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LAKE ONTARIO REGULATION UNDER TRANSPOSED CLIMATES[1]

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ABSTRACT: The implications of Lake Ontario regulation under transposed climates with changed means and variability are presented for seasonal and annual time scales. The current regulation plan is evaluated with climates other than the climate for which it was developed and tested. This provides insight into potential conflicts and management issues, development of regulation criteria for extreme conditions, and potential modification of the regulation plan. Transposed climates from the southeastern and south central continental United States are applied to thermodynamic models of the Great Lakes and hydrologic models of their watersheds; these climates provide four alternative scenarios of water supplies to Lake Ontario. The scenarios are analyzed with reference to the present Great Lakes climate. The responses of the Lake Ontario regulation plan to the transposed climate scenarios illustrate several key issues: (1) historical water supplies should no longer be the sole basis for testing and developing lake regulation plans; (2) during extreme supply conditions, none of the regulation criteria can be met simultaneously, priority of interests may change, and new interests may need to be considered, potentially requiring substantial revision to the Boundary Waters Treaty of 1909; (3) revised regulation criteria should be based on ecosystem health and socio-economic benefits for a wider spectrum of interests and not on frequencies and ranges of levels and flows of the historical climate; and (4) operational management of the lake should be improved under the present climate, and under any future climate with more variability, through the use of improved water supply forecasts and monitoring of current hydrologic conditions.
(KEY TERMS: Lake Ontario; St. Lawrence River; regulation; climate change; climate variability; surface water hydrology; water policy.)

INTRODUCTION

Assessment of climate-related water resource impacts (both mean changes and changes in variability) on Lake Ontario is of interest because of the social, environmental, and economic significance of this natural resource. More than eight million people live within the lake's drainage basin, with the majority located along the shoreline in large metropolitan communities (Thorp and Allardice, 1994). The lake provides water for residential, commercial, and institutional facilities, agriculture, industry, electric power generation (in-stream hydroelectric, fossil fuel, and nuclear plants), navigation, sanitation, recreation, and habitat for wildlife, fish, waterfowl, and other aquatic life. The sport fishing industry alone demonstrates the environmental and economic importance of the lake; in 1985, the estimated economic impact of the industry was $141 million U.S. and $87 million Canadian (Michigan Sea Grant, 1990).

Lake Ontario is particularly sensitive to climate because it is the most-downstream lake in the chain of the five Laurentian Great Lakes; its level and outflow are an integration of the climate conditions over each lake's drainage basin. Previous climate change impact studies (Smith and Tirpak, 1989; Croley, 1990, 1993; Hartmann, 1990; Lee and Quinn, 1992), using general circulation model (GCM) outputs of double-carbon-dioxide ($2xCO_2$) climate change scenarios, show significant expected hydrologic impacts. These impacts culminate in projected decreases of Lake Ontario average annual outflows of 40 percent and, depending on how outflows are regulated, reduced average annual levels of about 1.4 m (Lee and Quinn, 1992).

These previous studies applied GCM-generated corrections to historical Great Lakes meteorological data to assess impacts of mean changes in climate, but changes in variability could not be assessed. For this study, we use transpositions of actual climates

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from the southeastern and south central continental United States because they incorporate natural changes in variability within existing climates, as well as mean changes. The Great Lakes Environmental Research Laboratory (GLERL) modeled the potential hydrology in the Laurentian Great Lakes under four transposed historical climate scenarios, ranging from 6° south and 0° west to 10° south and 11° west of the Great Lakes (Croley *et al.*, 1996). Lengthy (at least 40 years) and detailed records of daily weather at about 2,000 sites were used to represent physically plausible and coherent scenarios of alternative climates. Such data sets incorporate reasonable values and frequencies of extreme events, ensuring representation and transposition of desired temporal and spatial variability over the Great Lakes. GLERL estimated the Great Lakes hydrology of each transposed climate by applying their system of hydrologic models to these data and comparing outputs to a base case derived from historical data. The scenarios represent analog climates that could occur under global warming, as suggested by recent 2xCO_2 GCM simulations (Houghton *et al.*, 1992).

Changes in climate variability have previously been unexplored, yet they could pose significant problems for water resource managers. We focus on the response of Lake Ontario regulation to the transposed climates because the International Joint Commission (IJC) is considering a review of its criteria governing the management of the levels and outflows of this international boundary water (Canadian and American). The criteria ensure that the lake is managed to best meet the different (and often conflicting) objectives of diverse interest groups. The regulation plan, which was designed to satisfy the criteria given the historical water supply sequence, is also being considered for modification or replacement by a new plan. Evaluation of the current regulation plan, given climates other than that for which it was developed and tested, can provide valuable insight into potential conflicts and management issues, into development of regulation criteria for extreme conditions, and into modification of the regulation plan.

We present here the changes in Lake Ontario hydrology and the response of the regulation plan under the transposed climates, on seasonal (monthly) and annual time scales. The sections that follow describe the present climate and dynamics of Lake Ontario, the institutional and technical framework of the lake's regulation, methodologies used to transpose climates, and estimates of their hydrological impacts. Lastly, ramifications for regulation that are associated with these impacts are presented.

LAKE ONTARIO DYNAMICS AND CLIMATE

The Lake Ontario basin, shown (transposed) in Figure 1, contains an area of approximately 80,000 km^2, 19,000 km^2 of which is water surface. Upstream Great Lakes flows enter Lake Ontario through the Niagara River and the Welland Canal, a diversion bypassing Niagara Falls for navigation and hydropower. There is also a small flow diverted from Lake Erie to Lake Ontario via the New York State Barge Canal System. Outflows from Lake Ontario are regulated by structures 169 km downstream from the lake's outlet in the St. Lawrence River between Massena, New York, and Cornwall, Ontario. Below the control structures, the drainage from the Ottawa River basin enters the St. Lawrence River near Montreal, Quebec. Their confluence is Lake St. Louis, the water levels of which are also considered in Lake Ontario regulation. From Lake St. Louis, the water flows through the St. Lawrence River to the Gulf of St. Lawrence and the ocean. Lake Ontario is deep, with an average depth of 86 m and a maximum depth of 244 m.

The behavior of Lake Ontario is governed by its huge storage of water and energy within the lake and its basin, and by flows from the upstream Great Lakes. Because of the large storage capacity of the upstream lakes and the limited discharge capacity of the Niagara River, inflows to Lake Ontario from the upstream lakes vary slowly over time (several years) and exhibit considerable persistence subsequent to changes in climate. In comparison, watershed and lake surface supplies to the lake (watershed runoff and lake precipitation less lake evaporation) can be highly variable, exhibiting persistence on a time scale of several months. Both sources of water exhibit definite seasonal trends. Lake Ontario annual precipitation is about 93 cm (expressed over the lake), annual runoff to the lake is about 169 cm, and annual lake evaporation is about 65 cm. In comparison, the annual inflow from the upstream lakes is 1,037 cm. The changes in Lake Ontario levels (changes in lake storage) are determined by these inflows and by the regulated outflows. Since regulation began, the average seasonal range in lake levels has been about 0.6 m, and the inter-annual range of levels is about 0.9 m. Prior to regulation, the inter-annual range in levels was about 1.4 m.

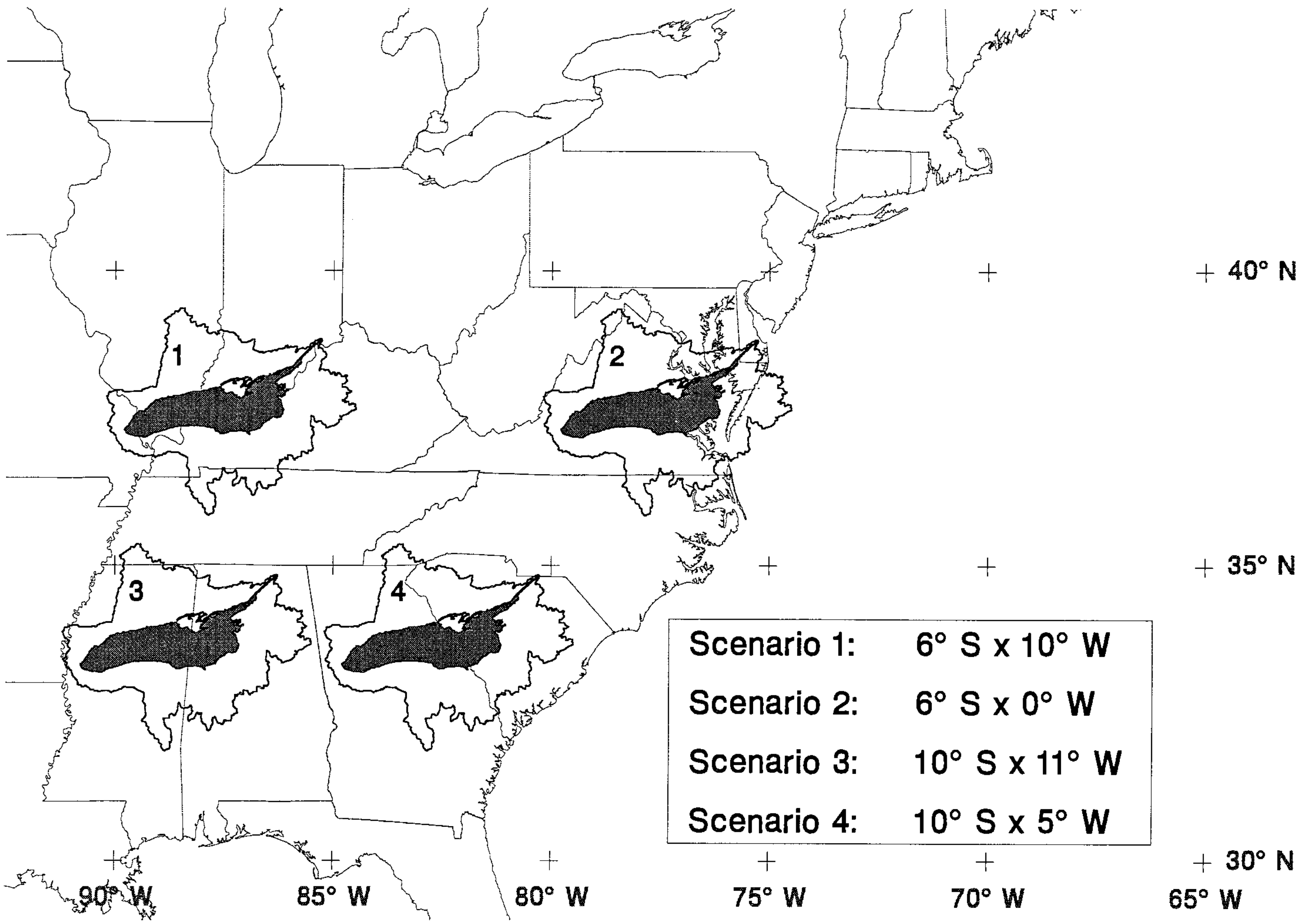

Figure 1. Transposed Climate Shifts to the Lake Ontario Basin.

LAKE ONTARIO REGULATION

Lake Ontario regulation encompasses an institutional decision-making framework, regulation objectives (i.e., criteria), and a computational response model (i.e., the regulation plan) designed to meet the criteria with the 1860-1954 supply sequence. Descriptions of these elements and their interactions follow. Additionally, problems of the regulation plan exhibited during extreme water supply sequences, and modifications to address them, are presented.

Institutional Framework

The International Joint Commission (IJC) established the International St. Lawrence River Board of Control in 1952 (IJC, 1952) to ensure that water discharges from Lake Ontario and through the International Rapids (St. Lawrence River) comply with the IJC's Orders of Approval. The St. Lawrence Seaway and Power Project altered river hydraulics and required regulation of Lake Ontario to maximize benefits from navigation and hydropower and to protect riparian interests. Lake Ontario regulation began in 1960 upon completion of the control works built as part of the Seaway project.

Reporting to the Board are the Regulation Representatives, the Operations Advisory Group, the Working Committee, and the River Gauging Committee. The two Regulation Representatives monitor and evaluate hydrologic conditions, conduct weekly regulation plan calculations, provide forecasts of weekly outflows and levels (updated monthly), advise the Board on regulation strategies, and relay direction from the Board of Control. The Operations Advisory Group (OAG) meets at least weekly to consider hydrologic information and regulation plan discharge, provided by the Regulation Representatives, and to recommend an outflow for the coming period to the Board. The OAG may propose a flow other than that specified by the regulation plan if it deems that conditions warrant. If both the OAG and Regulation Representatives recommend the same outflow, and it is consistent with the direction given by the Board, then it is implemented. If not, the matter is sent to the Board for decision. If the Board cannot reach a consensus, the decision is made by the IJC. This has happened during periods of extreme high or low water levels and outflows (D. Fay, Great Lakes St. Lawrence Regulation Office, Environment Canada, personal communication, 1996). Once an outflow decision is made, it is implemented by the agencies responsible for the operation of the control works.

The Working Committee is chaired by the Regulation Representatives with members selected from the OAG and the Board. It reviews proposed regulation plans and other technical matters related to lake regulation. The River Gauging Committee is also chaired by the Regulation Representatives and is responsible for ensuring that water levels and flows are reported accurately.

Regulation Criteria

There are 12 Criteria in the Orders of Approval for the regulation of Lake Ontario. The Criteria were developed in reference to "pre-project" conditions – the levels and flows that would have occurred in the past (1860-1954) with the actual water supplies to Lake Ontario adjusted for a diversion of 88 m^3s^{-1} out of the Great Lakes basin at Chicago and for a diversion of 142 m^3s^{-1} into the Great Lakes basin from the Hudson Bay watershed. The Criteria are described elsewhere (IJC, 1952, 1956; U.S. Army Corps of Engineers, 1991) and briefly summarized in Table 1. They intend benefits to three specific interests (navigation, hydropower, and riparian) without unacceptable adverse effects to any of them. Seaway navigation interests desire lake levels above low water chart datum to utilize full available draft, but do not desire high Lake Ontario outflows that result in high St. Lawrence River velocities and hazardous cross currents. Navigation interests at Montreal Harbor, to make effective use of their deeper draft vessels, desire higher than average outflows such that levels are about 1 m above chart datum. Hydropower interests desire uniform high minimum flows to maximize their firm power capacity on a long-term basis. Riparians upstream of the control works desire reductions in the range of water levels and frequency of extremes. Downstream riparians desire reductions in the range and frequency of extreme outflows, often in conflict with the desires of upstream riparians.

The Orders of Approval (IJC, 1952, 1956) also state that the project shall be operated to "safeguard as far as possible the rights of all interests affected by levels" on the upper St. Lawrence River and Lake Ontario. The Orders of Approval also specify that the operation of the project should not conflict with uses for domestic and sanitary purposes.

Regulation Plan

Lake Ontario's regulation plan, Plan 1958-D (International St. Lawrence River Board of Control, 1963), strives to satisfy the Criteria, with the exception of Criterion (k). The plan was implemented in 1963, succeeding earlier versions. The plan is operated weekly by the Regulation Representatives to recommend Lake Ontario outflows to the OAG. Maximum and minimum flow limitations in Plan 1958-D restrict Lake Ontario outflows to an annual range of 5,320 m^3s^{-1} to 8,780 m^3s^{-1}. One additional limitation restricts weekly outflow changes to 570 m^3s^{-1}. The plan satisfies the criteria [except for Criterion (k)] and other requirements of the Orders of Approval for 1860-1954. Criterion (k) was included to provide for supplies more extreme than those of 1860-1954. The IJC or the Board has authorized deviations from the plan to best meet Criterion (k) in the 1960s in response to low supplies and during the 1970s, 1980s, and 1990s in response to high supplies.

Problems and Modifications

Sanderson and Wong (1987), Hartmann (1990), Lee and Quinn (1992), and Lee *et al.* (1994) have shown that the plan lacks computational robustness during simulations with water supply sequences more extreme than those used in the plan's development. With persistent low supply sequences, regulated outflows exceed water supplies to the lake, and lake levels fall below the lower limit [Criterion (j)]. With persistent high supply sequences, water supplies exceed regulated outflows, and lake levels exceed the upper limit [Criterion (h)]. The plan fails numerically or returns unreasonable results under these circumstances.

Lee *et al.* (1994) improved the plan's robustness for low supplies by using a pre-project Lake Ontario discharge relationship and waiving minimum flow limitations when levels fall below 74.15 m. This helps limit impacts to no worse than under pre-project conditions, in the spirit of the Criteria. Lee *et al.* (1994) modified the plan for high supply conditions by considering Board operations during 1974-1989, a period

TABLE 1. Orders of Approval Lake Ontario Regulation Criteria.

Criteria	Description	Purpose
A	Montreal Harbor levels shall not be below pre-project conditions April 1-December 15.	Protect navigation interests in Montreal Harbor.
B	Lake outflows shall be as large as feasible with stable ice cover December 15-March 31.	Benefit winter hydropower operation.
C	Lake outflow shall not exceed pre-project conditions during spring break-up of ice.	Protect Montreal Harbor and downstream interests
D	Lake outflow shall not exceed pre-project conditions during Ottawa River spring flooding.	Protect Lake St. Louis, Montreal Harbor, and downstream riparian interests.
E	Lake minimum outflow shall ensure the maximum dependable flow for hydropower.	Protect hydropower interests.
F	Lake maximum outflow shall be low as possible.	Minimize channel excavation.
G	Lake extreme levels shall be reduced from those experienced.	Protect Lake Ontario riparian interests.
H	Monthly mean lake levels shall not exceed 75.37 m[a] with the supplies of 1860-1954[b].	Protect Lake Ontario riparian interests.
I	Monthly mean lake levels exceeding 75.07m[a] shall be less frequent than pre-project.	Protect Lake Ontario riparian interests.
J	April 1 lake level shall not be lower than 74.15m[a]; monthly mean levels shall not be lower than 74.15 m[a] April 1-November 30.	Ensure adequate levels for the navigation season.
K	When water supplies exceed those of 1860-1954[b], provide all possible relief to riparians; when water supplies are less than those, provide all possible relief to navigation and power interests.	Provide relief to riparian owners upstream and downstream. Provide relief to riparian owners upstream and downstream. stream.
*[c]	Protect navigation and riparians downstream at least as much as pre-project conditions.	Ensure past protection of navigation and riparian interests downstream.

[a]International Great Lakes Datum 1985.
[b]Adjusted for the Chicago and Hudson Bay watershed diversions.
[c]Supplementary Order.

of high supplies and lake levels. Deviations from the plan are reflected in the recorded levels and flows for this period. Because the complex plan deviation decisions of the Board cannot presently be incorporated, modifications were made to closely match simulated and recorded monthly levels and flows for 1974-1989. Between 74.15 m and 76.35 m, Plan 1958-D outflow specifications are used subject to modified maximum outflow limitations. Above 76.35 m, plan outflows are augmented to reduce storage above this level. Lee *et al.* (1994) describes plan modifications in detail.

The modified plan monthly average levels agreed with the 1974-1989 record; root mean square errors were 0.06 m to 0.15 m. The unmodified plan yielded root mean square errors of 0.52 m to 0.67 m. Similarly, modified plan flows had root mean square errors of 167 m^3s^{-1} to 634 m^3s^{-1}, while unmodified plan errors were 320 m^3s^{-1} to 807 m^3s^{-1} [see Figure 5 and Table 4 of Lee *et al.* (1994)]. We consider the modified plan acceptable for simulation; it is not used operationally.

CLIMATE TRANSPOSITION

GCMs predict that continuing increases in atmospheric trace gas concentrations will result in warmer conditions over the Great Lakes, comparable to southern climates, and drier conditions, comparable to western climates. We relocated climatic zones in the southeastern and south central United States to the Great Lakes basin to sample climatic differences in fluctuations over time. The major advantage of this approach is that the transposed data represent actual climates. Temporal variability, the frequency and magnitude of extremes, and spatial relationships are obviously realistic.

This technique takes advantage of the dense network of observing sites in the U.S. and Canada. By choosing latitudinal and longitudinal shifts, we can match meteorology predicted by GCMs or that is more extreme. There are approximately 2,000 climate (temperature and precipitation) stations in the areas of interest. For a 40-year period of daily measurements, this corresponds to about 30 million values for each variable. The development of such detailed scenarios, by means other than climate transposition, faces a monumental problem in ensuring that the large data sets have physically plausible temporal and spatial variability.

Daily maximum and minimum air temperatures, precipitation, and snowfall were obtained for the 43-year period of 1948-1990 from the dense array of stations in the National Weather Service's cooperative observer network. A subset also has daily wind speed, humidity, and cloud cover, located generally at National Weather Service offices and airport observing stations. We considered four separate climatic regimes based on published 2xCO_2 GCM ranges. Figure 1 depicts the Lake Ontario basin shift for each climate scenario. The first two climate regimes correspond roughly to the upper range of GCM predictions for temperature for the Great Lakes basin (Houghton *et al.,* 1992). Scenario 1 (from 6°S and 10°W) corresponds to warmer temperatures and mixed precipitation changes over the Great Lakes basin. The Lake Ontario climate would be 6.2°C warmer and 26 percent wetter than the present, similar to the present climate of the lower Ohio River valley. Scenario 2 (6°S x 0°W) corresponds to warmer temperatures and increased precipitation over the Great Lakes basin. The Lake Ontario climate would be 6.5°C warmer and 18 percent wetter than the present. The next two climate regimes went beyond the range of current GCM predictions to study response to a major climatic shock. Scenario 3 (10°S x 11°W) corresponds to high temperatures and mixed precipitation changes over the Great Lakes basin. The Lake Ontario climate would be 9.3°C warmer and 49 percent wetter than the present. Scenario 4 (10°S x 5°W) corresponds to high temperatures and increased precipitation over the Great Lakes basin. The Lake Ontario climate would be 9.7°C warmer and 33 percent wetter than the present. Detailed descriptions of the scenarios' climatology are available elsewhere (Croley *et al.,* 1996).

GLERL relocated all meteorological station data for each climate scenario, checked and corrected it by removing obvious outliers, and Thiessen-weighted to obtain areal averages over the 121 watersheds and seven lake surfaces of the Great Lakes basin for all days of record (1948-1992). They also reduced all historical data (base case) within the Great Lakes (1900-1990). GLERL developed, calibrated, and verified conceptual model-based techniques for simulating hydrological processes in the Laurentian Great Lakes (including Georgian Bay and Lake St. Clair as separate entities). GLERL integrated the models into a system to estimate net basin supplies to the lakes, lake levels, whole-lake heat storage, and water and energy balances for forecasts and for assessment of impacts associated with climate change (Croley *et al.,* 1996). These include models for rainfall-runoff (121 daily watershed models), over-lake precipitation (a daily estimation model), and one-dimensional (depth) lake thermodynamics (seven daily models for lake surface flux, thermal structure, and heat storage). The models were assessed partially by comparing modeled time series to historical time series for runoff, lake evaporation, water surface temperature, heat balances, and net basin supplies.

GLERL first applied the system of hydrological models to the (untransposed) historical daily meteorological time series of air temperature, precipitation, wind speed, humidity, and cloud cover within the Great Lakes basin. They modeled the 40 full years between 1951 and 1990 by arbitrarily using January 1, 1990 modeled values as initial conditions (for soil moisture, snow pack, ground water storage, and lake heat storage and surface temperature). GLERL repeated the simulation with end conditions used as initial conditions until there was no change; this became the estimate of the "base case" hydrology. (This required only one iteration for all sub-basins and lakes.) GLERL then used these initial conditions to estimate the Great Lakes hydrology of each transposed climate by directly applying the system of hydrological models to all transposed climate 40-year daily meteorological time series. The impacts were estimated by comparing the outputs for each transposed climate to the base case. The section that follows gives annual average (1951-1990 period) and seasonal estimates for both means and standard deviations for selected Lake Ontario variables.

HYDROLOGICAL IMPACT ASSESSMENT

Basin Meteorology

The overland air temperatures for all transposed scenarios are higher throughout the annual cycle than for the base case (Table 2). The differences are

TABLE 2. Average Annual Lake Ontario Climate and Transposed Climate Differences.

Variable	BASE	Scenario (Absolute or Relative Differences)			
		6°Sx10°W	6°Sx0°W	10°Sx11°W	10°Sx5°W
Overland Air Temperature[a]	7.2°C	6.2°C	6.5°C	9.3°C	9.7°C
Overland Precipitation[b]	934 mm	26%	18%	49%	33%
Snow Water Equivalent[b]	15.7 mm	-92%	-96%	-99%	-99%
Soil Moisture[b]	20.8 mm	-28%	-29%	-28%	-34%
Groundwater[b]	11 mm	-27%	-27%	-21%	-23%
Total Basin Moisture[b]	61 mm	-37%	-42%	-36%	-48%
Overland Evapotranspiration[b]	473 mm	52%	48%	88%	87%
Runoff as an Overland Depth[b]	461 mm	-1%	-14%	9%	-22%
Over-lake Air Temperature[a]	7.8°C	5.8°C	5.3°C	9.9°C	9.2°C
Lake Heat[b]	8.4 10^{17} cal	68%	62%	157%	144%
Ice Cover[b]	0.9%	-100%	-100%	-100%	-100%
Water Surface Temperature[a]	8.6°C	6.1°C	5.6°C	10.2°C	9.2°C
Lake Evaporation Depth[b]	645 mm	42%	21%	68%	66%
Over-lake Precipitation[a]	934 mm	242 mm	166 mm	461 mm	312 mm
Runoff as Overwater Depth[a]	1,701 mm	-19 mm	-238 mm	151 mm	-374 mm
Lake Evaporation Depth[a]	645 mm	272 mm	138 mm	438 mm	423 mm
Net Basin Supply[a]	1,990 mm	-49 mm	-210 mm	174 mm	-485 mm
Lake Inflow[a,d]	10,949 mm	-6,119 mm	60 mm	-6,446 mm	-102 mm
Total Supply[a]	12,939 mm	-6,168 mm	-150 mm	-6,272 mm	-587 mm
Lake Ontario Level[a,c]	74.81 m	-1.48 m	-0.03 m	-1.51 m	0.03 m
Lake Ontario Range[b]	0.56 m	32%	7%	64%	38%
Lake Outflow[b]	7,848 m^3s^{-1}	-48%	-1%	-48%	-4%
Lake St.Louis Level[a,c]	21.43 m	-1.33 m	-0.07 m	-1.35 m	-0.16 m
Lake St.Louis Range[b]	0.91 m	0%	16%	11%	30%

[a]Changes from Base Case are given as *absolute* differences.
[b]Changes from Base Case are given as *relative* differences.
[c]Levels are referenced to IGLD 85.
[d]Equivalent to Lake Erie outflow.

greatest for the southernmost scenarios (3 and 4). The difference is smallest during the late summer and largest during the late winter for all transposed scenarios (see Figure 2 for scenario 2). Changes in annual variability of air temperature are remarkably small. Table 3 shows the average annual steady-state standard deviation of air temperature, depicting the variability from year to year in the 40-year period. It appears artificial and is the result of truncation of annual air temperatures to the nearest 0.1°C before the standard deviation was calculated. The small change in variability did not warrant recalculation. Variability also changes little throughout the seasonal cycle for all scenarios. The seasonal patterns remain, with more variability associated with cooler temperatures.

Overland precipitation shows much more variability than air temperature among the scenarios. Precipitation is greater for all scenarios (Table 2). The northernmost scenarios (1 and 2) increase precipitation less than do the southernmost scenarios (3 and 4). Throughout the annual cycle, the Lake Ontario basin shows a shift in seasonal precipitation earlier for most scenarios; however, this shift is not apparent for scenario 2 in Figure 2. Changes in annual variability of precipitation are more pronounced than for air temperature (Table 3). Generally, the western scenarios (1, 3, and 4), which are also the wettest, are most variable (Table 3). The variation is greater than 100 percent for the most southwest scenario (3). Seasonally, the variability of precipitation is highest in the late summer and early fall, similar to the base case pattern but more pronounced. The pattern of variability in these scenarios is consistent with the known spatial distribution of precipitation variability. For instance, Griffiths and Driscoll (1982, Figure 7.22) show that the current Great Lakes region experiences a relative minimum of precipitation variability, which increases to the west and south.

Basin Runoff

Basin runoff in Table 2 decreases for scenarios 1, 2, and 4 as a net effect of increased overland air temperatures, increased evapotranspiration, and decreased total basin moisture [snow water equivalent, soil moisture, ground water, and surface storage (not shown in Table 2)]. Scenario 3 shows an increase because moisture reductions are offset by precipitation increases. Runoff decreases the most for the easternmost scenarios (2 and 4).

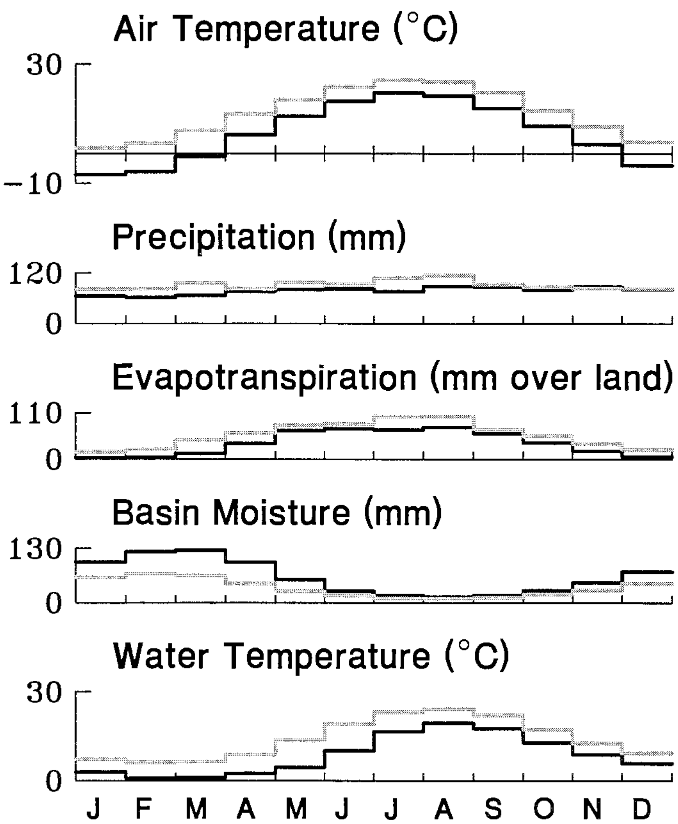

Figure 2. Seasonal Lake Ontario Average Meteorology and Hydrology for Scenario 2 (6°S x 0°W) (Black – Base Case; Gray – Scenario 2).

The increased air temperatures, consequent in all transposed climates, significantly alter the heat balance of the surface hydrology. The snow pack is almost completely eliminated and evapotranspiration increases significantly (Table 2). The greatest evapotranspiration increases and snow pack decreases occur in the southernmost scenarios (3 and 4), which increase air temperatures the most and make moisture less available in the soil and ground water zones. Table 2 shows a general lowering of soil moisture and ground water storage that results from either greater increases in evapotranspiration (scenarios 3 and 4) or lower increases in precipitation (scenarios 1 and 2). The total moisture storage is lowered for all scenarios by about one-third to one-half. The westernmost scenarios (1 and 3) show a slightly lower loss of moisture storage in the basin than do the easternmost (2 and 4).

Seasonal peak runoff shifts to earlier in the year for all four scenarios. This results from the loss of snow moisture storage; more winter runoff than the base case contributes to the runoff shift. It is also due in part to seasonal shifts in evapotranspiration. For the westernmost scenarios (1 and 3), the bulk of the annual evapotranspiration and the peak evapotranspiration occur earlier in the seasonal cycle. In scenarios 2 and 4, while evapotranspiration increases, the seasonal pattern is not significantly changed. Figures 2 and 3 depict the typical seasonal behavior of evapotranspiration and runoff for scenario 2.

Snow water variability is greatly decreased simply because snow water is greatly decreased toward its lower bound of zero (Table 3). Changes in variability of soil moisture, ground water, surface storage, and total basin moisture (-1.1 mm to +1.4 mm) are small with respect to both annual and seasonal values. Table 3 also shows more variable evapotranspiration for the southernmost scenarios (3 and 4) corresponding to the greatest and most variable precipitation; (Tables 2 and 3). This results from evapotranspiration being moisture limited; more variability in the moisture supply translates into more variability in evapotranspiration. A slight increase in runoff variability exists during the winter for all scenarios, corresponding to the absence of the snow pack; runoff then varies more with precipitation. The greatest consistent change, over all Great Lakes, in variability of both evapotranspiration and runoff, occurs on the Lake Ontario basin; it is exposed to the most-eastern part of each scenario with its most variable precipitation.

Lake Evaporation

All scenarios produce significant increases in lake evaporation. Table 2 shows increases of 21 percent to 68 percent, with the largest increase corresponding to the southernmost scenarios (3 and 4). The sum of insolation, reflection, net long wave exchange, sensible heat exchange, and latent heat exchange increase heat in storage 62 percent and 157 percent in Table 1, appearing as a constant amount higher throughout the seasonal cycle. This means that ice is eliminated (-100 percent for all four scenarios). The average steady-state increase in water surface temperature ranges from 5.6°C to 10.2°C with the largest resulting from the southernmost scenarios (3 and 4). Water surface temperatures peak earlier under the transposed climates than under the base case.

The variability associated with lake heat balance variables are summarized in Table 3. The stored heat

TABLE 3. Average Annual Lake Ontario Climate and Transposed Climate Variability.

Variable	BASE	Scenario (Relative Differences)			
		6°Sx10°W	6°Sx0°W	10°Sx11°W	10°Sx5°W
Overland Air Temperature Std. Dev.	0.60°C	0%	-17%	0%	0%
Overland Precipitation Std. Dev.	89.6 mm	99%	71%	149%	96%
Snow Water Equivalent Std. Dev.	10.3 mm	-83%	-93%	-97%	-99%
Soil Moisture Std. Dev.	2.3 mm	39%	30%	61%	35%
Groundwater Std. Dev.	1.4 mm	64%	43%	93%	64%
Total Moisture Storage Std. Dev.	11.2 mm	-17%	-35%	-12%	-32%
Overland Evapotranspiration Std. Dev.	41.3 mm	114%	115%	183%	162%
Runoff as Overland Depth Std. Dev.	55.2 mm	115%	60%	151%	67%
Over-Lake Air Temperature Std. Dev.	0.90°C	-33%	-33%	-44%	-33%
Lake Heat Std. Dev.	0.80 10^{17} cal	50%	50%	25%	38%
Ice Cover Std. Dev.	1.8%	-100%	-100%	-100%	-100%
Water Surface Temperature Std. Dev.	1.00°C	-40%	-40%	-60%	-50%
Lake Evaporation Depth Std. Dev.	60.2 mm	13%	15%	-3%	9%
Over-Lake Precipitation Std. Dev.	90 mm	99%	71%	149%	96%
Runoff as Over-water Depth Std. Dev.	204 mm	115%	60%	151%	67%
Net Basin Supply Std. Dev.	304 mm	102%	57%	141%	74%
Lake Inflow[a] Std. Dev.	1,016 mm	5%	-3%	-22%	50%
Total Supply Std. Dev.	1,222 mm	6%	2%	5%	41%
Lake Ontario Level Std. Dev.	0.09 m	433%	0%	411%	144%
Lake Ontario Range Std. Dev.	0.14 m	71%	21%	107%	57%
Lake Outflow Std. Dev.	741 m^3s^{-1}	1%	2%	-5%	42%
Lake St. Louis Level Std. Dev.	0.23 m	25%	6%	18%	51%
Lake St. Louis Range Std. Dev.	0.21 m	-41%	14%	-35%	28%

[a]Equivalent to Lake Erie outflow.

variability increases some for all scenarios and appears more uniformly spread across the seasonal cycle in every scenario than in the base case since the ice pack is eliminated. Since the ice pack is gone, its variability is zero, implying a relative change of 100 percent in Table 3.

The water surface temperature in Table 3 is less variable. Its variability also is spread more uniformly throughout the season than for the base case, again reflecting ice pack elimination. Peak variability shifts from summer to spring in all except scenario 2 and results from a change in seasonal heat storage. There are significant changes in developments of vertical thermal profiles in the lake and the lake's mixing throughout the annual cycle; biannual turnovers cease as the lake stays above 4°C throughout the year (Croley *et al.*, 1996). As a result of the loss of ice cover and increased heat storage throughout the annual cycle, evaporation occurs under the transposed climates in 95 percent to 97 percent of the annual cycle, compared with 84.2 percent of the annual cycle under the base case.

Lake Water Balance

Precipitation, runoff, and lake evaporation sum algebraically as the net basin supply to the lake and all are presented in Table 2 as over-lake depths and absolute differences. Net basin supply is less than the base case for all scenarios except scenario 3, where a precipitation and runoff increase were sufficient to offset evaporation losses. Net basin supply decreases 2 percent to 24 percent for scenarios 1, 2, and 4 compared to the base case, and increases 9 percent for scenario 3.

There is a shift in the peak net basin supplies under all transposed climate scenarios from April to March (Figure 3). Also, the net basin supplies are greater from December through March under the westernmost scenarios (1 and 3) than under the base case; for the easternmost scenarios (2 and 4), the net basin supplies are greater than the base case from January through March, with the minor exception in August of scenario 2, which is only slightly higher.

The variability associated with the net basin supplies and its components is summarized in Table 3. The annual variability of net basin supplies increases under all scenarios, from 57 percent to 141 percent.

Seasonally, the variability is distributed across the seasonal cycle approximately as the base case, but larger. There does appear to be generally greater increases in variability over the late summer-fall-winter-early spring, relative to the late spring-early summer.

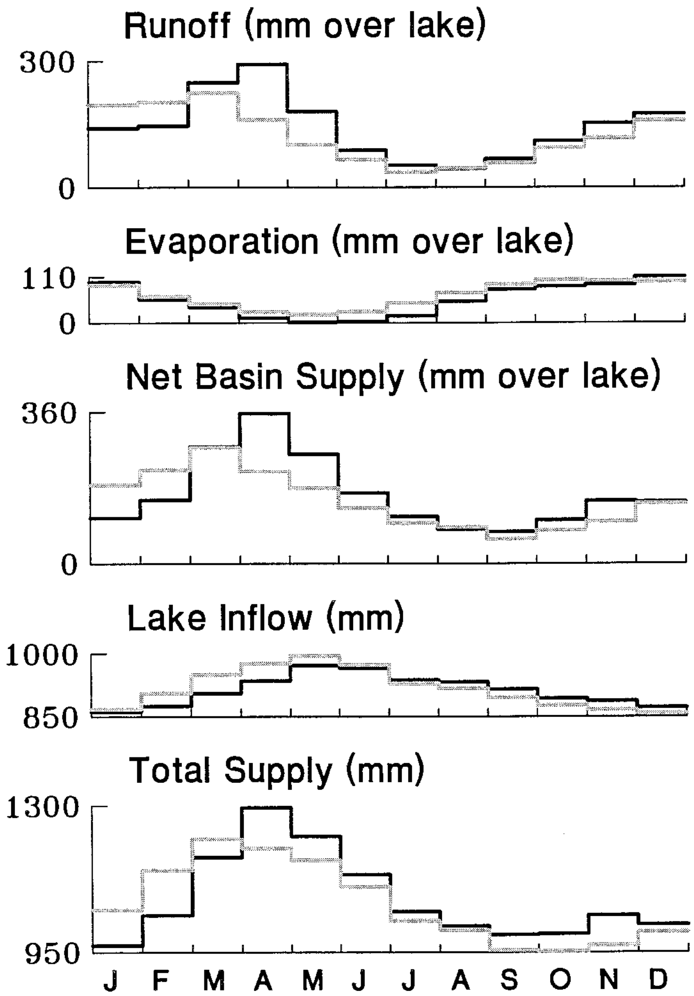

Figure 3. Seasonal Lake Ontario Average Total Supply and Components for Scenario 2 (6°S x 0°W) (Black – Base Case; Gray – Scenario 2).

Lake inflow (Lake Erie outflow) and net basin supply sum algebraically as the total supply; both are presented in Table 2 as over-lake depths and absolute differences. Lake inflows are significantly less than the base case for scenarios 1 and 3 (-56 percent and -59 percent, respectively) but are only slightly different for scenarios 2 and 4 (+1 percent and -1 percent, respectively). Since these flows are over five times greater than net basin supplies, they largely determine the total supplies to the lake. Total supplies drop 48 percent for scenarios 1 and 3 and only 1 percent and 5 percent for scenarios 2 and 4, respectively, even though scenarios 2 and 4 showed the greatest decreases in net basin supplies. Likewise, scenarios 1 and 3 have the highest drop in total supplies even though they showed the least change in net basin supplies. These results differ from earlier studies that used GCMs (Croley, 1990, 1993) in that both lake inflows and net basin supplies decreased concurrently. Scenarios 1 and 3 results are most similar to the earlier studies, in decreased total supplies.

There is no shift in the May seasonal peak of lake inflows under any scenario (Figure 3). For scenarios 2 and 4, winter-spring outflows are greater than the base case, and late summer-fall outflows are less. The seasonal shift in net basin supplies, however, does shift the peak total supply from April to March for all scenarios (Figure 3). Total supplies are greater than the base case during the winter-early spring months for scenarios 2 and 4 (due to higher winter runoff on all Great Lake basins), and lower for the late spring-summer-fall months (due to increased evaporation on all lakes).

The annual variability of lake inflows in Table 3 increases under scenarios 1 and 4 (5 percent and 50 percent, respectively), and decreases under scenarios 2 and 3 (-3 percent and -22 percent, respectively). Small increases in total supply variability occur for scenarios 1 through 3 (2 percent to 6 percent). A large increase in variability occurs under scenario 4 (41 percent), primarily due to the large variability of the lake inflows. Seasonally, the variability of the total supplies is distributed across the seasonal cycle approximately as it is in the base case, but larger.

LAKE REGULATION RESPONSE TO TRANSPOSED SCENARIOS

The response of the Lake Ontario regulation plan was evaluated for each scenario by routing the base case and transposed climate water supplies for 1951 through 1990 through the modified channel routing and lake regulation model of the Great Lakes system (Lee *et al.*, 1994). The water supplies were also routed through the unmodified model for comparison. Initial and other system conditions (diversions, consumptive uses, and connecting channel weed retardation) were those reported by Lee (1993). Because no ice formed in the climate transposition scenarios, ice retardation was neglected for the four scenarios. Ottawa River flows were treated by applying long-term average differences (between recorded flows in the St. Lawrence River at Montreal and from Lake Ontario) to the modeled Lake Ontario outflows. The complexity of, and the lack of a basin runoff model for, the regulated Ottawa River system precluded application of the transposed climate methodology there. The Great Lakes regulation and routing models were run to steady-state conditions for each scenario and the base case.

Scenarios 1 and 3

Average annual Lake Ontario levels are significantly less than the base case for the westernmost scenarios (1 and 3), -1.48 m and -1.51 m, respectively (Table 2), comparable to earlier studies (Lee and Quinn, 1992). These decreases are due to the 48 percent drops in the total supply, which are further reflected in lake outflow reductions of 48 percent. However, the average annual Lake Ontario range (defined as the annual maximum level minus the minimum) increased by 32 percent and 64 percent for scenarios 1 and 3, respectively (Table 2). Levels of Lake St. Louis (at Pointe Claire), downstream of Lake Ontario's control structures, also decline by 1.33 m and 1.35 m for scenarios 1 and 3.

There is no shift in the seasonal peak levels for scenario 1 from that of the base case (Figure 4). Peak levels shift from June to May for scenario 3 due to a more rapid decline in total supplies during the late spring and summer than either the base case or scenario 1. Peak outflows for both scenarios shift from May to June (Figure 4), attributable to the way outflows are specified entirely by the pre-project relationship because of the severe decline in lake levels. For the base case, Plan 1958-D releases higher outflows in the spring months than those specified by the pre-project relationship in order to compress the range of seasonal levels. There is a corresponding lag in peak levels from April to May for Lake St. Louis (Figure 4).

Average annual Lake Ontario level variability increased 433 percent and 411 percent, and Lake Ontario range variability increased 71 percent and 107 percent (Table 3). However, lake outflow variability changed only 1 percent and -5 percent for scenarios 1 and 3. Recall that lake outflows are specified under the modified regulation plan by the pre-project discharge relationship when lake levels fall below 74.15 m. Because of the large storage capacity of the lake relative to the pre-project discharge capacity, outflows are less variable than lake levels. This response, along with the increased variability of the total supplies, results in the greatly increased variability of lake levels while outflows are only slightly more variable.

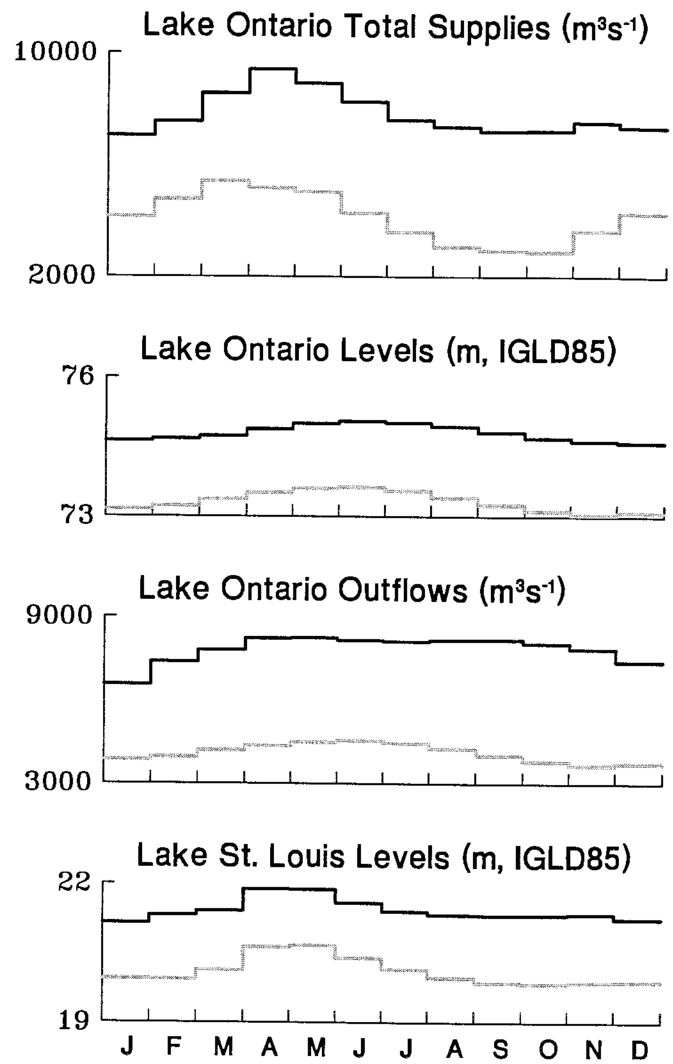

Figure 4. Seasonal Lake Ontario Average Total Supply and Regulation Responses for Scenario 1 (6°S x 10°W) (Black – Base Case; Gray – Scenario 1).

The regulation criteria (a-j) could not be satisfied simultaneously. For example, Criterion (j) (maintaining adequate navigation depths) was met by further reducing outflows in violation of the supplementary order (ensure past protection of navigation and riparians downstream). Or conversely, Criterion (a) (maintaining adequate navigation depths in Montreal Harbor) can be met by further reducing Lake Ontario levels in violation of Criterion (j).

Many of the criteria would be irrelevant under scenarios 1 and 3. Increased water temperatures and no ice negate the need for Criteria (b) and (c), which address ice formation and break-up. The significant decreases in Lakes Ontario and St. Louis levels negate the need for Criteria (d), (g), (h), and (i), addressing extreme high levels and outflows.

Criterion (k) would no longer be sufficient to provide relief to riparians under high levels or to navigation and hydropower under low levels. More decisions would be referred to the IJC as the regulation became more contentious in the OAG and Board of Control. Undoubtedly, other interests would seek entrance to the decision-making process and demand changed priorities. Such a precedent exists in the Board's recent attention to environmental and recreational boating interests. The decreases in total basin moisture would increase demand for domestic, sanitary, and irrigation water. Increasing consumptive use would further decline lake levels and outflows. Domestic and sanitary uses are given precedent over navigation and hydropower by the Boundary Waters Treaty. Consideration of other interests and severe climate change impacts would probably force decision making above the IJC into higher legislative and executive levels of the Canadian and U.S. governments, potentially requiring a revised Boundary Waters Treaty.

Use of the unmodified regulation plan with the scenarios, computationally "drains" the lake because specified outflows exceed total supplies. New regulations would be needed. We demonstrated one alternative in our modifications; another might lower the maximum and minimum flow and lake level limitations and alter other parameters appropriately for a changed climate. Both alternatives permanently lose water storage. A third alternative would reduce outflows to equal total supply, maintaining levels typical of the present climate. The difficulty would be recognizing a climate shift before a permanent reduction in lake volume occurs. With any of these alternatives, downstream interests would suffer due to decreased flows, but some riparian benefits would be preserved with the third alternative.

Scenario 2

The regulation plan responds to scenario 2 very much like the base case for average annual water levels and outflows of Lakes Ontario and St. Louis, while the average annual ranges increase by 7 percent and 16 percent, respectively (Table 2). Seasonal patterns of levels and outflows on both lakes are similar, but spring values are higher than the base case, and fall values are lower, reflecting increased spring runoff and fall evaporation. Level and outflow variability on both lakes do not increase significantly although the range variability does (Table 3).

The response of the modified and unmodified regulation plans is shown in Figure 5 for scenario 2. With the unmodified plan, total supplies exceed the maximum outflow limits beginning in 1973, causing levels to rise beyond the upper limit [Criterion (h)]. With the modified plan, outflow limits are relaxed under extreme supply sequences, and average monthly levels below 75.37 m are maintained. A similar response is observed with the base case.

Scenario 2 illustrates that a total supply regime similar to the past 40 years may occur with an altered climate as far as Lake Ontario is concerned. One significant difference would be the absence of ice cover, permitting higher winter outflows than specified in the plans and reducing seasonal peak outflows and lake levels. Criteria (b) and (c) could be ignored, and winter and spring outflows increased, so long as Criterion (d) is not violated (lake outflow should not exceed pre-project outflows during Ottawa River spring flooding).

Under this scenario, the present plan could be modified to better meet the regulation criteria. The existing institutional structure and the Boundary Waters Treaty would not likely change. Minimum base flows for hydropower could increase and become seasonally more uniform. A year-round ice-free season would benefit navigation. Riparians and recreational boaters would benefit from reduced seasonal fluctuations in levels and flows. However, environmental interests would most likely suffer from increased lake temperatures, reduced lake turnovers, and reduced ranges.

The outflow capacity could be increased through additional channel excavation [Criterion (f)] to help manage high supplies. However, the IJC Levels Reference Study (Levels Reference Study Board, 1993) concluded the costs probably would be prohibitive.

Scenario 4

Scenario 4 is similar to scenario 2 in terms of its impact on annual average lake levels and outflows (Table 2). However, the average annual ranges increase by 38 percent and 30 percent, respectively for Lakes Ontario and St. Louis. Scenario 4 increases total supplies following 1965, but with more variability and extremes than either the base case or scenario 2. It also exhibits much lower total supplies for 1954-1960 and 1967-1973. There are no shifts in the peak level and outflow on Lakes Ontario and St. Louis, but there is greater seasonal variability. Spring values are higher than the base case, and late fall values are lower, reflecting increased spring runoff and fall evaporation. The variability of the average annual levels, outflows, and ranges on Lakes Ontario and St. Louis increases significantly (Table 3). Thus, scenario 4 resembles the present regime's average levels and outflows but has much more variability and extremes in total supplies.

The response of the modified and unmodified regulation plans are similar to that of scenario 2

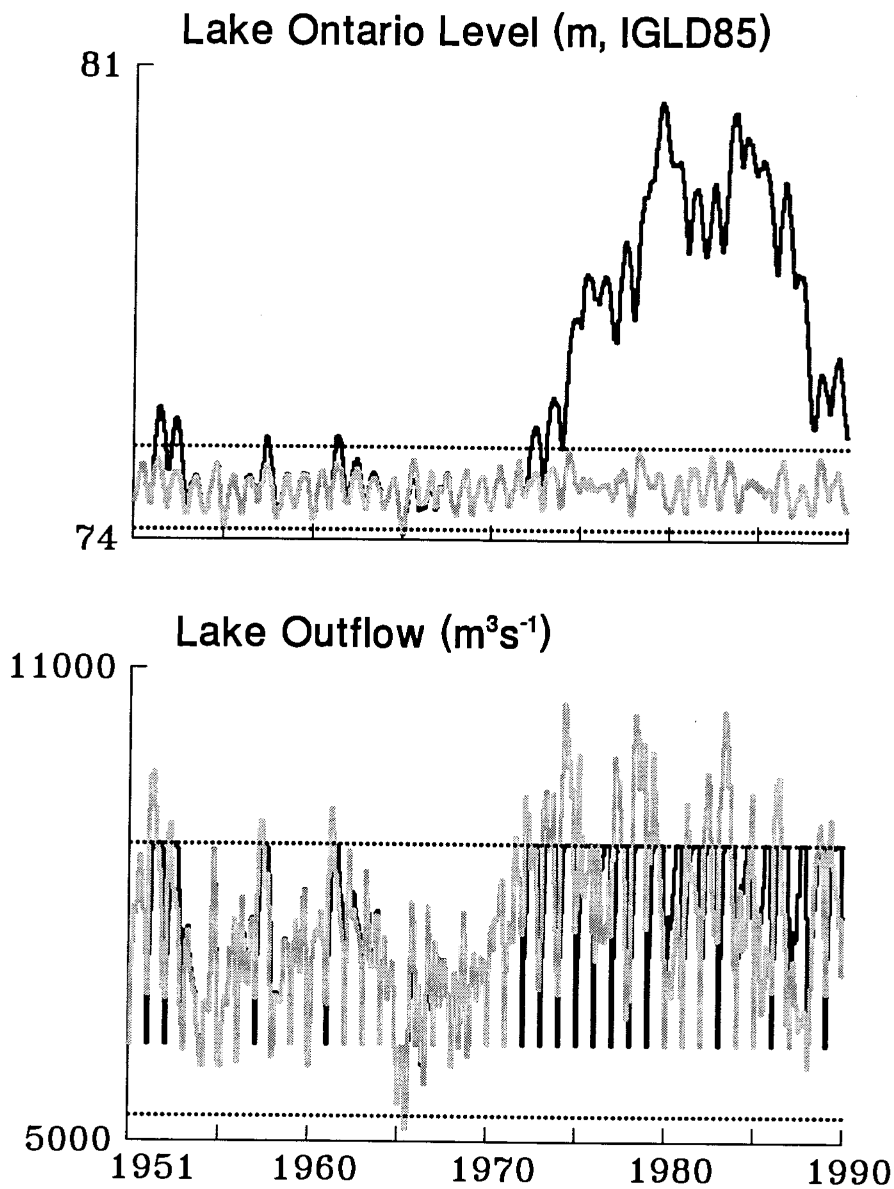

Figure 5. Annual Lake Ontario Average Lake Levels and Outflows for Scenario 2 (6°S x 10°W) and Regulation Plan Limits (Black – Unmodified Plan; Gray – Modified Plan).

(Figure 5). Again, with the unmodified plan, total supplies exceed the maximum outflow limits beginning in 1973, causing levels to rise beyond the upper limit [Criterion (h)]. With the modified plan, outflow limits are relaxed and levels are maintained near the upper limit. During the extreme low supply periods, 1954-1960 and 1967-1973, Lake Ontario levels fall below the lower limit [Criterion (j)] with the unmodified plan because the minimum outflow limits are greater than total supply. However, the modified plan reduces outflows, and the levels rise correspondingly. Because beginning levels in 1954 and 1967 are not below the lower limit (74.15 m), outflows are a function of a supply indicator integral to Plan 1958-D. The supply indicator is the difference of the weighted past total supplies from the weighted observed supplies (1860-1954). The weights are sensitive to long-term supply changes, but not to short-term changes (International St. Lawrence River Board of Control, 1963) and are not a good index of future supplies during rapid and large transitions, particularly for the second half of 1957 (Figure 6). Note also the frequent seasonal lag with total supplies. The low supply indicators result in low plan outflows and high lake levels, peaking in 1957. This artifact of the modified plan would not be tolerated in actual practice; Criterion (k) would be

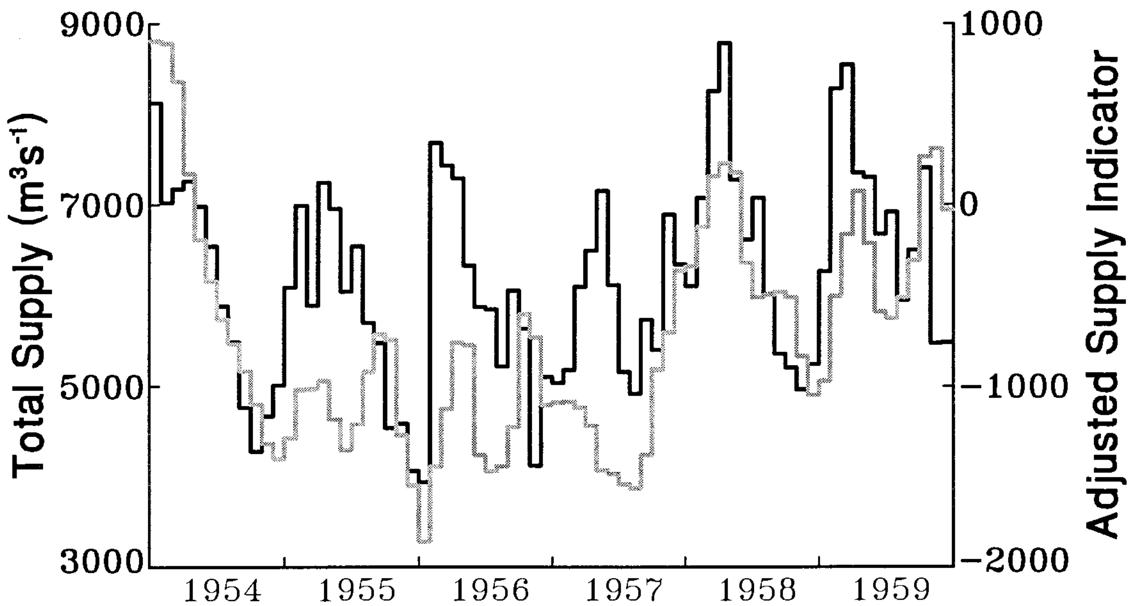

Figure 6. Lake Ontario Total Supply and Adjusted Supply Indicator, 1954-1959, for Scenario 4 (10°S x 5°W) (Black – Total Supply; Gray – Adjusted Supply Indicator).

invoked to compromise between the minimum outflow limits and the low plan outflows. Changes to the modified and unmodified plans (a more sensitive supply indicator and revised outflow limits) to address these problems are recommended.

Revision of the regulation plan as discussed under scenario 2 would not be as successful under scenario 4 due to the increased variability in total supplies, which has serious implications for lake management. Croley and Lee (1993) show that present water supply forecasts of the U.S. Army Corps of Engineers and Environment Canada (made with the smaller present variability in total supplies) are only marginally better than climatology for one-month outlooks and the same or worse for six-month outlooks. Skill would decrease further with increased variability in total supplies. Skill can increase only with improved long-range (> 30 days) quantitative weather forecasts, observations of current hydrologic conditions, and the use of risk assessment (Lee *et al.,* 1997) and probabilistic forecasts (Croley, 1996) in decision-making. Also required are revision of expectations and better education as to the limits of lake regulation and forecasting, and development *a priori* of management plans for extreme conditions.

CONCLUSIONS

Historical water supplies should no longer be the sole basis for the testing and developing of lake regulation plans. We must consider alternate climates to more fully understand plan response. Also, the regulation criteria cannot be met simultaneously during extreme supply conditions. Interests and their priorities may change under alternate climates. The institutional structure of lake regulation may be affected; decisions may be relegated to higher government authorities when issues cannot be resolved within the current structure. Revision of the Boundary Waters Treaty may be one result. The criteria in the Orders of Approval established engineering design requirements for the Seaway and hydropower project given the 1860-1954 climate regime(s). Revisions to the criteria (and any regulation plan that embodies them) must now focus on operational and adaptive requirements for existing and alternative climate regimes, such as ecosystem health, economics, and social benefits to a wider spectrum of interests.

Plan improvements require better weather forecasting and observation of current hydrologic conditions, risk assessment and probabilistic forecasts in decision-making, revision of expectations and better education as to the limits of lake regulation and forecasting, and development *a priori* of management plans for extreme conditions. Hydrologic predictions are now available that utilize new long-range meteorological forecasts and probabilistic techniques (Croley, 1996); evaluation of the predictions remains. Lee *et al.* (1997) show probabilistic forecast use to assess risk in operational lake level decisions. Education on lake regulation limitations is an ongoing activity that recently suffered from budgetary reductions. Development of management plans for extreme conditions remains to be implemented. These initiatives should be explored by the International St. Lawrence River Board of Control and its Working Committee.

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