Chapter 8

The Role of Multi-Lake Regulation in Addressing Extreme Water Levels

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Lake Superior Regulation:
Addressing Uncertainty in Upper Great Lakes Water Levels

Final Report to the International Joint Commission

by the
International Upper Great Lakes Study
Chapter 8 analyzes the feasibility and implications of addressing extreme high and low water levels by means of multi-lake regulation that would seek to benefit the Great Lakes-St. Lawrence River system as a whole.

8.1 Introduction

The primary mandate of the International Upper Great Lakes Study (the Study) was to provide recommendations to the International Joint Commission (IJC) on how to better manage upper Great Lakes water levels and flows to the benefit of all interests served by the upper Great Lakes system. In turning to the question of Lake Superior regulation, the Study Board recognized early on that it would be difficult to design a single regulation plan that would be optimal for all future conditions, given the high level of uncertainty associated with future hydrological conditions of the basin. Moreover, it became apparent that extreme water levels equalling or exceeding the range of levels observed in the past could be experienced in the future, and that Lake Superior regulation alone could do little to reduce the risk posed by such extremes, particularly downstream of Lake Superior.

The Study Board concluded that to more fully address changing water levels in the upper Great Lakes basin, there was a need to look beyond the existing system of Great Lakes regulation, and consider alternative approaches for managing and adapting to uncertain future conditions. One such option is multi-lake regulation – the possibility of operating regulation structures to control Great Lakes water levels and flows, within certain limits, to benefit the Great Lakes-St. Lawrence River system as a whole. In theory, this could be achieved either by using the existing two structures on the St. Marys and St. Lawrence rivers, with modified regulation rules that consider the entire state of the system, or by combining modified regulation rules at the existing structures with new control structures at one or more of the additional Great Lakes connecting channels, such as the St. Clair, Detroit and Niagara rivers.

In October 2009, the Study Board sought direction from the IJC on the extent to which the Study should address this issue. The IJC responded in a letter to the Study Board in April 2010, after consulting with governments. The IJC re-emphasized its request that the Study conduct an examination of climate change impacts on water levels, and specifically directed that the Study should:

“...include consideration of a full range of options available to all potentially affected sectors across the Great Lakes-St. Lawrence River system at an exploratory level.”

8.2 The Study’s Approach to Multi-Lake Regulation Analysis

8.2.1 Study Strategy

The Study Board developed a strategy to guide its multi-lake regulation analysis based on the direction provided by the IJC and lessons learned from past studies of multi-lake regulation in the Great Lakes-St. Lawrence River system. Previous studies conducted by the IJC have concluded that the costs of multi-lake regulation far outweigh the benefits, with the most recent study recommending “that Governments

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1 This section is based on peer-reviewed research on multi-lake regulation commissioned by the Study (International Upper Great Lakes Study [IUGLS], 2011).

2 Currently, the Great Lakes-St. Lawrence River system is regulated at two locations: at the outlet of Lake Superior on the St. Marys River, and at the outlet of Lake Ontario on the St. Lawrence River. These two structures are operated to regulate water levels for the upper Great Lakes and Lake Ontario, respectively.
give no further consideration” to any multi-lake regulation scenario considered at that time (Levels Reference Study, 1993). However, since that time, researchers have gained a greater appreciation of the possible impacts on water levels and flows that might result from climate change and the risks these changes may pose to various Great Lakes interests.

The Study’s analysis of hydroclimatic conditions in the upper Great Lakes basin (Chapter 4) concluded that there exists considerable uncertainty regarding future net basin supplies (NBS) and the associated impacts on water levels and flows. However, the Study also concluded that it is likely that water levels outside of the range of those experienced in the past will occur in the future. Knowing from past experience that extreme high and low water levels can cause difficulties to interests throughout the Great Lakes system (see Chapter 3), the precautionary principle would suggest that planners and decision makers must be prepared for such occurrences in the future. By allowing for the adjustment of water levels and flows, within certain limits, multi-lake regulation may be able to help prevent undesirable water level conditions, and provide one means of preparing for an uncertain future.

As a result, the Study Board strategy focused on the potential of multi-lake regulation to address the impacts of uncertain future hydrological conditions in the Great Lakes-St. Lawrence River system. The main components of the Study’s multi-lake regulation strategy were to:

- investigate the capacity of multi-lake regulation to reduce the frequency of occurrence of extreme water level conditions within the Great Lakes-St. Lawrence River system in the future, including:
  - selecting a range of possible extreme NBS scenarios for plan development and assessment;
  - developing, through the use of optimization tools and the selected NBS scenarios, new regulation rules (in the form of rule curves) for the existing two control structures on the St. Marys and St. Lawrence rivers, as well as hypothetical structures in the St. Clair and/or Niagara rivers; and,
  - evaluating the regulation plans developed against two objectives: a frequency-based objective, linked to reducing the frequency of occurrence of extreme water levels in the future over that which would occur under current regulation conditions; and a cost-minimization objective to help estimate the performance-cost tradeoffs involved with reducing the risks from extreme water levels;
- briefly review the environmental and institutional considerations associated with multi-lake regulation; and,
- review the additional issues and limitations related to multi-lake regulation that were not considered directly in this analysis, but that would need to be investigated if additional studies concerning the feasibility of multi-lake regulation were pursued in the future.

### 8.2.2 Limitations of Analysis

The Study Board recognized that it was beyond the scope of the exploratory analysis to evaluate the direct impacts of the different multi-lake regulation plans on the key interests. Such an analysis would require updating the Study’s version of the Shared Vision Model (SVM) developed to evaluate Lake Superior regulation plans (see Chapter 5) to include Lake Ontario and the St. Lawrence River, and then linking this with the multi-lake system optimization model to incorporate the different plan performance

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3 A planning and decision-making principle that states that “where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.”
indications into the objective function. However, given that most Great Lakes interests generally face adverse consequences when water levels exceed historical extremes (see Chapter 3), extreme water levels (both high and low) provide an acceptable metric for representing adverse water level conditions for these interests.

Two other notable limitations of the Study’s multi-lake regulation analysis must be considered when assessing the multi-lake plan results outlined below. First, when developing the plans in this analysis, no consideration was given to the flows or water levels that would result in the connecting channels (i.e., the rivers connecting each of the Great Lakes, including the St. Marys, St. Clair, Detroit and Niagara). Second, as discussed in section 8.3.3, multi-lake plans were developed for the Great Lakes without consideration given to the lower St. Lawrence River. By placing no limits on flows and water levels and ignoring the impacts in the connecting channels and lower St. Lawrence River, the multi-lake regulation plans developed provided an illustration of the best performance that could be achieved on the Great Lakes themselves. However, in reality, to implement any multi-lake regulation plan, consideration would have to be given to the impacts of such a plan on interests throughout the Great Lake-St. Lawrence River system, and not just the lakes themselves. These limitations and their consequences on multi-lake regulation plan results are discussed in greater detail in section 8.6.

8.3 Multi-Lake Regulation Plan Development

8.3.1 Extreme Net Basin Supply Scenarios

Acknowledging the uncertainty about the future climate and its impacts on the hydrology of the Great Lakes-St. Lawrence River system, a multi-NBS scenario approach was used in developing the multi-lake regulation plans for this analysis. This approach involved using a number of different NBS scenarios to represent a range of possible future severe climate conditions. It also allowed for the development of robust multi-lake regulation plans able to provide improved system-wide performance for each NBS scenario.

Eight different NBS scenarios were chosen from the 50,000-year stochastic NBS dataset produced for the Lake Ontario-St. Lawrence River Study (Fagherazzi et al., 2005; International Lake Ontario-St. Lawrence River Study Board, 2006) to develop the multi-lake regulation plans. It was necessary to use this dataset as opposed to the different NBS scenarios used for Lake Superior regulation plan formulation and evaluation because the multi-lake analysis involved evaluations of Lake Ontario and the St. Lawrence River that were not assessed as part of the Upper Lakes Study. The 50,000-year stochastic dataset is based on historically recorded net basin supplies, and changing climate conditions may result in supplies outside of the range that this dataset describes. Nonetheless, the eight scenarios were identified as being diverse in terms of generating a range of high and low lake levels overall as well as differentially across the Great Lakes (Figure 8-1). Therefore, the Study concluded that the selected scenarios provided an acceptable starting point for developing plans and evaluating the feasibility of multi-lake regulation as a means of dealing with possible extreme conditions in the future. In addition, the multi-lake regulation NBS scenarios were chosen to be 70 to 80 years in length, in contrast to the 109-year NBS scenarios used for Lake Superior plan formulation and evaluation, in order to improve computational efficiency while providing similar initial water level conditions to ensure consistency among the different scenarios (for additional information on the NBS scenarios used, see Tolson et al., 2011).

The eight NBS scenarios were used in plan development and initial evaluations of the plan results. Validation experiments were subsequently performed by simulating the most promising multi-lake regulation plans developed over the full 50,000-year stochastic NBS sequence from the Lake Ontario-St.
Lawrence River study. The multi-lake regulation plans would be expected to perform best under the more extreme scenarios represented by the eight NBS scenarios discussed above, but the full 50,000-year stochastic simulation allowed for a more detailed assessment of plan performance over a greater variety of possible future scenarios.

8.3.2 Regulation Scenarios

The Study investigated four multi-lake regulation scenarios, based on the following control configurations (Table 8-1):

- **Two-point**, which involved developing new multi-lake regulation rules for the existing structures at the outlets of Lake Superior and Lake Ontario (on the St. Marys and St. Lawrence rivers, respectively);
- **Four-point**, which involved developing new multi-lake regulation rules for all four upper lakes, including the existing structures and hypothetical structures at the outlets of Lake Michigan-Huron and Lake Erie, thereby providing the greatest level of control of water levels in the entire system among all the scenarios;
- **St. Clair three-point**, which involved developing new multi-lake regulation rules for the existing structures, as well as rules for a hypothetical structure at the outlet of Lake Michigan-Huron on the St. Clair River; and,
- **Niagara three-point**, which involved developing new multi-lake regulation rules for the existing structures, as well as rules for a hypothetical structure at the outlet of Lake Erie on the Niagara River.
The analysis considered the scenarios in this two-point, four-point and three-point order. Considering two-point and four-point scenarios first allowed the analysis to establish the upper and lower boundaries of multi-lake regulation results. Three-point scenarios, therefore, represented opportunities to further refine a multi-lake regulation plan within these boundaries.

Table 8-1
Multi-lake Regulation Scenarios

<table>
<thead>
<tr>
<th>Regulation Scenario</th>
<th>Location of Control Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Point</td>
<td>Existing Control</td>
</tr>
<tr>
<td>Four-Point</td>
<td>Existing Control</td>
</tr>
<tr>
<td>St. Clair Three-Point</td>
<td>Existing Control</td>
</tr>
<tr>
<td>Niagara Three-Point</td>
<td>Existing Control</td>
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</tbody>
</table>

Note that this analysis did not include development of any multi-lake regulation plans involving a control point on the Detroit River, the outlet of Lake St. Clair. Based on past studies, it was determined that the structural and excavation requirements of controlling Detroit River flows would increase the costs of multi-lake regulation plans substantially. Moreover, management of Lake St. Clair water levels was still possible within certain limits through a combination of modifications to the Lake Michigan-Huron outflow using a structure on the St. Clair River, and as a result of backwater effects transmitted from Lake Erie, with its outflow controlled by a structure on the Niagara River. A structure on the Detroit River would provide a greater degree of control, at additional cost, but this was not investigated as part of this exploratory analysis.

In developing and evaluating the different regulation scenarios, it was recognized that multi-lake regulation would have system-wide impacts. Therefore, the analysis selected seven evaluation points to represent water levels at key locations throughout the Great Lakes-St. Lawrence River system (Figure 8-2).

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4 Water levels and flows in the St. Clair-Detroit River system, including Lake St. Clair, depend in large part on water levels at the system’s upstream and downstream boundaries at lakes Michigan-Huron and Erie, respectively. As a result, when water levels of Lake Erie rise or fall, the impact is partly transmitted upstream to Lake St. Clair.
8.3.3 Consequences of Excluding Lower St. Lawrence Evaluation Points

While water levels at all seven evaluation points were simulated in this analysis, a preliminary evaluation (Tolson et al., 2011) showed that even for the best four-point plans, including the lower St. Lawrence River evaluation points in the multi-lake regulation plan objective function caused significant degradation in plan performance at evaluation points upstream. Furthermore, plan results were mixed on the lower St. Lawrence River, being somewhat worse or better, depending on the NBS scenario, compared to what they would be under the current regulation scenario (i.e., regulation with the existing plans at the outlets of lakes Superior and Ontario only).

Control of lower St. Lawrence River levels is difficult using only regulation structures located upstream, because the lower St. Lawrence River, being at the downstream end of the Great Lakes-St. Lawrence River system, would be susceptible to large fluctuations in flow from the regulation structures at the outlet of Lake Ontario on the upper St. Lawrence River. Without providing structures on the lower St. Lawrence, there is no direct means of mitigating the impacts of these fluctuations. Consideration of additional structures in the lower St. Lawrence River was beyond the scope of this analysis. As well, significantly greater benefits were achieved upstream when this evaluation point was not included in the objective. Therefore, all further plans developed in the analysis considered only the six evaluation points upstream of the lower St. Lawrence to assess the best performance that could be achieved through multi-lake regulation at these upstream locations.
However, it was recognized that as achieving best-performance upstream from the multi-lake regulation plans developed would have a detrimental impact on the lower St. Lawrence River, the IJC would require, under the *Boundary Waters Treaty*, as a condition of its approval of any such plan, that “suitable and adequate provision” be made to protect interests in the lower St. Lawrence River. This condition would require additional structures and excavation on the lower St. Lawrence to mitigate adverse impacts of changes in Lake Ontario outflow. As a result, it was assumed that all multi-lake plans developed in this analysis would need to be augmented with additional downstream mitigative measures on the lower St. Lawrence to protect interests in that area. The design of such measures was not assessed in this analysis for the specific plans developed, but is discussed in general terms in section 8.6.3.

### 8.3.4 Rule Curve Formulation

Multi-lake regulation plans, using the six evaluation points upstream of the lower St. Lawrence only, were developed for each of the four different regulation scenarios, and consisted of a set of rule curves developed at each control point. The rule curves define the regulation plan release as a function of the existing water level conditions in the system. Rule curves at each point were defined by three components, each of which was represented by a separate piece-wise linear function relating target releases from that control point to the water levels in the system. In general, if water levels upstream were relatively higher than water levels downstream, then flows were increased, whereas if water levels downstream were relatively higher than water levels upstream, then flows were decreased. Separate rule curves were applied in each of two seasons (summer/open-water months and winter/ice-affected months) at each control point, and the length and slope of each of the rule curve components were the parameters solved through optimization (see Tolson et al. [2011] for more information on the development of the rule curves).

<table>
<thead>
<tr>
<th>Rule Curves</th>
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</thead>
<tbody>
<tr>
<td>The mathematical rules defining water releases at each control point under the hypothetical multi-lake regulation scenarios modelled in this Study. Rule curves define the release of water as a function of the existing water level conditions in the system.</td>
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### 8.3.5 Objective Function Formulation

Given these regulation scenarios and general rule curve definitions, it was necessary to solve for the full set of rule curve parameters (*i.e.*, decision variables). This was accomplished by optimizing plan performance at the system evaluation points, with the various NBS scenarios used as inputs to run the model. Plan performance was measured with what was known as the frequency-based objective. Tradeoffs between plan performance and a second cost-based objective were also investigated.

**Frequency-based Objective**

The primary goal of this analysis was to determine whether it would be possible, through multi-lake regulation, to prevent the future occurrence of extreme water level conditions throughout the Great Lakes-St. Lawrence River system. Knowing from past experience that extreme high and low water levels cause difficulties to most Great Lakes interests, and understanding that future climate conditions could result in extreme water level conditions in the future, a precautionary approach suggests that all interests must be prepared for such occurrences. One method of preparing for the future is to develop means of adapting to extreme water level conditions (see Chapter 9). Another method is to try to prevent such extreme...
conditions from occurring, or reduce the frequency at which they occur, through multi-lake regulation plans.

All multi-lake regulation plan results were compared to a set of simulated historical water levels at each evaluation point, which were simulated in a similar way as were the base case simulations performed for the restoration analysis described in Chapter 7 (see section 7.2.2). The monthly maximum and minimum simulated levels represent the range of water levels that would have occurred in the past 109 years, given the existing regulation plans (Plan 77A for Lake Superior and Plan 58DD for Lake Ontario) and current conveyance properties of the connecting channels.

The simulated historical maximum and minimum monthly water levels at each evaluation point are illustrated in Figure 8-3. These represent a range of extreme levels for each evaluation point. The multi-lake regulation plans were developed with the objective of keeping water levels at each location within these ranges for all of the extreme future NBS scenarios presented in section 8.3.1. By reducing the frequency of exceeding these extreme water levels throughout the system, the potential benefits resulting from any multi-lake regulation plan would be distributed among all lakes (though not necessarily evenly), as would the potential adverse impacts.

Early in the analysis, it was determined that it would be impossible for a single regulation plan to achieve perfect system performance, given the range of severe future NBS scenarios evaluated, as it was not always possible to maintain water levels at all evaluation points within their simulated historical ranges, even with additional regulation structures. Therefore, the multi-lake regulation plans were developed to improve the system’s performance, relative to what system performance would be under the base case scenario of current Great Lakes regulation (i.e., lakes Superior and Ontario regulated with the existing regulation plans), at every evaluation location and for every NBS scenario considered.

Improvements in performance required reducing the frequency by which the simulated extremes from the base case regulation scenario were exceeded. Prior to optimization, the system was simulated for each of the eight NBS scenarios considered under base case regulation conditions and the frequency by which the monthly average water level at each evaluation point exceeded the simulated historical range (shown in Figure 8-3) was recorded. The optimization model then identified a multi-lake regulation plan (defined by a set of rule curves at each control point) that maintained or preferably reduced the number of times that the plan violated these same extremes. All evaluation point results were given the same weight of importance in the objective function. Referred to as the frequency-based objective, the objective function was formulated such that the first priority was to reduce the frequency of violating the extremes at each of the different evaluation points and for each NBS scenario to at least the frequencies observed under base case regulation. That is, the first priority was to improve performance throughout the system over what would occur under the existing regulation scenario. Once this was achieved, the second priority was then to maximize the overall improvements gained throughout the system. This approach was designed to generate regulation plans that did not degrade performance, relative to what would occur under the base case regulation scenario, at any of the evaluation points. The frequency-based objective function is described mathematically in Tolson et al. (2011).
Cost-based Objective

A second objective, referred to as the cost-based objective, was formulated to capture the costs of controlling the outflow from lakes Michigan-Huron and Erie and to illustrate the tradeoffs between costs and plan performance (as represented by the frequency-base objective). If the controlled outflow through the St. Clair and Niagara rivers, respectively, as determined from the rule curves, is required to be higher than the natural connecting channel flow at the same upstream and downstream lake levels, then excavation is needed to increase the conveyance capacity of that particular connecting channel. On the other hand, if the controlled outflow is required to be less than the natural connecting channel flow, then a structure is needed to restrict flow and hold back water on the upstream lake.

Due to the exploratory nature of this multi-lake regulation analysis, detailed up-to-date cost estimates for the different plans were not assessed. Instead, structural and excavation costs were estimated based on cost estimates obtained during the IJC’s Levels Reference Study (Levels Reference Study Board [LRSB], 1993). From these previous studies, it was assumed for this analysis that a control structure on both the St. Clair River (to restrict the outflow from Lake Michigan-Huron) and on the Niagara River (to restrict
the outflow from Lake Erie) would each cost about $0.5 billion\(^5\). These structural costs were assumed constant for all degrees of flow reduction relative to natural connecting channel flow and for any range of lake levels. The excavation costs were estimated as a function of increased flow in the St. Clair and Niagara rivers, and are summarized in Figure 8-4. The excavation costs of the multi-lake plans were estimated by interpolating (or extrapolating, if necessary) the largest increase in flow of the St. Clair and Niagara rivers determined to be required when compared to current conditions. Note that in the Niagara River, the cost to increase flows through excavation is much less than the costs to increase flows in the St. Clair River by an equivalent amount, because the Niagara is much steeper in slope and is controlled by a natural weir at the head of the river. Thus, a much smaller section of the Niagara River would need to be excavated to provide the required flow increase as compared to the same increase in flow required in the St. Clair River, where large amounts of excavation throughout the channel would be required due to the more gradual slope of this channel. Summation of the excavation and structural costs for each plan yielded an estimate of the total cost of regulation associated with controlling the outflow of Lake Michigan-Huron and Lake Erie.

Note that the cost estimates determined in this way are subject to a significant amount of uncertainty. The construction costs presented in this analysis have been adjusted for inflation, but the actual cost of construction, materials and any additional requirements (e.g., the need for an environmental assessment) may differ today from what they were during the Levels Reference Study in the early 1990s. Furthermore, for plans developed in this analysis, the amount by which flows would need to be decreased from natural conditions was in some cases much greater than that required for plans developed in the Levels Reference Study. As a result, more extensive structures providing greater control may be required for the plans developed in this analysis. Similarly, for the excavation requirements, in many case a large extrapolation of costs beyond the largest values provided in Figure 8-4 was necessary. In such instances, the uncertainty in the excavation cost estimates would be high.

Furthermore, the costs of the multi-lake regulation plans developed estimate capital costs of construction and excavation needed to control Lake Michigan-Huron and Lake Erie outflows only. The estimates do not include the ongoing operation and maintenance costs that would also be required. They also do not consider requirements for additional mitigation, notably the structures and excavation that would be required in the lower St. Lawrence River to mitigate the impacts of changes in flow caused by the multi-lake regulation plans.

\(^5\) All costs have been updated to 2010 U.S. dollars unless otherwise noted. See Bruxer and Carlson, 2010.
Therefore, as in the restoration analysis summarized in Chapter 7, the estimates of costs presented in this chapter are intended to provide an indication of the order of magnitude as a basis of comparison. The estimates allow for comparisons of the tradeoffs between multi-lake regulation plan performance and the costs to achieve it, but they do not represent a reliable estimate of future costs.

8.4 Multi-Lake Regulation Results

The results presented in this section summarize some of the best-performing multi-lake regulation plans found in this analysis, based on the specific way in which this optimization analysis was formulated (see Tolson et al., 2011). However, because of the complexity of the problem and the large number of variables being solved, the best solutions obtained likely do not represent exact globally optimal solutions. The various multi-lake regulation plans were optimized repeatedly with different initial rule curve parameters to improve the probability of closely approximating the globally optimal solution, but there may be other multi-lake plans that provide better results.

In addition, because of the specific way in which the optimization problems were formulated, the results are solution-specific. That is, while the best plans in terms of overall performance (as measured using the frequency-based objective) are presented in this chapter, there were also plans that provided similar overall performance, and these plans might provide better performance for certain evaluation points, but at the expense of performance at others.

Therefore, the results of the final, locally optimal solutions found in this exploratory analysis described below are meant to provide an illustration of the benefits – measured in terms of their impacts on water levels – that may be achieved through multi-lake regulation. They also show the tradeoffs that result from considering different multi-lake regulation options, and provide preliminary estimates of the costs to implement such plans. However, in addition to looking at the multi-lake plans that perform best overall, decision makers would need to review a more comprehensive list of multi-lake plans, and weigh the tradeoffs between plan performance at different evaluation points, and between plan performance and cost, to make an informed decision on multi-lake regulation if it were required at some point in the future.

8.4.1 Base Case Regulation Results

The base case regulation scenario (i.e., using the existing regulation plans for lakes Superior and Ontario at the time of the Study only) was simulated with each of the eight different NBS scenarios. Base case regulation results are presented in subsequent sections in comparison to the multi-lake regulation plans developed. These base case simulations show that for some extreme NBS scenarios, extreme lake levels (both high and low) exceeding the simulated historical range of levels will be experienced at unacceptably high frequencies. Therefore, multi-lake regulation plans that reduce the frequency of such extremes would be considered beneficial to most of the key interests.

8.4.2 Two-point Plan Using Existing Control Structures

The regulation plans currently in operation at the outlets of Lake Superior and Lake Ontario take into consideration water level conditions both upstream and downstream when determining flow releases. However, these plans function independently of each other. To assess whether these two regulation structures could be managed simultaneously to achieve the multi-lake objectives formulated in this
analysis, a two-point multi-lake regulation plan using only the existing control points was optimized using the frequency-based objective. Since only the existing structures at the outlets of Lake Superior and Lake Ontario would be used in this case, there would be no additional costs incurred under such a scenario upstream of the lower St. Lawrence River.

Results of the best-performing two-point multi-lake regulation plan (as measured by the frequency-based objective function results) are shown in Figure 8-5. For each of the six evaluation points, a plot of the frequency of going beyond the simulated historical extremes, or the exceedance frequency (y-axis), for each of the eight NBS scenarios (x-axis) is shown. Exceedance frequency is calculated as the ratio of the number of months when the average level exceeds the monthly simulated historical extremes over the total number of months in that scenario.

As illustrated, results for the two-point multi-lake plan showed limited success. The plan did not reliably improve upon the base case performance everywhere and for every NBS scenario. For example, simulated plan results showed almost no reduction in the frequency that the simulated historical extreme water levels were exceeded for lakes Michigan-Huron, St. Clair and Erie for any of the NBS scenarios, and in some cases the exceedance frequency was found to increase slightly. The only
evaluation points where noticeable differences in plan performance were observed were upstream of the existing regulation structures, including on the regulated lakes themselves, Superior and Ontario, and on the upper St. Lawrence River. Furthermore, even these results showed a mix of improved and degraded performance, depending on the NBS scenario, when compared to the base case.

From these results, it was concluded that if a number of possible future climate scenarios are considered, then extreme water levels exceeding those simulated from the historical record will be unavoidable given only the two existing control points in the system, even when the two structures are managed to regulate the entire system. This is especially true on lakes Michigan-Huron, St. Clair and Erie, where no structures exist to control flow. Therefore, more frequent extreme water levels may be experienced in the future unless additional measures, such as additional control structures for multi-lake regulation, are provided.

### 8.4.3 Tradeoffs between Plan Performance and Costs

Given the limited success of the two-point plan, consideration was next given to multi-lake regulation plans incorporating additional new hypothetical control points on the St. Clair and/or Niagara rivers. It was recognized that providing additional control points on the St. Clair and Niagara rivers would involve significant costs, including billions of dollars for both excavation and control structures. Furthermore, as noted above, this does not include the costs of any mitigative measures on the lower St. Lawrence River near Montreal, which were not assessed directly. These costs of mitigation likely would require additional billions of dollars beyond the estimated costs required for the St. Clair and Niagara rivers (see section 8.6.3).

In an attempt to minimize the high costs of regulation while still maintaining significant system performance improvements, a bi-objective optimization model was developed and solved to minimize both the frequency-based objective and the cost objective, allowing for an assessment of the tradeoffs between improved system performance and associated regulation costs. This involved iteratively solving the bi-objective problems for each regulation scenario (four-point, St. Clair three-point and Niagara three-point) to continually improve an approximate relationship between frequency and cost objectives. The performance-versus-cost tradeoff relationships for each of the three regulation scenarios are provided in Figure 8-6, with the frequency-based objective function results from each plan plotted on the x-axis, and the costs to implement the respective plans provided on the y-axis. The frequency-based objective function value does not have interpretable units (see Tolson et al., 2011). However, a negative value of the frequency-based objective is preferred in this analysis, as it generally implies that the frequency of violating the simulated historical extremes is improved over or equal to the base case regulation strategy everywhere and for all eight NBS scenarios; that is, the plan is able to improve performance throughout the system, regardless of the NBS scenario chosen. In contrast, a positive value implies that there is at least one evaluation point in at least one NBS scenario that performs worse than the base case. Note that while the frequency-based objective provides an aggregated measure of system-wide performance for each multi-lake regulation plan, overall plan quality is best assessed by looking in greater detail at multiple aspects of performance, such as the disaggregated results shown in Figure 8-5 and the additional figures that follow. Again, it must also be emphasized that the cost estimates presented are order of magnitude estimates, at best, as they are extrapolated – in some cases significantly – beyond the range of the flow increase versus cost relationships presented in section 8.3.5. The cost estimates also do not include costs required to mitigate impacts in the lower St. Lawrence River, which could be substantial.
Figure 8-6 indicates that the costs and system-wide performance of the multi-lake regulation plans varies widely. Referring to the four-point plan tradeoff relationship, of interest were one cluster of multi-lake regulation plan solutions found close to the best known frequency-based objective function value of approximately -22, with an estimated cost of almost $29 billion. Another interesting cluster of four-point plans had a somewhat higher (approximately -13) but still negative frequency-based objective function value, but with a lower cost of about $6 billion. The $29 billion plan would be expected to provide the best overall performance of any plan, but the $6 billion four-point plan is noteworthy in that it also appears to provide good performance, as represented by the negative frequency-based objective function value, but at a much lower cost.

As the costs of the St. Clair and Niagara River structures were estimated to be approximately the same (about $0.5 billion each), the large differences in cost between plans is related to differences in the amount and location of excavation required. Specifically, a much greater flow increase over existing conditions is required in the St. Clair River for the $29 billion four-point plan than for the $6 billion four-point plan, and as noted in section 8.3.5, the cost to increase flows through excavation is relatively expensive in the St. Clair River due to the gradual slope of this channel.

The tradeoff relationships for both the St. Clair and Niagara three-point multi-lake regulation plans are also illustrated in Figure 8-6. None of the St. Clair River three-point plans was able to provide improved performance throughout the system for all eight NBS scenarios, as indicated by the large positive values for all frequency-based objective functions. This was despite the fact that the costs of the St. Clair River three-point plans were found to be relatively high, with the best-performing plan costing $23 billion. Interestingly, many of the four-point plans were found to cost much less than the best St. Clair three-point plans, yet they performed far better overall, again the result of the high costs of St. Clair River excavation.

In contrast to the St. Clair three-point plans, numerous Niagara River three-point plans were found to provide acceptable frequency-based objective function values (i.e., values below zero), indicating that these plans improved performance over the base case at all evaluation points and for all eight NBS
scenarios. Furthermore, the Niagara plan providing the maximum benefits was estimated to cost about $2 billion, far less than the St. Clair three-point plans costing upwards of $23 billion, and less than the best-performing four-point plans. The lower costs of the Niagara three-point plans, though rough estimates only, are a result of there being no need for costly excavation in the St. Clair River.

Another important observation from Figure 8-6 is that the best-performing Niagara three-point plan costing an estimated $2 billion had a slightly better (lower) frequency-based objective value than the $6 billion four-point plan. However, because frequency-based objective function results describe overall, aggregated system-wide performance, disaggregated results are needed to provide more details on plan performance for each of the different evaluation points individually and on the tradeoffs between costs and performance. The disaggregated results, illustrating the tradeoffs between plan performance and cost, are explored in the following sections for the four plans of interest highlighted in Figure 8-6, and summarized in Table 8-2.

<table>
<thead>
<tr>
<th>Plan</th>
<th>Frequency-Based Objective Value*</th>
<th>Structure Costs (billion $US)</th>
<th>Excavation Costs (billion $US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$29 billion Four-point</td>
<td>-22</td>
<td>St. Clair: $0.5 Siemens: $0.5</td>
<td>St. Clair: $27.0 Siemens: $1.3</td>
</tr>
<tr>
<td>$6 billion Four-point</td>
<td>-13</td>
<td>St. Clair: $0.5 Siemens: $0.5</td>
<td>St. Clair: $3.9 Siemens: $1.2</td>
</tr>
<tr>
<td>$23 billion St. Clair Three-pt.</td>
<td>159</td>
<td>Siemens: $0.5 Siemens: --</td>
<td>Siemens: $22.4 Siemens: --</td>
</tr>
<tr>
<td>$2 billion Niagara Three-pt.</td>
<td>-17</td>
<td>Siemens: -- Siemens: $0.5</td>
<td>Siemens: -- Siemens: $1.4</td>
</tr>
</tbody>
</table>

* The frequency-based objective function does not have interpretable units; however, a negative value describes generally improved performance overall (see note in Figure 8-6). The plans shown in this table provided the best frequency-based objective function value for each combination of regulation scenario and cost.

### 8.4.4 Performance of the $29 and $6 Billion Four-Point Plans

Any water management decision, including any decision made with regards to multi-lake regulation, must be made by balancing system performance with costs. The $6 billion version of the four-point multi-lake plan was found to provide a moderate level of improvement over the base case in terms of the frequency-based objective, improving performance throughout the system and for all NBS scenarios, but at a much lower cost than the $29 billion four-point solution. For these reasons, water managers might be expected to choose the $6 billion solution over the $29 billion solution. However, this decision would require greater knowledge and information of how the reduction in cost affects overall plan performance, including the performance at each of the separate evaluation points specifically.

The $6 billion four-point plan results are presented and compared to the $29 billion four-point plan results in Figure 8-7. As illustrated, the majority of the costs of either plan are related to excavation in the St. Clair River. This excavation is responsible for about $27 billion of the total cost in the upper lakes of the $29 billion plan, and about $3.9 billion of the total cost of the $6 billion plan. The difference in cost is related to the maximum increase in flow required over that which would occur under the current conveyance capacity of the St. Clair River. For the $29 billion plan, excavation would be required to provide an increase in flow of about 9,450 m$^3$/s (about 334,000 ft$^3$/s). For the $6 billion plan, excavation would be required to provide an increase in flow of about 1,750 m$^3$/s (about 62,000 ft$^3$/s).
Overall, though some degradation of the results does occur when plan costs are reduced, the frequency-based results of the $6 billion multi-lake plan were satisfactory and comparable to those obtained from the $29 billion plan. Both plans show improvement (as represented by reduced or maintained frequency of occurrence of extreme water levels) at all evaluation points and in all NBS scenarios.

Exceedance frequency is equal to the percentage of months simulated for each NBS scenario that exceed the simulated historical extreme water levels. Plan performance was greatest for Lake Erie, where water levels could be kept within simulated historical extremes nearly 100 percent of the time for both four-point plans. Performance at the other evaluation points was better than the base case under all scenarios for both four-point plans, but extreme water level conditions could not be eliminated, and there would be some degradation of plan performance if plan costs were reduced.

In terms of the cost versus performance tradeoffs, average improvement on Lake Erie was greatest at almost 100 percent in both plans for all eight NBS scenarios; that is, water levels on that lake could almost always be kept within the historically simulated range, regardless of the NBS scenario experienced. But at the other five evaluation points, notably lakes Michigan-Huron and St. Clair, certain NBS scenarios showed greater degradation of plan performance than others when the plan costs were reduced from $29 billion to $6 billion. For example, on Lake Michigan-Huron, performance was significantly degraded under NBS scenario 4 in the $6 billion plan compared to the $29 billion plan. This reflects the fact that scenario 4 was one of the relatively wetter NBS scenarios, and by reducing the amount of excavation in the St. Clair River to reduce the costs of the four-point plan from $29 billion to $6 billion, the capacity of the St. Clair River to convey water is reduced, as is the ability of the plan to
lower the water levels of Lake Michigan-Huron when they are at high extremes. On a similar note, because increased flows are only necessary when levels are high, it is not surprising that performance under some of the driest NBS scenarios – in particular scenarios 1, 3 and 4 – was found to be approximately equal for both four-point plans. Interestingly, the $6 billion plan did provide significant improvements over the $29 billion plan in scenario 7.

To summarize, while the four-point plans were able to maintain Lake Erie within the range of simulated historical extremes for all NBS scenarios, this was not possible for the other evaluation points, regardless of the amount of control provided in the St. Clair and Niagara rivers. Notable improvements were seen at all evaluation points in both plans, but even the best-performing and most costly $29 billion plan was not able to entirely prevent violations of the simulated historical extremes at all evaluation points. Therefore, even given additional regulation capabilities, it would not be possible to avoid extreme water level conditions beyond those experienced in the past under the NBS scenarios considered in this analysis.

**8.4.5 Performance of the $23 Billion St. Clair Three-point Plan**

The overall, system-wide results of the best-performing St. Clair River three-point plan were shown in section 8.4.3 to be worse, as measured by the frequency-based objective function, than either of the best-performing four-point plans or the best-performing Niagara River three-point plan. Furthermore, the best-performing St. Clair three-point plan did not provide improved performance throughout the system for all evaluation points, despite a relatively high cost of $23 billion (which also does not include the additional costs required for mitigative measures in the lower St. Lawrence).

While the system-wide aggregated results indicate that the St. Clair three-point plan is dominated by the other multi-lake regulation plan solutions, they do not provide details on each of the different evaluation points specifically. However, even the disaggregated results of the $23 billion St. Clair River three-point plan, summarized in Figure 8-8 in comparison to the $6 billion four-point plan from section 8.4.4, show clearly that the $23 billion St. Clair plan is inferior in terms of performance and cost both overall and at each evaluation point.

In general, the $6 billion four-point plan performed better under nearly all NBS scenarios and at all evaluation points. Of particular note is that even on Lake Michigan-Huron, where both plans provide a structure on the St. Clair River to control this lake’s outflow, the $6 billion four-point plan was better able to reduce the frequency that water levels exceeded the simulated historical extremes. It should be noted that these results are solution-specific, and that it may be possible to improve the performance on Lake Michigan-Huron for both plans. However, this would come at the expense of other evaluation points, and would reduce overall plan performance. These results confirm that a three-point multi-lake regulation plan involving a control structure on the St. Clair River would be less effective and more costly than a four-point plan involving control structures at the outlets of both Lake Michigan-Huron and Lake Erie.
The results from the tradeoff relationships described in section 8.4.3 suggested that overall, system-wide performance could be improved substantially under certain Niagara River three-point regulation plans, and at a significantly reduced cost compared to either of the four-point plans described above. Figure 8-9 compares the frequency-based results of the $2 billion Niagara River three-point plan with the $6 billion four-point plan. Like the $6 billion plan, the Niagara three-point plan reduces or maintains the frequency of exceeding extremes at all evaluation points and for all NBS scenarios. The $2 billion Niagara three-point plan results show similar benefits to those provided by the $6 billion four-point plan at all evaluation points downstream of Lake Michigan-Huron, though there generally appears to be some degradation of plan performance for lakes Superior and Michigan-Huron.
However, even for Lake Michigan-Huron, performance was mixed, with NBS scenarios 4 and 6 showing improved performance in the Niagara three-point plan compared to the four-point plan. Both of these are relatively high (wetter) NBS scenarios. As described in section 8.4.4, to reduce the four-point plan costs from $29 billion to $6 billion, excavation was reduced and therefore the $6 billion plan is not able to release as much water from Lake Michigan-Huron when desired during a wet scenario. By design, the Niagara three-point plan does not involve excavation in the St. Clair River; the improved performance for scenarios 4 and 6 in the Niagara three-point plan is likely instead the result of the greater increase in channel capacity in the Niagara River in this plan, allowing for greater flows in the Niagara River when desired during wet conditions, which would draw down Lake Erie, and subsequently Lake Michigan-Huron as a result of backwater effects transmitted through the Detroit and St. Clair rivers. Regardless, compared to the base case, the Niagara River three-point plan provides improved performance throughout the system, including on Lake Michigan-Huron, for all NBS scenarios, and at substantially less cost than the four-point plans reviewed.
8.4.7 Summary of Top Performing Multi-Lake Regulation Plans

Figure 8-10 summarizes the results of the best-performing multi-lake regulation plans reviewed in this analysis. As shown, there are tradeoffs in plan performance that result from the different regulation scenarios and from reducing costs of the different plans. In some cases, the costs can be reduced without substantially degrading plan performance. For example, though there was some degradation of plan performance, the $6 billion four-point plan performed nearly as well as the more expensive $29 billion four-point plan, and in fact performed better under some NBS scenarios at some evaluation points, as was shown in Figure 8-7. The significant difference in costs of these two plans is primarily the result of the extensive excavation that would be required in the St. Clair River to increase flows when necessary during periods of high water supplies.

Furthermore, the high costs of excavation in the St. Clair River, coupled with the need to maintain water levels downstream on Lake St. Clair and Lake Erie, made it impossible to develop a three-point multi-lake regulation plan with a structure in the St. Clair River that could improve performance at all evaluations points, despite the high costs ($23 billion) of such a plan. In contrast, a three-point plan with a structure on the Niagara River was able to provide benefits for all evaluation points at an estimated cost of only $2 billion. However, there are tradeoffs of reducing the costs of the multi-lake regulation plans. For example, the $2 billion Niagara three-point plan provided less benefits to lakes Superior and Michigan-Huron than either of the four-point plans.

Plan results shown to this point have been separated by evaluation point only. Results can be further disaggregated by looking at the results of the validation experiment performed by simulating the different plans for the full 50,000-year stochastic NBS sequence. For example, using the full 50,000-year simulation results, the frequency of violating low extreme water levels can be separated from the frequency of violating the high extreme water levels at each evaluation point, further illustrating the tradeoffs between the different multi-lake regulation plans (Figure 8-11).
For example, the $2 billion Niagara plan was earlier shown to improve performance at all evaluation points for all eight NBS scenarios. However, the results shown in Figure 8-11 would suggest that this plan provides minimal improvement over the base case for Lake Michigan-Huron, and in particular does very little to reduce the frequency of exceedance for the low extreme. That is, the $2 billion Niagara three-point plan developed in this analysis, though benefiting the system overall, would not improve the situation of low water levels currently existing on Lake Michigan-Huron. The $23 billion St. Clair three-point plan does slightly better for Lake Michigan-Huron, but at the expense of Lake Erie. Both four-point plans reduce the frequency of occurrence of both high and low extreme levels at all evaluation points, with the exception of Lake St. Clair, where the $29 billion four-point plan causes an increase in upper extreme violations when simulated for the full 50,000-year simulation. This surprising result may be due to the large fluctuations in flow from Lake Michigan-Huron, the effect of which would be magnified on the much smaller Lake St. Clair. These results could also indicate that the flow equations used in this analysis for the St. Clair and Detroit rivers, which were empirically developed from measured flows under natural conditions, may break down at the extreme flows called for at all times under the $29 billion four-point plan. In any case, this validation result indicates that the $29 billion four-point plan, while performing well for the eight extreme NBS scenarios chosen for plan development, may not
perform nearly as well under less extreme conditions, as would be represented by the full 50,000-year stochastic NBS simulation that is based on historically observed supplies.

Furthermore, because the frequency of exceeding extremes is a dimensionless measure of the number of times the simulated historical extremes are exceeded, the analysis presented above does not provide any information on the magnitude by which the extremes are exceeded in one plan versus another. To better illustrate these impacts, histograms were developed to show both how often and by how much the extreme water levels were exceeded over the full 50,000-year NBS sequence. Examples of the histograms developed from the 50,000-year stochastic simulation for the $6 billion four-point plan are provided for Lake Superior in Figure 8-12. In addition to reducing the frequency of extremes, the $6 billion four-point multi-lake plan also generally reduces the amount by which these extremes are exceeded when such events do occur. In fact, for each of the different plans, a reduction in the frequency of the extremes was found to coincide with a reduction in their magnitude at most evaluations points.

However, there were some exceptions, one of which occurred on Lake Michigan-Huron for the $6 billion four-point plan, where the upper extreme was found to be violated by a higher magnitude slightly more often than under the base case, especially at the highest levels of exceedance. This observation suggests that under this multi-lake regulation plan, flooding on Lake Michigan-Huron might be greater under some future scenarios than under the base case.

In general, the results from the four top performing plans outlined above indicate that multi-lake regulation can provide a means of reducing the risk of occurrence of extreme lake levels resulting from severe NBS conditions. The multi-lake plans reviewed not only reduced the frequency at which extreme lake levels – both high and low – would occur, in most cases they also reduced the magnitude by which the simulated historical extremes would be exceeded when such events did occur. However, none of the plans reviewed was able to eliminate the occurrence of extreme lake levels entirely, indicating that even with multi-lake regulation, Great Lakes interests must be prepared to adapt to more extreme conditions in the future than have been experienced in the past. This finding underscores the need to develop and implement a comprehensive adaptive management strategy to address future uncertainty in upper Great Lakes water levels (see Chapter 9).
8.5 Environmental and Institutional Considerations of Multi-Lake Regulation

Chapter 7 considered the adverse environmental impacts in the St. Clair River that would occur if various restoration structures reviewed were constructed (section 7.5). These same impacts would also likely arise with multi-lake regulation, as any structure built in the St. Clair River (whether a fixed restoration or an adjustable regulation structure) would disrupt the natural ecosystem at this location. For example, a possible location for a dam to be constructed in the St. Clair River would be in the upper reaches, close to Lake Huron, where the channel is narrowest and the water surface slope is highest (for possible hydroelectric generation). However, as noted in section 7.5, this location is also the primary spawning ground for the endangered Lake Sturgeon. In addition, any structure constructed in the St. Clair River could disturb contaminated sediments contained within the river bed. Furthermore, transient downstream impacts caused by temporarily restricting or also increasing (in the case of multi-lake regulation) connecting channel flows significantly could be detrimental to some upper Great Lakes ecosystems, including the Lake St. Clair fishery.

Environmental impacts in the other connecting channels were not reviewed, but as in the case of the St. Clair River, there may be environmental issues that would need consideration if structures and excavation were conducted in the Niagara River and lower St. Lawrence River as well. Such issues require further study.

In addition, section 7.6 discussed the institutional considerations of building structures in the St. Clair River. These considerations would apply equally to both restoration and regulation structures, and to any of the channels where structures might be considered as part of a multi-lake regulation plan, including the Niagara and lower St. Lawrence rivers. Similar to restoration structures in the St. Clair River, multi-lake regulation would require the ongoing commitment and financing of the governments of Canada and the United States. Given the geographic extent of the projects and the magnitude of the structures and excavation required, the necessary planning, environmental reviews, regulatory approvals and design steps likely would take 20 years or more.

A specific institutional issue that must be considered for any multi-lake regulation plan would be the requirement that such plans, to be implemented, must be supported throughout the Great Lakes-St. Lawrence River system. Such support would be unlikely unless benefits of such plans could be demonstrated throughout the system, including the lower St. Lawrence River. This was not achieved in any of the plans described in this exploratory analysis. To do so would require modifying the objectives of the multi-lake plans, and significant increases in the capital costs of implementing them.

8.6 Additional Considerations

8.6.1 Improving Multi-Lake Plan Performance through Climate Prediction

Due to the uncertainty on the future climate and its impacts on water supplies to the Great Lakes-St. Lawrence River system, the multi-lake regulation plans presented in the preceding sections were developed with consideration given to a range of possible NBS scenarios. As a result, the plans developed are able to improve system performance under a variety of possible conditions. However, as an additional consequence, improved performance for any one particular NBS scenario is sacrificed in order to provide better overall performance over the broad range of conditions considered.
If it were possible in the future to predict climate conditions and NBS scenarios with certainty (something that is not possible now), multi-lake plans could be developed to provide a greater level of performance for the predicted future conditions. To demonstrate the benefits that could be gained from optimizing using only one specific NBS scenario, two multi-lake plans – a four-point plan and a three-point Niagara plan – were developed using NBS scenario 7 only, which represents one of the drier NBS scenarios used in the multi-lake regulation analysis (note that some of the scenarios used in Lake Superior plan formulation and evaluation were drier than even this scenario). In an extreme dry scenario, plan performance would benefit more from restricting flows than increasing them, and as a result, a multi-lake regulation plan optimized for only a single dry scenario would be less costly to implement, as there would be less of a need to incur the high costs required to increase flows through excavation.

The two best solutions found were a four-point plan costing $1.1 billion and a three-point plan costing an estimated $1.8 billion (note that similar to all other plans developed in this analysis, the costs of mitigative measures that may be required in the lower St. Lawrence River were not included). Figure 8-13 shows that the $1.8 billion Niagara three-point plan was able to eliminate the occurrence of water levels exceeding the simulated historical extremes at all evaluation points, while the $1.1 billion four-point plan also performed extremely well under this specific NBS scenario. As expected, both of these specialized plans performed significantly better than the $6 billion four-point plan, which was developed with consideration given to all eight NBS scenarios.

The results of these two plans, which were optimized using only a single NBS scenario, suggest that plan performance could be substantially improved with perfect knowledge of the future. Even with imperfect but improved knowledge, it may be possible to develop multi-lake regulation plans that deliver better performance and at lower costs. As a result, it may be advisable to revisit such plans as knowledge improves about the future climate conditions and the resulting impacts on water levels in the Great Lakes.
However, even then, such a plan could only be implemented if there were great certainty in the predicted future conditions. This would be difficult to achieve. Lacking such certainty, if such a plan were implemented then it would pose a significant risk to the system should average or high water level conditions return at some point in the future. Such fluctuations can occur, and therefore, a range of possible NBS scenarios, based to some degree on predictions and their level of uncertainty, would also need to be investigated to ensure that any plan developed is robust and able to provide acceptable performance if conditions change.

Finally, as noted, the three-point plan involving only a new control point established on the Niagara River performed better for the entire system than the four-point plan developed with control points on both the St. Clair and Niagara rivers. This may indicate a possible order of precedence for building additional control structures in the upper Great Lakes: a structure built in the Niagara River during low water conditions could be used to raise levels upstream, and with a relatively small amount of excavation required, at least initially; however, if conditions in the basin were to return to wet or even average conditions in the future, additional excavation would be required immediately so as not to adversely affect upstream interests during high conditions. It must be noted that this assessment would need to consider downstream interests, notably those on the lower St. Lawrence River, where mitigative structures and excavation would also be required.

### 8.6.2 Additional Hydrological Effects and Impacts on the Key Interests

Although the frequency-based results are an important part of the analysis, by design, the plans were developed to reduce the frequency of extreme water levels at each of the different evaluation points only. As a result, no consideration was given to the impacts such plans would have on flows in the connecting channels. By attempting to maintain water levels at each of the evaluation points within their simulated historical ranges, the connecting channel flows would be modified from normal flows.

As an example, Figure 8-14 compares flows from the $6 billion four-point multi-lake plan and the base case plan for Lake Superior outflows (St. Marys River) and Lake Michigan-Huron outflows (St. Clair River). The findings indicate that the flows required under the $6 billion four-point multi-lake plan show greater variability than the base case. That is, by attempting to maintain the water levels of the lakes upstream and downstream of this point within their historical range, the flows in the channel must greatly exceed their own historical range. Similar results were seen for the other connecting channels and in the other multi-lake plans.

While the impacts of connecting channel flow changes were not evaluated, it is likely that such variations would have negative consequences for different interests served by the upper Great Lakes system.
Furthermore, reducing the frequency of exceeding historical extreme lake levels would be beneficial to many of the key interests. For example, reducing the frequency of extreme high lake levels would reduce flood damages for coastal interests, while reducing the frequency of extreme low lake levels may be beneficial to some wetlands, notably those on Georgian Bay.

However, changes to the water level regimes of the Great Lakes may also have negative consequences. For example, the same wetlands that would benefit from the reduced frequency of occurrence of extreme low lake levels, could be adversely impacted by reduced water level variability, which is considered to be important for wetland health.

The impacts of multi-lake regulation, positive or negative, on the key interests in the Great Lakes and connecting channels were not evaluated directly in this exploratory analysis. Such an assessment would be required if multi-lake regulation is considered in the future as a means of dealing with extreme water levels.

### 8.6.3 Lower St. Lawrence River Mitigative Requirements

Any changes to the outflows from Lake Michigan-Huron or Lake Erie due to multi-lake regulation would cause changes to the supplies to the lakes downstream, including Lake Ontario. As such, the outflow through the St. Lawrence River would also be modified, and the effects of such modifications would require mitigative measures at a minimum. More likely, measures to improve conditions in the lower St. Lawrence River would be required to gain system-wide political support for multi-lake regulation. Such measures would include additional structures to restrict flow and maintain adequate depths for navigation and environmental purposes during dry conditions, and additional excavation to pass higher flows to prevent flooding during wet conditions.

Designs and rule curves for lower St. Lawrence River structures were not developed in this analysis. However, the analysis did undertake a literature review of previously proposed mitigative measures for
the lower St. Lawrence River (Bruxer and Carlson, 2011). This review included a comprehensive evaluation of mitigative requirements in the St. Lawrence River made during the Levels Reference Study (Hydrosult et al., 1993). The measures required in the lower St. Lawrence River resulting from the multi-lake regulation plans developed during the Levels Reference Study were assessed with two design objectives. The first would improve conditions in the lower St. Lawrence over those of the basis of comparison (i.e., the simulated historical conditions), as previous experience had shown that the lower St. Lawrence River was subject to adverse conditions under relatively extreme scenarios. However, the Levels Reference Study found that improving conditions over the basis of comparison would be too expensive, with the costs of required excavation alone exceeding $120 billion.

The focus, therefore, shifted to the second design objective, which would maintain basis of comparison conditions in the lower St. Lawrence River and mitigate any increased impacts from further regulation of the Great Lakes. These structures would be significant as well, requiring control structures and excavation of a spillway near Lac Saint-Louis and Montreal, and additional and extensive excavation and control structures to mitigate increased flow conditions downstream of Montreal Harbour to Donnacona, approximately 70 km (about 43 mi) downstream of Trois-Rivières (Figure 8-15).

The cost of the mitigative measures would depend on the regulation plans chosen, the design objectives, and the targeted water level and flow regime in the St. Lawrence River. The Levels Reference Study restricted multi-lake regulation plan development to plans that would decrease flows by no more than 1,130 m³/s (40,000 ft³/s) below what was identified as the minimum design flow of 5,210 m³/s (184,000 ft³/s), and plans that would increase flows by no more than 1,700 m³/s (60,000 ft³/s) above what was determined to be the maximum design flow of 14,500 m³/s (510,000 ft³/s). The costs of the mitigative measures required on the lower St. Lawrence River were based on these amounts of flow decrease and increase, and were estimated to be between approximately $3.5 and $5.1 billion for excavation alone. The additional combined cost of control structures at all locations was about $400 to $900 million, depending on the design. Again, these measures would only maintain basis of comparison conditions. To improve conditions and provide benefits to the lower St. Lawrence River, excavation costs would need to increase to about $120 billion.

To provide an appreciation of the costs of mitigative measures that might be required in the lower St. Lawrence River for plans developed in the current analysis, Table 8-3 compares the resulting flow increases and decreases in the lower St. Lawrence River estimated for the multi-lake regulation plans developed in this analysis to those plans developed in the 1993 Levels Reference Study (LRSB, 1993). The extreme lower St. Lawrence River flows determined for the multi-lake plans developed in this analysis shown in the table are the monthly extremes based on the full 50,000-year simulations. In contrast to the Levels Reference Study, in this analysis no limits were placed on the amount that flows could be increased or decreased over natural conditions. As indicated, with the exception of the $29 billion four-point plan, this resulted in a range of flow changes that is far greater than the range outlined in the Levels Reference Study. In fact, the increases and decreases over the Levels Reference Study maximum and minimum design flows, respectively, for plans developed in this analysis were in most cases two to three times greater than the plans designed in the Levels Reference Study. As the total cost of mitigative measures in the lower St. Lawrence was estimated in the Levels Reference Study to be about $6 billion, the costs to mitigate adverse conditions on the lower St. Lawrence River for the different multi-lake plans developed in this analysis would likely be far greater than this amount. The range of lower St. Lawrence River flows for the $29 billion four-point plan, on the other hand, was actually within the range of flows investigated in the Levels Reference Study. Though lower St. Lawrence River mitigative requirements were not directly assessed, this result suggests that while the costs of the $29 billion four-point multi-lake regulation plan were significantly higher than the other plans reviewed for the St. Clair and Niagara rivers, the costs to provide mitigative measures in the lower St. Lawrence River
for this plan may be much less. This further suggests that the lower St. Lawrence River requirements must be considered in future studies.

Figure 8-15
Potential Lower St. Lawrence River Mitigative Measures

Note: Two mitigative options were investigated for the lower St. Lawrence River from Montreal Harbour to Donnacona. The first involved extensive dikes and three control structures spanning part of the channel; the second involved two full control structures, which would fully span the channel, along with powerhouses and locks for navigation. Both options involved extensive excavation to prevent flooding during high flows.

Note that these costs are those that are required to maintain the existing conditions on the lower St. Lawrence River. The evaluation points upstream for the multi-lake regulation plans developed in this analysis were not subject to the same constraint. Rather, the frequency of exceeding historical extremes was only reduced or maintained, but not eliminated. Therefore, it may be more acceptable that this constraint on the lower St. Lawrence River be relaxed to some degree.

Nonetheless, based on the results presented in Table 8-3, the multi-lake plans developed in this analysis would require extensive mitigative measures in the lower St. Lawrence River. Furthermore, this comparison indicates that the costs to provide such mitigation could be greater than the costs of the combined structures and excavation required on the St. Clair and Niagara rivers for the multi-lake plans.
reviewed. Therefore, multi-lake regulation should not be studied again unless consideration is given to the requirements in both the lower St. Lawrence River and the upper Great Lakes.

Table 8-3
Lower St. Lawrence Extreme Flow Range Comparison

<table>
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<th>Plan</th>
<th>Upper Great Lakes Study Multi-Lake Regulation Plans</th>
<th>Levels Reference Study Multi-Lake Regulation Plans</th>
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<tr>
<td></td>
<td>Max Lower St. Law. Flow</td>
<td>Min Lower St. Law. Flow</td>
<td>Costs of Lower St. Lawrence Mitigation</td>
</tr>
<tr>
<td>Base Case</td>
<td>16,000 m³/s (565,000 ft³/s)</td>
<td>4,000 m³/s (141,000 ft³/s)</td>
<td>Not assessed</td>
</tr>
<tr>
<td>$29B 4-pt</td>
<td>16,100 m³/s (569,000 ft³/s)</td>
<td>4,500 m³/s (159,000 ft³/s)</td>
<td>*An increase of 1700 m³/s (60,000 ft³/s) over design flows</td>
</tr>
<tr>
<td>$6B 4-pt</td>
<td>19,900 m³/s (703,000 ft³/s)</td>
<td>2,600 m³/s (92,000 ft³/s)</td>
<td>16,800 m³/s (593,000 ft³/s)</td>
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<tr>
<td>$23B St. Clair 3-pt</td>
<td>16,800 m³/s (593,000 ft³/s)</td>
<td>1,200 m³/s (42,000 ft³/s)</td>
<td>1,200 m³/s (42,000 ft³/s)</td>
</tr>
<tr>
<td>$2B Niagara 3-pt</td>
<td>19,400 m³/s (685,000 ft³/s)</td>
<td>1,600 m³/s (57,000 ft³/s)</td>
<td>19,400 m³/s (685,000 ft³/s)</td>
</tr>
</tbody>
</table>

1. Source: LRSB, 1993
8.7 Key Points

With respect to the analysis of addressing extreme water level conditions in the upper Great Lakes through multi-lake regulation, the following points can be made:

- Multi-lake regulation involves regulating the Great Lakes-St. Lawrence River system to benefit the entire system as a whole. In this analysis, multi-lake regulation plans were developed that considered using both the existing structures on the St. Marys and St. Lawrence Rivers, and hypothetical structures on the St. Clair and Niagara Rivers, to reduce the frequency of occurrence of extreme water levels under possible extreme future net basin supply scenarios.

- Four-point multi-lake regulation plans, involving the existing structures as well as new control points on the St. Clair and Niagara rivers, could be designed to reduce – relative to the base case existing system of regulation – the frequency of occurrence of extreme water levels across multiple extreme NBS scenarios and at all evaluation points in the system. Three-point plans involving the existing structures and a new control point on the Niagara River could also provide improved performance throughout the system under all NBS scenarios. Three-point plans involving the existing structures and a new control point on the St. Clair River could not be designed to achieve this objective.

- Additional control points normally require both the construction of adjustable control structures, such as a dam, to restrict flows during dry conditions, as well as excavation to increase channel conveyance, and increase flows during wet conditions. The cost of excavation is significant, and is normally much greater than the cost of the control structures themselves. This is particularly true for the St. Clair River, where the gradual slope of this channel would require extensive excavation costing several billion dollars to allow for the increases in flows required by the various plans developed in this analysis.

- Multi-lake regulation plans must be developed with consideration given to the impacts on water levels throughout the system, including the lower St. Lawrence River. Though not assessed directly in this analysis, extensive mitigative measures costing several billion dollars and involving both control structures and excavation, would be necessary in the lower St. Lawrence for any multi-lake regulation plan developed.

- Many of the same environmental and institutional considerations as discussed in the restoration analysis (Chapter 7) apply equally to multi-lake regulation.

- The analysis indicated that while system-wide multi-lake regulation could reduce the frequency and magnitude of extreme events at all evaluation points (with the exception of the lower St. Lawrence River), it could not eliminate such events entirely. Extreme water levels in the future may be unavoidable, even with additional regulation capabilities, and therefore additional adaptive measures may be required.

- Should the governments of Canada and the United States decide to revisit multi-lake regulation as an option for addressing extreme water level conditions in the future, the following tasks will need to be considered:
  
  - evaluating the impacts of multi-lake regulation on connecting channel flows and specific Great Lakes interests;
  - updating the designs and cost estimates of regulation structures and excavation requirements for new control points on the St. Clair and Niagara rivers;
o evaluating the impacts and mitigative measures required in the lower St. Lawrence River;
o developing plans for specific NBS scenarios, such as persistent dry conditions in the Great Lakes basin, while coordinating this effort with climate prediction efforts; and,
o designing an optimal order of implementing multi-lake structures and excavation based on existing conditions at the time such measures are to be taken.

8.8 Recommendation

Past studies of the potential for multi-lake regulation to address water level conditions in the Great Lakes system have consistently dismissed the concept on the basis of historical water supplies. The Study’s exploratory analysis considered more severe water supply conditions, and concluded that multi-lake regulation may have potential to address extreme water levels in the upper Great Lakes basin, particularly if the region experiences the types of extreme NBS sequences that were examined as part of this analysis. Considerable uncertainty remains regarding the future climate and its impact on Great Lakes hydrology. This uncertainty, along with environmental concerns, institutional requirements and the high costs pose significant challenges for moving forward with multi-lake regulation. Furthermore, there may be adaptive measures that could more effectively address risks related to extreme water level conditions.

Therefore, based on the findings presented in this chapter, the Study Board recommends that:

Further study of multi-lake regulation in the Great Lakes-St. Lawrence River system should not be pursued at this time.