-term storm events) in response to various hydrometeorologic factors, including precipitation, evaporation, surface runoff, wind, and atmospheric pressure (*e.g.*, Quinn, 1988; Irvine and Eberhardt, 1992). The water levels of lakes Superior and Ontario are regulated, to some extent, by control works on the St. Marys River and the St. Lawrence River. Outflows from Lake Superior are specified by Regulation Plan 1977, which is administered by the International Lake Superior Board of

Control. The Board has two members, one from the US Army Corps of Engineers and one from Environment Canada. Plan 1977 considers water inputs and outputs for Lake Superior (*i.e.*, net basin supply), as well as the water levels on lakes Michigan/Huron in determining the outflow rate for each month. Plan 1977 also specifies a minimum flow in the St. Marys River to maintain navigation, power production and suitable fish habitat, and an attempt is made to keep water levels on Lake Superior between 600.5 and 602 ft (183.0 and 183.5m, International Great Lakes Datum (IGLD) 1958)(Yee *et al.*, 1990).

Lake Ontario has been regulated since 1960 and outflows from the lake currently are specified under Plan 1958-D, which is administered by the St. Lawrence River Board of Control. The Board consists of eight members, representing the US Army Corps of Engineers, Environment Canada, Transport Canada, and five other state, provincial, and local agencies. Plan 1958-D attempts to maintain Lake Ontario water levels between 242.8 and 246.8 ft (74.0 and 75.2 m, IGLD 1958). Under extreme conditions, the St. Lawrence River Board of Control has the power to deviate from the flows prescribed by Plan 1958-D. In this paper, the variances from the flows prescribed by Plan 1958-D are termed "deviations." During extreme high levels, regulation is operated to provide all possible relief to riparians up and downstream, while during low levels regulation is operated to provide all possible relief to commercial navigation and hydropower production (Yee *et al.*, 1990).

The various interest groups that use the Great Lakes can have competing views on what constitutes a "desirable" range of water-level fluctuation, and this can pose a challenge to the management of the lakes (Clamen, 1988). For example, riparian interests may prefer moderate water levels with limited fluctuation. Hydropower and commercial navigation interests benefit from higher water, although extreme levels do not provide operational benefits. Fish, wildlife, and wetland interests would prefer a range of periodic fluctuations.

Over the last twenty years, there have been several studies, under the auspices of the International Joint Commission (IJC), that have examined the relationships between water levels and uses of the Great Lakes (*e.g.*, IJC, 1973; 1981; 1985). The IJC was established under the terms of the Boundary Waters Treaty (1909) between the United States and Canada. The Treaty gave the IJC the responsibility of investigating and making recommendations on specific problems along the common border, as well as ruling on applications for the use, obstruction, or diversion of boundary waters (Clamen and Parsons, 1989). The Lake Superior and St. Lawrence River Boards of Control are appointed by and responsible to the IJC. In 1986, the IJC was asked by the US and Canadian governments to investigate methods to alleviate the impacts of fluctuating levels and flows on interest groups using the Great Lakes (IJC, 1986). This request was initiated primarily by citizen riparian groups concerned with property damage resulting from high water levels (Clamen, 1988; Todd and Kangas, 1988; IJC, 1993a, b). The resulting Great Lakes-St. Lawrence River Basin Water Levels Reference Study (Reference) was conducted in two phases. Phase I of the Reference examined hydrometeorologic aspects of fluctuating levels and flows, qualitatively evaluated the adverse consequences of these fluctuations, identified possible measures to alleviate the adverse consequences, and developed a framework to evaluate these measures. A Phase I report was released for public review in September 1989 (IJC, 1989).

Phase II of the Reference provided a more detailed evaluation of measures that fall into two broad categories: i) land use measures (*e.g.*, setback requirements, flood elevation, and protection requirements, real estate disclosures, acquisition of "at risk" land); and ii) water level regulation measures. Over 150 regulation measures were identified and these ranged from revision of the current plans for lakes Superior and Ontario, to construction of regulatory works on all lakes.

The acceptability of the various proposed measures was assessed by the Reference Study Board using a multi-objective, multi-criteria process. The Reference Study Board developed 41 planning objectives that generally had the aim of reducing financial, social or environmental losses to interests due to erosion, flooding, or low water levels. Furthermore, the success of each measure in meeting the multiple objectives was evaluated using four core criteria: i) overall economic impact – a measure would be acceptable if it allowed, at a minimum, the existing economic performance in the basin to be maintained. Positive economic impacts were preferable; ii) environmental impact – was a qualitative assessment using impact on wetlands (including ecological productivity) as an indicator; iii) equitable distribution of impacts between all interests – to assess the distribution, the Study Board examined the relative magnitude of the impact and whether it was positive or negative; and iv) feasibility (technical and socio-political) – technical feasibility required that a measure be responsive to changing conditions, have predictable outcomes once put into effect, and be reliable under extreme conditions. Socio-political feasibility assessed whether a measure could be implemented within existing legal frameworks, fit within current public policy, and was acceptable to the public (IJC, 1993a).

The multi-objective, multi-criteria evaluation process was applied through a series of meetings and workshops. The first occurred in 1991 when study participants assessed the identified measures, reducing them to a more manageable number (33) for further detailed evaluation. In 1992, a workshop attended by 70 study participants (including citizens-at-large and interest-group representatives) was held to evaluate the remaining 33 measures. This evaluation was done using a questionnaire that asked the participants to rate the measures based on a compendium of information for each measure. Results of the workshop were reviewed by senior US and Canadian government representatives, and the results also were presented at four public forums for additional comment. Final refinements were made subsequent to the public forums and the recommendations for measure implementation were made by the Study Board (IJC, 1993a).

Three factors, in particular, distinguished the latest Reference from past IJC studies. First, land use measures were evaluated in addition to different regulation scenarios. Second, the multi-objective, multi-criteria evaluation process moved away from the strict benefit:cost analyses done in past. Finally, there was much greater public involvement in the study process with the inclusion of a Citizens Advisory Committee (IJC, 1993b).

Three of the proposed regulation scenarios ultimately received the most detailed evaluation (IJC, 1993a): i) additional water-level regulation to include construction of control works on Lake Erie (measure 1.18); ii) modification of current regulation plans (measure 1.21); and iii) crisis water-level management (measure CR32). The primary objective of this paper is to assess, at a planning level, the impacts that measures 1.18 and 1.21 could have on hydropower production at the major projects on the Great Lakes. These measures are the focus of this paper because they were amongst those that received the most detailed evaluation under the Reference (IJC, 1993a), and because they represent two different approaches to Great Lakes water-level management: construction of additional regulation structures *vs.* modification of existing regulation plans. By focusing on these measures, the general methodology of evaluating impacts to hydropower production under the recent Great Lakes Water Levels Reference will be illustrated. The impacts to hydropower under these two scenarios also will be discussed in context with the impacts determined by the Reference Study Board (IJC, 1993a) for other interests using the Great Lakes. The focus of measure CR32 differs from the other measures, concentrating on shorter-term crisis management. Some of the actions included in this measure may not be acceptable under the current institutional structure and policy; the benefits, impacts, and challenges of this measure therefore are not developed here (see also, David *et al.*, 1988).

2. Study Locations

As Figure 1 indicates, the major hydropower projects on the Great Lakes are located along the St. Marys, Niagara and St. Lawrence rivers. Three projects are located on the St. Marys

River and are operated by the Edison Sault Electric Company (US), the US government, as represented by the US Army Corps of Engineers, and Great Lakes Power Limited (Canadian). Electricity generated at the US government plant is sold to the Edison Sault Electric Company. The projects on the Niagara River are operated by the New York Power Authority (NYPA), Ontario Hydro, and the Canadian Niagara Power Company. Although the Canadian Niagara Power Company services its own customers, Ontario Hydro operates the dispatch from the plant. Projects on the St. Lawrence River have been constructed at two locations. The upstream project (at Cornwall, Ontario and Massena, New York) is operated by Ontario Hydro and NYPA. The two downstream projects (just above the confluence with the Ottawa River) are operated by Hydro-Quebec. The aggregate capacities of the projects on the St. Marys, Niagara and St. Lawrence rivers are 104; 4,731 and 3,466 MW, respectively. In total, this represents approximately 7% of all capacity (thermal, nuclear, and hydro) in the states of New York and Michigan, and the provinces of Ontario and Quebec (Irvine *et al.*, 1993).

3. Study Approach

The basic methodology for this study was similar to past References (IJC, 1973; 1981), and is outlined in detail by Irvine *et al.* (1993). Briefly, monthly mean levels and flows data (1900-1989) for a basis of comparison (BOC) scenario and regulation scenarios of interest were used to drive hydropower production models for the major projects. Output from the models for all scenarios included annual energy in gigawatt hours (GWh) and monthly capacity (power) in megawatts (MW). Energy and capacity impacts were evaluated by comparing modelled production for the BOC and scenario of interest. The economic impact of each scenario was calculated using a range of replacement values and the difference between the mean energy and mean capacity for the BOC and the scenario of interest.

The monthly mean levels and flows (1900-1989) for the BOC scenario were standardized to reflect a consistent (*i.e.*, constant and recent) hydraulic regime (*e.g.*, diversions into and out of the lake, consumptive use withdrawals, outlet conditions of each lake) (IJC, 1992). The Study Board determined that the BOC used for evaluations in the Reference would include the previously-discussed deviations from the regulation plan for Lake Ontario. The fluctuations in energy and power production under the BOC and the associated economic impacts have been evaluated more fully by Irvine *et al.* (1995). The monthly mean levels and flows (1900-89) also were developed for measures 1.18 and 1.21 (IJC, 1993c).

In the most general sense, the relationship between hydropower production and water levels and flows can be expressed as:

[1] $P = \eta(Q\gamma H)/550$

where P is power in horsepower (h.p., where 1 h.p. = 0.746 kilowatts (kW)), Q is the flow rate in ft^3/second (cfs), γ is water density (62.4 lbs/ft^3), H is net head in feet, and η is an efficiency factor. Power represents the rate at which a plant can produce electrical energy and is, in effect, an instantaneous quantity. Electrical energy (*e.g.*, kilowatt hours (kWh)) is represented by the area under a time plot of power (*i.e.*, power integrated over time). Both peak power demand and energy requirements must be met by a utility to avoid interruptions. The production models used in this study were a more complicated variation of equation 1 and considered factors such as: flow allocations (between units or for environmental, navigation, or tourist purposes); efficiency ratings of the generating units; Ontario Hydro pumped storage operations; unit outages (*e.g.*, for maintenance); and head/capacity loss due to ice constraints. Planned expansions and/or retooling and replacement of older, less efficient units, to the year 2000, also were included in the models. The models are described in detail by Irvine *et al.* (1993).[1]

The ranges of energy and capacity replacement values used to evaluate the eco-

1/ A copy of the full report can be obtained from the corresponding author.

nomic impacts are shown in Tables 1 and 2. In past References, economic impacts were determined using a single "most likely" replacement value (*e.g.*, IJC, 1973; 1981). The range of values identified in this study are meant to reflect the different possible replacement options for each utility, differences in peak and off-peak values, and general uncertainty in identifying absolute replacement values. The replacement options were determined through extensive discussions with the utilities, power pools, and public service commissions, as well as a review of the available literature (Irvine *et al.*, 1993).

It is worth noting that replacement values generally have decreased since the Reference work was completed, and that more recent "most likely" values are lower than those presented in Tables 1 and 2 (Irvine, 1995). This decrease is related to various factors, including government policy, a slow increase in electricity demand, and excess capacity resulting from economic slowdowns (Bernard and Genest-Laplante, 1994; New York Public Service Commission, 1994; Ontario Hydro, 1994; Irvine, 1995). The change in replacement values over a two-to-three-year period emphasizes the importance of identifying a range of values in a planning-level study of a dynamic system.

When evaluating economic impacts to hydropower production associated with a scenario of interest, both energy and capacity replacement values normally are considered (IJC, 1973; 1981; Irvine *et al.*, 1993). The energy values (Table 1) may be related to variable costs, including fuel replacement, as well as some costs for operations, maintenance, administration, electrical transmission, and distribution. Capacity values (Table 2) may be related to fixed costs (capital and fixed operations) for electrical generation, transmission, and distribution (*e.g.*, Ontario Hydro, 1994).

Irvine *et al.* (1990) also identified impacts that could be incurred by thermal and nuclear power units, particularly under low-water conditions. These impacts were not quantitatively evaluated in Phase I of the Reference, and the Study Board specifically did not desire a more detailed evaluation in Phase II.

3.1 Description of Proposed Regulation Scenarios

A brief summary of measures 1.18 and 1.21 is provided below as a guide to the intent of the measures. Detailed descriptions of each measure, including the hydrology and hydraulics/structural requirements, are provided in IJC (1993c). The overall objective of measure 1.18 (or, three-lake plan) was to compress the level fluctuation on lakes Michigan, Huron, and Erie. This would be accomplished using the backwater between lakes Erie and Michigan/Huron, and storage on Lake Superior. The historical seasonal patterns of fluctuations on the lakes would be maintained, in order to minimize environmental impacts. Lake Erie levels would be kept below long-term average during periods of high supplies, and above long-term average during periods of low supplies. The measure would require dredging and construction of control works in the Niagara River (hence, "three-lake plan") as well as mitigation works along the St. Lawrence River to compensate for increased and decreased flows downstream of Cornwall, Ontario.

Measure 1.21 (or, two-lake plan) represents modifications to the two existing regulation plans. The measure modifies the outflow forecasts used in Plan 1977, increases the maximum winter outflow limit, modifies the balancing relationship for lakes Superior and Michigan/Huron, and revises the minimum flow limit during periods of low levels on Lake Superior. Plan 1958-D is modified by increasing maximum flow limits to better reflect actual practice (*i.e.*, the "deviations" as discussed previously),[2] changes the seasonal outflows to balance better the needs of recreational boating and commercial navigation interests, and provides a more coordinated assessment of spring outflows from Lake Ontario and the Ottawa River to reduce the frequency of spring flooding in Montreal (IJC, 1993c).

2/ While the plan attempts to follow the pattern of deviations that frequently occur under Plan 1958-D, it is not possible to mimic exactly the deviations since these are consensus decisions made by the St. Lawrence River Board of Control.

Table 1: Monetary Values of Energy (¢/kWh)[1]

	Michigan Projects[2]	Great Lakes Power	Ontario Hydro[2]	New York Projects[2]	Hydro-Quebec
Range	3.17-6.50	1.76-3.22	1.67-4.66	3.05-3.85	1.67-3.85
Most Likely	3.29	2.56	1.82	3.27	2.5

1/ The values are taken to represent 1992 US dollars and an exchange rate of 0.833 was used to convert Canadian dollars.

2/ For brevity, "Michigan Projects" represent Edison Sault and the US government projects; "Ontario Hydro" represents the Ontario Hydro projects on the Niagara and St. Lawrence rivers; while "New York Projects" represents the NYPA projects on the Niagara and St. Lawrence rivers.

Table 2: Monetary Values of Capacity ($/kW/year)[1]

	Michigan Projects	Great Lakes Power	Ontario Hydro	New York Projects	Hydro-Quebec
Range	50.00-300.00	105.26-270.60	26.32-48.15	32.41-76.21	50.00-270.60
Most Likely	127.44	142.94	36.70	43.05	71.21

1/ The values are taken to represent 1992 US dollars and an exchange rate of 0.833 was used to convert Canadian dollars.

4. Results

The mean and standard deviation of energy and capacity output from each project for the BOC, measure 1.18 and measure 1.21 are summarized in Tables 3, 4, and 5. The summary statistics for energy (GWh) represent annual production (*i.e.*, a sum of twelve months of energy production). The capacity (MW) summary statistics reflect production levels for the month in which peak demand typically is observed (with the exception of New York state). Accordingly, the capacity statistics for the three St. Marys River projects reflect production in the month of December. Capacity statistics for Ontario Hydro and Hydro-Quebec reflect production in the month of January, although it was noted that Hydro-Quebec may experience peak demand any time between December and March (Irvine *et al.*, 1993). Peak demand in upstate New York generally occurs in the winter, while downstate New York experiences summer peaks. Although there is seasonality in demand, it was not clear that any particular month should be used in the case of New York state. After consultation with personnel at NYPA, it was decided that the capacity summary statistics for the New York projects would be calculated using the data for all months.

One measure of impact that each scenario has on energy and capacity is the percentage difference from the BOC, as presented in Tables 4 and 5. Annual energy duration curves for the two scenarios are plotted with the BOC energy duration curves in Figures 2(a) and 2(b). Comparison of energy duration curves provides an indication of the impacts on energy production over the entire range of water levels and flows at the individual sites.

A non-parametric Wilcoxon Signed Rank Test was used to determine differences in the relative frequency distributions of energy and capacity between the BOC and the scenario of interest. Using the paired-difference Wilcoxon approach, it is expected, on average, that half the differences in pairs would be negative and half would be positive if there is no difference in the two distributions. Furthermore, it follows that positive and negative differences of equal absolute magnitude should occur with equal probability (Mendenhall, 1979). This non-parametric approach was used for testing to avoid the restrictive assumptions made in standard parametric tests (*e.g.*, populations normally distributed with equal variances and independence of individual observations). Results of the Wilcoxon testing are presented in Table 6.

The positive or negative impacts that the scenarios could have on energy and capacity as compared to the BOC can be assigned mon-

Table 3: Summary of Energy and Capacity Production under the Basis of Comparison (BOC) Scenario

Project	Annual Energy (GWh)		Monthly Capacity (MW)	
	Mean	S.D.[1]	Mean	S.D.
Edison Sault	232.06	27.15	27.82	5.43
US Government	151.73	4.83	18.60	0.55
Great Lakes Power	417.28	25.37	49.00	4.46
Ontario Hydro,Niagara R.	13,783.81	1,862.59	2,145.09	192.84
NYPA, Niagara R.	14,290.29	1,940.62	2,395.00	27.00
Ontario Hydro, St. Lawrence R.	6,601.38	521.22	731.45	33.10
NYPA, St. Lawrence R.	6,609.40	553.59	825.00	57.00
Hydro-Quebec	12,357.75	669.82	1,303.37	55.74

1/ Standard Deviation

Table 4: Summary of Energy and Capacity Production, Measure 1.18 (Three-Lake Plan)

Project	Annual Energy (GWh)			Monthly Capacity (MW)		
	Mean	S.D.[1]	% Difference[2]	Mean	S.D.	% Difference[2]
Edison Sault	198.41	26.84	-14.5	23.80	7.82	-14.45
US Government	152.32	4.51	0.39	18.68	0.68	0.43
Great Lakes Power	382.11	26.34	-8.43	44.58	6.93	-9.02
Ontario Hydro, Niagara R.	13,697.39	2,299.61	-0.63	2,050.81	345.12	-4.40
NYPA, Niagara R.	14,244.98	2,415.40	-0.32	2,371.00	89.00	-1.00
Ontario Hydro, St. Lawrence R.	6,561.68	624.32	-0.60	745.72	67.24	1.95
NYPA, St. Lawrence R.	6,585.56	664.17	-0.36	815.00	72.00	-1.21
Hydro-Quebec	12,199.68	853.61	-1.28	1,322.54	129.48	1.47

1/ Standard Deviation
2/ Calculated as: (Scenario Value - BOC Value) / BOC Value * 100

Table 5: Summary of Energy and Capacity Production, Measure 1.21 (Two-Lake Plan)

Project	Annual Energy (GWh)			Monthly Capacity (MW)		
	Mean	S.D.	% Difference	Mean	S.D.	% Difference
Edison Sault	233.03	26.00	0.420	27.64	5.25	-0.650
US Government	150.38	3.36	-0.890	18.47	0.40	-0.700
Great Lakes Power	416.71	22.60	-0.140	48.77	4.23	-0.470
Ontario Hydro, Niagara R.	13,796.01	1,802.68	0.090	2,146.73	191.55	0.080
NYPA, Niagara R.	14,301.43	1,877.35	0.080	2,396.00	23.00	0.040
Ontario Hydro, St. Lawrence R.	6,601.08	502.79	-0.004	733.31	34.23	0.250
NYPA, St. Lawrence R.	6,609.28	534.19	-0.002	825.00	56.00	0.000
Hydro-Quebec	12,369.71	655.90	0.100	1,308.89	58.86	0.420

etary values using the replacement costs shown in Tables 1 and 2. In general, the economic impacts associated with each scenario were calculated as follows:

[2] minimum economic impact ($) $= (E_{minv} \times \Delta E) + (C_{minv} \times \Delta C)$;

[3] most likely economic impact ($) $= (E_{mlv} \times \Delta E) + (C_{mlv} \times \Delta C)$;

[4] maximum economic impact ($) $= (E_{maxv} \times \Delta E) + (C_{max} \times \Delta C)$;

where E_{minv}, E_{mlv}, and E_{maxv} are, respectively, the minimum, most likely, and maximum energy values, measured in $/kWh; ΔE is the difference in annual mean energy production between the scenario and the BOC (kWh) (data in Tables 3 to 5); C_{minv}, C_{mlv}, and C_{maxv} are the minimum, most likely, and maximum capacity values, respectively ($/kW/year); and ΔC is the difference in mean capacity (for the month of peak demand) between the scenario and the BOC (kW)(data in Tables 3 to 5). Because of the replacement options, the economic impact calculations for the

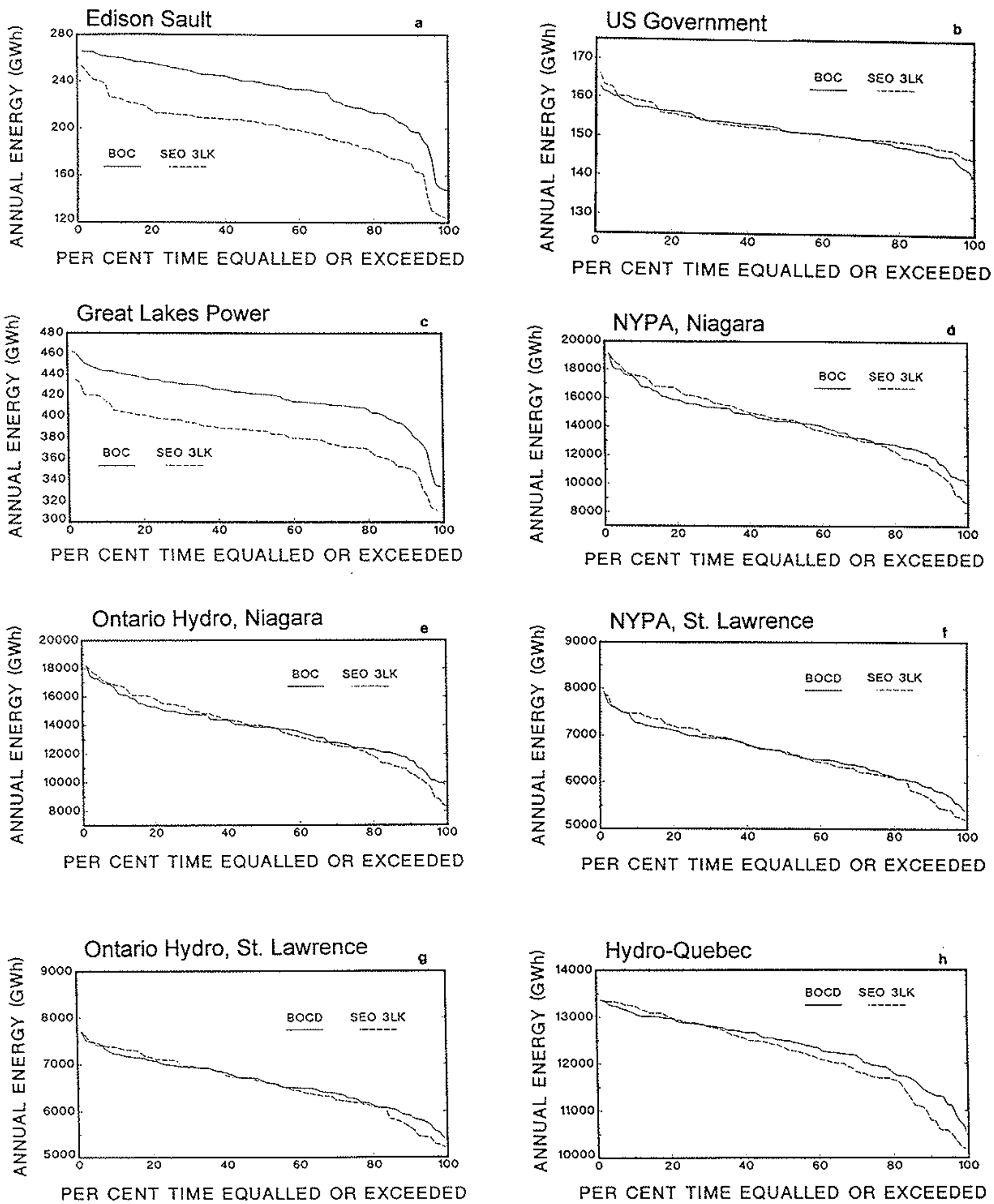

Figure 2a: Energy Duration Curves, BOC and Measure 1.18 (Three-Lake Plan)

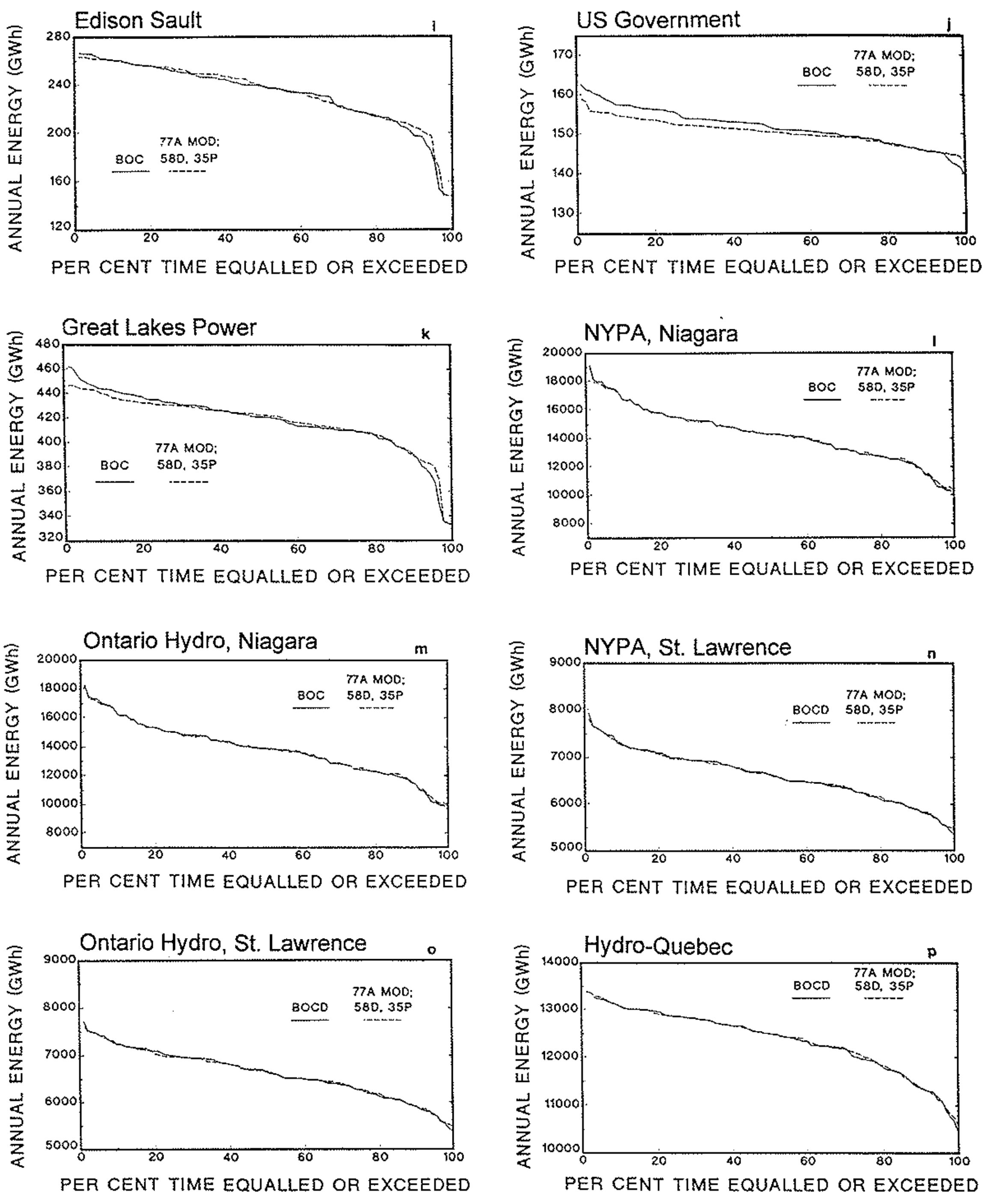

Figure 2b: Energy Duration Curves, BOC and Measure 1.21 (Two-Lake Plan)

Table 6: Results of Wilcoxon Signed Rank Tests

Project	Energy		Capacity	
	Measure 1.18	Measure 1.21	Measure 1.18	Measure 1.21
Edison Sault	different[1]	not different[2]	different	different
US Government	not different	different	not different	different
Great Lakes Power	different	not different	different	different
Ontario Hydro, Niagara R.	not different	not different	different	not different
NYPA, Niagara R.	not different	not different	different	not different
Ontario Hydro, St. Lawrence R.	not different	not different	different	different
NYPA, St. Lawrence R.	not different	not different	not different	not different
Hydro-Quebec	different	not different	not different	different

1/ different from the BOC at a confidence level of 95% (α=0.05)
2/ not different from the BOC at a confidence level of 95% (α=0.05)

Edison Sault and US government projects were an exception to the general approach (equations 2 to 4, above). According to the options identified for these projects, the following economic calculations were made:

[5] minimum economic impact ($) $= (E_{minv} \times \Delta E) + (C_{mlv} \times \Delta C)$;

[6] most likely economic impact ($) $= (E_{mlv} \times \Delta E) + (C_{mlv} \times \Delta C)$;

[7] maximum economic impact ($) $= (E_{mlv} \times \Delta E) + (C_{maxv} \times \Delta C)$.

The results of the economic calculations are presented in Table 7. Because these results were calculated using differences between mean energy and capacity, the values reflect the annual dollar impacts that are expected, on average, for a hydrologic scenario identical to the period 1900 through 1989. However, results for the Wilcoxon tests indicated that there was no significant difference between production under the BOC and the scenarios of interest at some of the sites (*cf.* Table 6). The usefulness of calculating economic values for non-significant differences is discussed below.

Table 7: Total Annual Economic Impacts (All Projects), Measures 1.18 and 1.21 (1992 $US)

Measure	Low Impact	Most Likely Impact	High Impact
1.18 (Three-Lake Plan)	-11,931,504[1]	-14,790,065	-20,479,581
1.21 (Two-Lake Plan)	1,039,262	1,334,542	2,991,623

1/ A negative number represents an economic loss to the hydropower system as compared to the BOC; positive numbers represent net economic gains.

5. Discussion

Measure 1.18 generally had a larger impact and that impact was more frequently negative, as compared to measure 1.21. On a percentage basis, impacts were greatest for the upper lake projects, Edison Sault and Great Lakes Power. These impacts also were well-illustrated by the energy duration curves (Figures 2(a) and 2(b)), which were shifted downward as compared to the BOC. However, measure 1.18 performed slightly better than the BOC at both the high and low ends of the production range for the US government project (Figures 2(a) and 2(b)), and the result was average production levels that were greater than the BOC.

The negative impacts for the Edison Sault and Great Lakes Power projects also were suggested by the results of the Wilcoxon tests (Table 6). The energy duration curves for the Niagara River projects indicated that the measure had a worse performance than the BOC during lower production periods (50-100% exceedances). The Wilcoxon tests indicated a significant negative impact to capacity at the Niagara projects (see also the % difference column in Table 4), although there was not a statistically significant impact to energy. The Wilcoxon tests indicated a significant negative impact to energy production at the Hydro-Quebec projects for measure 1.18, and this impact also was evidenced in the energy duration curves (Figures 2a and 2b).

Measure 1.21 had significant negative impacts on capacity at all St. Marys River projects and a significant negative impact on energy at the US government project. The relatively small impacts to energy production at the Niagara and St. Lawrence River projects were reflected by the small percentage differences from the BOC (Table 5), the energy duration curve shapes (Figures 2(a) and 2(b)), and the Wilcoxon test results (Table 6). Measure 1.21 had a significant positive impact on capacity at the Ontario Hydro (St. Lawrence) and Hydro-Quebec projects.

For the entire system, there was a negative economic impact associated with measure 1.18, in the range of \$11.9 to \$20.5 million/year (1992 \$US). All sites, except the US government project, were calculated to experience negative economic impacts under this scenario. Positive economic impacts, in the range of \$1 to \$3 million/year (1992 \$US) were calculated for the entire system under measure 1.21. The small negative impacts at the Edison Sault, US government, Great Lakes Power, and NYPA St. Lawrence projects were offset by positive impacts at the other sites.

The economic impacts as presented in Table 7, and as calculated by Irvine *et al.* (1993) for the Reference, assume that there is a real difference between the energy and capacity production under the BOC and the scenario of interest. However, the Wilcoxon test provided mixed results with respect to statistically significant differences between the BOC and scenarios of interest. The economic impacts in Table 7 therefore have additional uncertainty related to true statistical differences between the BOC and the scenarios of interest. The differences in data between the scenarios were not statistically evaluated for the Reference because of study time constraints, potential difficulties in explaining the statistical testing to the public, and a consensus that at a planning level rigorous testing was not necessary. Given the magnitude of impacts to hydropower, as compared to some other interests (discussed below), the omission of statistical testing from the Reference may not be critical.

There is one additional consideration in the evaluation of impacts as presented in Tables 4, 5, and 6. As noted previously, the Reference Study Board determined that the BOC "with deviations" would be the baseline against which all scenarios would be compared. The BOC "with deviations" data represent the discretionary actions made by the St. Lawrence River Board of Control between 1960 and 1989. The "deviations" decision-making process was not hindcast since it is a consensus expert opinion. The "with deviations" scenario therefore does not contain "deviations" for the period 1900 through 1959. The various scenarios of interest also do not contain "deviations." As a result, Irvine *et al.* (1995) suggested that two distinct subpopulations potentially could exist in the "with deviations" scenario. Irvine *et al.* (1995) examined BOC energy production at the St. Lawrence projects for two periods, 1900-1959 and 1960-1989 using the Wilcoxon test. There was no significant difference (α=0.05) between the two periods for the Hydro-Quebec projects. There was a significant negative impact (α=0.05) under the "with deviations" period (1960-89) at the Ontario Hydro and NYPA projects. These differences due to "deviations" indicate that the calculated impacts for the Ontario Hydro and NYPA St. Lawrence projects should be viewed with caution.

5.1 Comparison of Regulation Scenario Impacts for All Interests

The IJC (1993a) provided estimates of the total economic costs and benefits associated with measures 1.18 and 1.21 and these are presented in Tables 8 and 9. Details regarding the development of the cost estimates are provided by the IJC (1993a). Table 8 indicates that the hydropower interest would incur the greatest negative economic impacts of any interest under measure 1.18. However, the estimated impacts to hydropower are an order of magnitude less than the estimated annual cost of implementation and maintenance of the measure. Some uncertainty in the hydropower estimates would not be critical, given the order of magnitude difference in the costs of implementation. Although measure 1.18 technically was feasible, the negative economic impacts

Table 8: Total Economic Impacts, Measure 1.18 ($ million/year)[1]

Positive	12.80	Flooding and erosion reduction on S, M, H, SC, E[2]
	27.20	Avoided cost of shore protection, M, H, E
	3.80	Canadian commercial navigation
Total Benefits	43.80	
Negative	3.00	Flooding and erosion increase, O, STL
	0.20	Increased cost of shore protection, S
	14.80	Hydropower loss
	3.30	US commercial navigation loss
	0.10	US recreational boating loss
Total Negatives	21.40	
Annual Cost of Implementation and Maintenance:		
Niagara River	46.20	
St. Lawrence River	275.30	
Total Costs	299.00	

1/ After IJC, 1993a

2/ S - Lake Superior; M - Lake Michigan; H - Lake Huron; SC - Lake St. Clair; E - Lake Erie; O - Lake Ontario; STL - St. Lawrence River

and potential environmental impacts were large enough that the Study Board recommended the US and Canadian governments give no further consideration to the measure.

Measure 1.21 could provide small average annual economic benefits in the areas of flood and erosion damage, hydropower, commercial navigation, and recreational boating (Table 9). Because measure 1.21 simply contains revisions to current regulation plans, no additional structural works and associated capital costs would be required. The Study Board determined that environmental impacts would be incurred only on Lake Ontario, the measure technically was feasible, and likely had characteristics that fit within the current policies of the US and Canadian governments. As a result, the Study Board recommended that the regulation plans of lakes Superior and Ontario be modified to achieve water levels and flows similar to those described under measure 1.21 (IJC, 1993a).

Table 9: Total Economic Impacts, Measure 1.21 ($ million/year)[1]

Positive	0.60	Flood reduction
	0.50	Erosion reduction
	1.30	Hydropower gain
	4.10	Commercial navigation gain
	0.30	Recreational boating gain
Total Benefits	6.80	
Negative	0	no cost implementation

1/ After IJC, 1993a

6. Conclusion

Measure 1.18 (which included construction of new regulatory works for Lake Erie) generally had a larger impact on hydropower production, and this impact more frequently was negative as compared to impacts associated with revisions to current regulation plans (*i.e.*, measure 1.21). The negative economic impact to the entire hydropower system under measure 1.18 was estimated in the range of $11.9 to $20.5 million/year (1992 $US). Small economic benefits to the entire hydropower system were calculated to range between $1 and $3 million/year (1992 $US) under measure 1.21.

It is emphasized that the estimated impacts (positive and negative) to hydropower interests were done at a planning level. The intent of this study was to provide relative comparisons with planning-level impact estimates for other interests that utilize the Great Lakes. Measure 1.21 appears to provide benefits to multiple interests and the Study Board recommended the implementation of a measure of this type. The Study Board also recommended the implementation of various land-use and shoreline-management measures, including erosion and flood-setback guidelines. Construction of additional control structures was not recommended by the Study Board (IJC, 1993a). The 18-member Citizens Advisory Committee generally supported the recommendations of the Study Board, although four of the members strongly believed that three-lake regulation should receive further consideration (IJC, 1993b). The electric power industry and its customers in the basin can benefit from higher water, although at extreme levels water is spilled. However, the industry has made its investment and development decisions based on historical water levels data and has not actively petitioned for a measure that would produce "higher" levels. Given the planning level nature of the Reference it would seem that prior to implementation of any measure, a more rigorous analysis will have to be performed.

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References

Bergmann-Baker, U., J. Brotton and G. Wall (1995) 'Socio-Economic Impacts of Fluctuating Water Levels on Recreational Boating in the Great Lakes,' *Canadian Water Resources Journal* 20:3:185-94.

Bernard, J.T. and E. Genest-Laplante (1994) 'Analyse du Plan de Developpement d'Hydro-Quebec 1992-2010,' *Energy Studies Review* 6:2:143-53.

Botkin, D.B. and E.A. Keller (1995) *Environmental Science* (New York: John Wiley and Sons, Inc.).

Botts, L. and B. Krushelnicki (1987) *The Great Lakes An Environmental Atlas and Resource Book* (Chicago: US EPA, Great Lakes National Program Office) Report EPA-905/9-87-002.

Clamen, M. (1988) 'Fluctuating Great Lakes Water Levels: Expectations and the IJC,' *The Great Lakes: Living with North America's Inland Waters* (Bethesda MD: American Water Resources Association), pp. 75-81.

Clamen, M. and D. Parsons (1989) 'IJC Challenges in an Era of Uncertainty,' *WATERPOWER '89* (New York: American Society of Civil Engineers), pp. 114-23.

David, M.H., E.F. Joeres, E.D. Loucks, K.W. Potter and S.S. Rosenthal (1988) 'Effects of Diversions on the North American Great Lakes,' *Water Resources Bulletin* 24:1:141-48.

Dawson, C.P. and Voiland, M.P. (1988) 'The Development of the Lake Ontario Sportfishery: Socioeconomic Impacts in New York State,' *The Great Lakes: Living with North America's Inland Waters* (Bethesda, MD: American Water Resources Association), pp. 259-68.

Hydro-Quebec (1992) *Development Plan 1993* (Montreal: Hydro-Quebec).

International Joint Commission (1973) *Regulation of Great Lakes Water Levels, Appendix F, Power* (Washington: International Joint Commission).

—(1981) *Lake Erie Water Level Study, Appendix E, Power* (Washington: International Joint Commission).

—(1985) *Great Lakes Diversions and Consumptive Uses* (Washington: International Joint Commission).

—(1986) *Reference Request from the Governments of Canada and the United States on the Adverse Consequences of Fluctuating Water Levels in the Great Lakes-St. Lawrence River Basin* (Washington: International Joint Commission).

—(1989) *Living with the Great Lakes: Challenges and Opportunities, Phase I Progress Report* (Washington: International Joint Commission).

—(1992) *Final Report Basis of Comparison Great Lakes-St. Lawrence River System, Task 19.3.3., Task Group 2, Working Committee 3, Phase II Water Levels Reference Study.*

—(1993a) *Levels Reference Study Great Lakes-St. Lawrence River Basin* (Washington: International Joint Commission).

—(1993b) *Levels Reference Study Great Lakes-St.*

Lawrence River Basin Annex 5 Citizens Advisory Committee (Washington: International Joint Commission).

—(1993c) *Levels Reference Study Great Lakes-St. Lawrence River Basin Annex 3 Existing Regulation, System-wide Regulation and Crises Conditions* (Washington: International Joint Commission).

Irvine, K.N. (1995) *Interim Report Hydropower Evaluations for the Lake Ontario Regulation Assessment Study*. Report to the Buffalo District US Army Corps of Engineers, Economics Section.

Irvine, K.N. and A.J. Eberhardt (1992) 'Multiplicative, Seasonal ARIMA Models for Lake Erie and Lake Ontario Water Levels,' *Water Resources Bulletin* 28:2::385-96.

Irvine, K.N., B. Price, R.J. Guido, T. Muir and R.B. Chang (1990) 'Fluctuating Great Lakes Levels and Flows: Implications for Electric Power Generation,' *The Operational Geographer*, 8:2:17-22.

Irvine, K.N., M. Leonard and S.W. Taylor (1993) *Hydropower Evaluation for the Mainstem Projects in the Great Lakes-St. Lawrence River Basin*. Report to Working Committee 3, International Joint Commission, Great Lakes Water Levels Reference, Phase II.

Irvine, K.N., S.W. Taylor, M. Leonard, K. McFarland, and E.J. Pratt. (1995) 'Impacts of Fluctuating Water Levels and Flows to Hydropower Production on the Great Lakes: Planning for the Extremes,' *The Great Lakes Geographer* 2:1:67-85.

Mendenhall, W. (1979) *Introduction to Probability and Statistics*, Fifth Edition (North Scituate: Duxbury Press).

New York Public Service Commission (1994) Schedule of Long Run Avoided Cost Estimates, Quarterly Update, Case 93-E-0175.

Ontario Hydro (1994) *Prediction of Incremental System Values of Power and Energy*. ISVPE94, November, 1994.

Ontario Ministry of Natural Resources (1995) *Lake Erie Fisheries Report 1994*, Report to the Great Lakes Fishery Commission.

Quinn, F.H. (1988) 'Great Lakes Water Levels, Past, Present, and Future,' *The Great Lakes: Living with North America's Inland Waters* (Bethesda, MD: American Water Resources Association), pp. 83-92.

Siemer, W.F. and T.L. Brown (1994) 'Motivations and Satisfactions of Lake Ontario Boating Salmonid Anglers,' *Journal of Great Lakes Research* 20:2:457-70.

Stokoe, P. and M. Trott (1993) *Development Potential and Other Benefits from Restoration, Enhancement and Protection of Great Lakes Basin Watersheds* (Toronto: Hickling Corporation) Report 5159, for Environment Canada.

Todd, M.J. and J.W. Kangas (1988) 'Great Lakes Water Resources Management,' *The Great Lakes: Living with North America's Inland Waters* (Bethesda, MD: American Water Resources Association) pp. 93-102.

US Army Corps of Engineers (1991) *Commercial Navigation on Great Lakes-St. Lawrence* (Update Letter No. 67, North Central Division, Chicago, IL).

Waxmonsky, R.W. (1992) 'US Commercial Navigation on the Great Lakes: An Overview,' *Middle States Geographer* 25:74-78.

Yee, P., R. Edgett and A. Eberhardt (1990) *Great Lakes-St. Lawrence River Regulation* (Chicago: US Army Corps of Engineers, North Central Division).