International Upper Great Lakes Study

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

Final Report to the International Joint Commission
March 2012

Report Cover

Changing water levels can have significant effects on the lives of the more than 25 million people who live and work in the upper Great Lakes region. The front cover shows an integrated view of the key interests served by these waters. In the centre of the image is a photograph of the control structures at the outlet of Lake Superior on the St. Marys River, the only location in the entire Great Lakes basin upstream from Niagara Falls where water levels can be affected by regulation.

Under the *Boundary Waters Treaty of 1909*, *domestic and sanitary water uses, navigation*, and *power and irrigation* are given order of precedence. These uses must be taken into account in the development of regulation plans. Today, it is recognized that other interests have rights under the Treaty, consistent with the International Joint Commission's balancing principle – providing benefits or relief to interests affected by water levels and flows without causing undue detriment to other interests. With this in mind, the International Upper Great Lakes Study added the interests of ecosystems, coastal zone uses and recreational boating and tourism to its analysis of Lake Superior regulation and uncertainty in future upper Great Lakes water levels.

In addition, the Study recognized that First Nations in Canada, Native Americans and Métis represent an important perspective in the upper Great Lakes. For thousands of years, and continuing into the present, many Native American communities and First Nations have relied on the natural resources of the Great Lakes to meet their economic, cultural and spiritual needs.

Front cover graphic: Syed M. A. Moin
Study Logo: John Nevin, Communications Advisor

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For More Information on the Study

For more information on the International Upper Great Lakes Study, please visit the Study's website: www.iugls.org.

Information can also be obtained by writing to either of the following addresses:

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March 16, 2012

Hon. Joe Comuzzi
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Dear Chairpersons Comuzzi and Pollack:

The International Upper Great Lakes Study Board is pleased to submit its final report, ***Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels***.

The International Upper Great Lakes Study was launched five years ago to address a recurring challenge in the upper Great Lakes system: *how to manage fluctuating lake levels in the face of uncertainty over future water supplies to the basin while seeking to balance the needs of those interests served by the system*.

The Study's first report, ***Impacts on Upper Great Lakes Water Levels: St. Clair River***, addressed changes in the St. Clair River. It was submitted to the International Joint Commission in December 2009. The information from that report generated a critical new understanding of the St. Clair flow regime and the implications for upper Great Lakes water levels.

Our second and concluding report focuses on the formulation and evaluation of options for a new regulation plan for Lake Superior outflows. It also addresses restoration and multi-lake regulation as alternative approaches for dealing with extreme water levels beyond those addressed by Lake Superior regulation alone, and considers the important role that adaptive management can play to help all parties better anticipate and respond to extreme water levels in the future.

We believe that the Study reflects the best of what the International Joint Commission does: it has brought together some 200 scientists, engineers, planners and technical experts from both the United States and Canada for nearly five years of rigorous planning and scientific investigations; it has produced more than 100 separate technical reports that stand as a true legacy for future researchers; it has involved a strong commitment to public engagement at virtually every step; and, it has benefited from an unprecedented level of independent expert peer review.

The result is a set of pragmatic but pivotal recommendations that we believe will enable the International Joint Commission to more effectively address the uncertainties associated with a changing climate and extreme water levels. Most importantly, we are recommending a new regulation plan for Lake Superior, one that will perform well regardless of future water supplies and in a manner that is equitable for all the interests.

Our recommendations are submitted unanimously. They are the outcome of careful consideration of all the scientific information as well as extensive deliberations on how to incorporate climate uncertainty into the regulation plan evaluation process.

Finally, we would like to express our sincere appreciation to the International Joint Commission for the opportunity to serve on the Study Board.

Respectfully submitted,

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Acknowledgements

The International Upper Great Lakes Study gratefully acknowledges the many individuals from Canada and the United States who contributed to the planning, applied research, writing and review of this report. Their collaborative efforts have produced a comprehensive report, based on sound science and peer-reviewed analysis, that will enable the International Joint Commission to more effectively address the uncertainties associated with a changing climate and extreme water levels in the upper Great Lakes.

A detailed list of contributors to the Study is provided in the Annex.

Members of the International Upper Great Lakes Study Board served from 2007 to 2012, directing the Study's planning and analysis and developing recommendations for the International Joint Commission. Photo taken at the final meeting of the Study Board, in February 2012, at the Canadian office of the International Joint Commission, in Ottawa, ON.

Members (left to right): Dr. John Boland, Dr. Syed Moin (Study Co-Manager), Dr. Donald Burn, Dr. James Bruce, Ted Yuzyk (Study Co-Chair), Dr. Eugene Stakhiv (Study Co-Chair), Jonathan Gee, James Bredin, David Powers, Dr. Jonathan Bulkley, Dr. Anthony Eberhardt (Study Co-Manager). (Missing: Allan Chow).

Photo credit: Jacob Bruxer, Environment Canada

Executive Summary

Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels is the second and final report of the bi-national International Upper Great Lakes Study (the Study). The Study was launched by the International Joint Commission (IJC) in 2007 to:

- examine physical processes and possible ongoing changes in the St. Clair River and their impacts on levels of lakes Michigan and Huron[1] and, if applicable, evaluate and recommend potential remedial options; and,
- review the regulation of Lake Superior outflows and assess the need for improvements to address both the changing conditions of the upper Great Lakes and the evolving needs of the many interests served by the system.

The Study's first report, ***Impacts on Upper Great Lakes Water Levels: St. Clair River***, addressed changes in the St. Clair River. It was submitted to the IJC in December 2009.[2]

The geographical scope of the Study was the upper Great Lakes basin, from the headwaters of Lake Superior downstream through lakes Michigan, Huron, St. Clair and Erie and their connecting channels (the St. Marys, St. Clair and Detroit rivers, the Straits of Mackinac and the upper Niagara River).

The IJC appointed a 10-member bi-national Study Board to direct and manage the Study. Members were drawn from the two federal governments, state and provincial governments, universities and the public.

1 For the purposes of the Study, lakes Michigan and Huron were considered a single lake because they have the same surface water elevation due to their shared connection to the broad and deep Straits of Mackinac.

2 Available at the Study's website: www.iugls.org

The Challenge

The Study addressed a recurring challenge in the upper Great Lakes system: *how to manage fluctuating lake levels in the face of uncertainty over future water supplies to the basin while seeking to balance the needs of those interests served by the system.*

The waters of the upper Great Lakes meet many diverse needs of the more than 25 million people who live in the basin: from drinking water to electrical power generation, from industrial manufacturing to food crop irrigation, from recreational boating to commercial shipping. They are important to the economic and cultural lives of Native American communities and First Nations. The lakes and connecting rivers also maintain wetlands and fisheries.

In the entire upper Great Lakes basin, water levels are affected by regulation at only one location upstream from Niagara Falls: at the outlet of Lake Superior on the St. Marys River. The IJC issued Orders of Approval in 1914 for hydropower development on the St. Marys River and the first Lake Superior regulation plan was implemented in 1921. Since 1921, seven different regulation plans have been used to determine Lake Superior outflows. The current plan, **1977A**, has been in force since 1990.

The rationale for reviewing the existing plan is based on several important factors that have emerged over the past 20 years since the current plan was implemented. First, there is considerable uncertainty about future water supplies and corresponding water levels in the Great Lakes basin as a result of natural climate variability and human-induced climate change. Compounding this uncertainty are the impacts of glacial isostatic adjustment, the differential adjustment of the earth's crust that has the effect of gradually "tilting" the Great Lakes basin over time. Second, there is better information available today than 20 years ago about the hydrology and hydraulics of the Great Lakes. Researchers have more confidence in the newer models that describe how the system performs under a variety of conditions. Finally, there is an understanding that any new regulation plan must address the needs of a wide spectrum of interests served by the upper Great Lakes system.

The Key Interests Served by the Upper Great Lakes System

The Study looked at the current and emerging conditions and perspectives of the key interests likely to be affected by possible future changes in water levels in the upper Great Lakes basin (**Chapter 3**). Based on this analysis, the Study Board concluded that:

- Under the *Boundary Waters Treaty of 1909*, *domestic and sanitary water uses, navigation*, and *power and irrigation* are given order of precedence. These uses must be taken into account in the development of regulation plans. Today, it is recognized that other interests, such as ecosystems, coastal zone uses and recreational boating and tourism uses have rights under the Treaty, consistent with the IJC's balancing principle, which provides for benefits or relief to interests affected by water levels and flows without causing undue detriment to other interests.
- Most of the key interests have demonstrated their capacity to adapt to changes in water level conditions that have been within historical upper or lower ranges. However, future water levels that are outside these ranges would require some interests to carry out more comprehensive and costly adaptive responses than any undertaken to date.
- For thousands of years, and continuing into the present, Native American communities and First Nations have relied on the natural resources of the Great Lakes to meet their economic, cultural and spiritual needs. A fundamental ongoing concern of indigenous peoples is the extent to which they are involved in the decisions of governments in the United States and Canada with regard to the Great Lakes.

Hydroclimatic Conditions: Past, Present and Future

A major task of the Study was to improve understanding of hydroclimatic conditions in the upper Great Lakes system, focusing on the possible impacts of climate variability and climate change on future water levels (**Chapter 4**). Based on this analysis, the Study Board concluded that:

- The Great Lakes basin is a complex system whose dynamics are only partially understood. Despite these uncertainties, however, it is clear that lake evaporation is increasing and likely will increase for the foreseeable future, due to the lack of ice cover, increasing surface water temperatures and wind speeds. Analysis indicates that in the Lake Michigan-Huron basin this increased evaporation is being largely offset by increases in local precipitation.
- In the Lake Superior basin, however, increasing evaporation has not been compensated for by increased precipitation. As a result, water supplies have been declining in general in this basin. This is consistent with the current understanding of climate change. Unless changes in the precipitation regime occur, which is possible, water supply conditions in Lake Superior will continue to decline, on average, despite the possibility of higher supplies at times.
- Thus, changes in levels in the upper Great Lakes over the next 30 years may not be as extreme as previous studies have predicted. Lake levels are likely to continue to fluctuate, but still remain within the relatively narrow historical range. While lower levels are likely, the possibility of higher levels at times cannot be dismissed. Both possibilities must be considered in the development of a new regulation plan.
- Beyond the next 30 years, some projections by climate models of more extreme water levels (both higher and lower) in the upper Great Lakes may have more validity, though there is still a great deal of uncertainty regarding those projections.
- Therefore, in terms of water management and lake regulation, the best approach is to make decisions in such a way as to not overly rely on assumptions of particular future climatic and lake level conditions or specific model projections. *Robustness* – the capacity to meet regulation objectives under a broad range of possible future water level conditions – must be a primary attribute of any new regulation plan.

Regulation Plan Formulation and Evaluation

A primary objective of the Study was to develop and evaluate alternative Lake Superior regulation plans to determine if a new plan could improve on the performance of **1977A** – particularly in the context of the considerable uncertainty about future climatic conditions and corresponding water levels on the upper Great Lakes.

The Study Board established clear objectives for a new Lake Superior regulation plan and a set of decision criteria against which to evaluate alternative plans (**Chapter 5**). Study scientists and engineers developed more than 100 alternative plans to meet the objectives, using a variety of scientific approaches. The Study Board evaluated these plans using shared vision planning, an iterative and collaborative process in which participants undertake a series of practice decisions to better understand the implications of any regulatory decision. Through this process, the long list of alternative plans was reduced to four. One of the final four plans was identified as the most *robust* – it performed better than or as well as any of the other options, regardless of the future water supply conditions applied in its evaluation. As a final step in the selection process, plan formulators developed three variations of the preferred plan as part of an optimization analysis. One of the variations was selected as the recommended plan (**Chapter 6**).

The Study Board concluded that the new plan, named **Lake Superior Regulation Plan 2012**, will bring several benefits compared to the existing plan:

- If future water supplies become significantly drier under climate change, then the new plan will do a better job preserving water levels on Lake Superior, while taking into account the downstream lakes.
- If future water supplies are much drier than historical conditions, then the new plan will still be able to avoid infrequent but serious adverse effects on the spawning habitat of lake sturgeon, an endangered species, in the St. Marys River. Under **1977A**, adverse effects on fish habitat would be more frequent under drier conditions.
- The new plan will provide modest benefits compared to the existing plan for commercial navigation, hydroelectric generation and coastal zone interests, under both wetter and drier water supply conditions.
- Month-to-month changes in flow on the St. Marys River with the new plan will be smaller, giving the St. Marys River a more natural flow relationship to Lake Superior levels, an important factor in sustaining the health of the river's ecosystems.

The Limits of Lake Superior Regulation:

Considering Restoration of Lake Michigan-Huron Levels and Multi-lake Regulation

The Study Board recognized that Lake Superior regulation on its own has limited ability to affect the levels of Lake Michigan-Huron or address risks of extreme lake levels downstream of Lake Superior. In addition, it was recognized that the impacts of climate change and climate variability on future water levels would introduce uncertainty to any regulation effort. As a result, the Study Board concluded that to more fully address uncertainty in upper Great Lakes water levels there was a need to look beyond the existing system of Great Lakes regulation and consider alternative approaches for managing and responding to uncertain future conditions.

At the direction of the IJC, the Study Board considered the feasibility and implications of raising water levels of Lake Michigan-Huron by means of restoration structures in the St. Clair River to compensate for past natural and human-induced changes (**Chapter 7**). The IJC did not request that the Study Board make any recommendation with respect to restoration options. Based on this analysis, the Study Board concluded that:

- Several of the restoration options reviewed are technically feasible. Construction cost estimates ranged from about $30 million to about $170 million, depending on the technology and level of restoration provided.
- Restoration structures in the St. Clair River would result in adverse effects on certain key interests served by the upper Great Lakes system. Commercial navigation and recreational boating and tourism interests would benefit, while coastal zone interests, hydroelectric generation and indigenous peoples would be adversely affected.
- Positive environmental effects would be concentrated in the wetlands of the Georgian Bay region, which have suffered during low water levels in the past and would benefit from higher Lake Michigan-Huron levels. In contrast, restoration structures would adversely affect important fish habitat in the St. Clair River system, and would have adverse effects on the Lake St. Clair fishery.

The Study Board also considered the feasibility of multi-lake regulation – operating existing and new regulation structures to benefit the Great Lakes-St. Lawrence River system as a whole (**Chapter 8**). The Study analyzed multi-lake regulation plans that used 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 water supply scenarios. Based on this analysis, the Study Board concluded that:

- The potential for multi-lake regulation to address extreme water levels is limited by the uncertainty of future climatic conditions and water supplies, very high costs, environmental concerns and institutional requirements.
- Extreme water levels in the future may be unavoidable, even with additional regulation capabilities.

Adaptive Management

With the concurrence of the IJC, the Study Board expanded the scope of the Study's work to include a more comprehensive consideration of the role of adaptive management in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels (**Chapter 9**). Based on this analysis, the Study Board concluded that:

- Given the limitations of Lake Superior regulation and the adverse impacts and costs of restoration structures and multi-lake regulation, adaptive management has an important role to play in addressing the risks of future changes in water levels in the upper Great Lakes. Regardless of the Lake Superior regulation plan adopted by the IJC, ongoing monitoring and modelling efforts will be required to assess risks and address uncertainties and changing conditions.
- Information and education are powerful components of adaptive management. They contribute to both anticipating and preventing lake level-induced damage, particularly when focused on understanding risk, the limits of regulation, inherent uncertainties and system vulnerability.
- An effective adaptive management strategy must include six core elements:
  - bi-national hydroclimatic monitoring and modelling;
  - ongoing risk assessment;
  - information management and outreach;
  - tools and processes for decision makers to evaluate their actions;
  - a collaborative regional adaptive management study for addressing water level extremes; and,
  - the integration of water quality and quantity modelling and activities.
- Existing legal, regulatory and programmatic efforts related to adaptive management vary considerably from one jurisdiction to the next. Federal, state and provincial governments generally provide the policy and regulatory framework, while site-specific selection and application of adaptive risk management measures are largely local government responsibilities.
- Application of a comprehensive adaptive management strategy requires leadership and strengthened coordination among institutions on both sides of the international border. No bi-national organization currently is responsible for coordinating data and information on an ongoing basis for adaptive management efforts in the Great Lakes basin. Efforts to coordinate approaches and promote consistency across jurisdictions have been limited and generally have focused on accommodating seasonal lake level fluctuations and the occasional extreme high and low water events. Furthermore, little focus has been placed on long-term implications of climate change-induced impacts and the need for new adaptive risk management measures.

Public Concerns about Upper Great Lakes Water Levels

Public involvement was a core element of the Study from the outset. Recognizing the many interests concerned with the future of water levels in the upper Great Lakes, the IJC appointed a bi-national Public Interest Advisory Group to provide advice to the Study Board on issues related to the Study and advice and support in the development and implementation of the Study Board's public information and engagement activities (**Chapter 10**). These activities included a series of 12 public meetings around the Great Lakes basin, attended by more than 1,200 people, to present preliminary findings, respond to questions and receive public comments. Based on the results of these activities, the Study Board concluded:

- There was general support among participating individuals and organizations for an improved regulation plan for Lake Superior outflows. However, the issue did not generate extensive comment, as there was general agreement that any new plan would mean only marginal changes from the existing plan.

- Public views on other key water level issues within the Study's mandate differed strongly depending on geographical location:
  - Many residents in the Georgian Bay region of Ontario, as well as several other communities upstream from the St. Clair River, supported restoration structures and multi-lake regulation, arguing that important wetlands in Georgian Bay will be lost unless some form of water level restoration is achieved for that area.
  - In contrast, many individuals residing along the shorelines of much of Lake Michigan and the western and southern shorelines of Lake Huron expressed concerns about the negative shoreline effects of higher water levels resulting from restoration structures or multi-lake regulation. Those living downstream of the upper St. Clair River, including along Lake St. Clair and Lake Erie as well as some First Nations and Native American communities, expressed concerns about the environmental impacts of lower water levels even for a few years in their areas. Others opposed to multi-lake regulation said the approach was impractical given its high cost.

Study Board Recommendations

On the basis of the Study's analysis and findings, and in accordance with its mandate, the Study Board makes the following recommendations to the IJC:

1. *The IJC should approve* ***Lake Superior Regulation Plan 2012*** *as the new plan for regulating Lake Superior outflow and advise governments that the* ***1977A*** *plan will be replaced with the new plan.*
2. *The IJC should prepare and issue new integrated Orders of Approval that consolidate all of the applicable conditions and requirements of the original and Supplementary Orders, as well as the additional considerations required to implement the recommended new plan,* ***Lake Superior Regulation Plan 2012****.*
3. *The IJC should seek to improve scientific understanding of hydroclimatic processes occurring in the Great Lakes basin and the impacts on future water levels as part of a continuous, coordinated bi-national effort. In particular, the IJC should endorse the following initiatives as priorities and strongly recommend ongoing government support:*
   - *strengthening climate change modelling capacity in the Great Lakes basin in light of the promising preliminary results identified in the Study; and,*
   - *enhancing hydroclimatic data collection in the upper Great Lakes basin.*
4. *An adaptive management strategy should be applied to address future extreme water levels in the Great Lakes-St. Lawrence River basin through six core initiatives:*
   - *strengthening hydroclimatic monitoring and modelling;*
   - *ongoing risk assessment;*
   - *ensuring more comprehensive information management and outreach;*
   - *improving tools and processes for decision makers to evaluate their actions;*
   - *establishing a collaborative regional adaptive management study for addressing water level extremes; and,*
   - *promoting the integration of water quality and quantity modelling and activities.*
5. *The IJC should seek to establish a Great Lakes-St. Lawrence River Levels Advisory Board to champion and help administer the proposed adaptive management strategy for the entire Great Lakes-St. Lawrence River system.*
6. *The IJC should work with governments to pursue funding options and coordinate adaptive management efforts.*
7. *Further study of multi-lake regulation in the Great Lakes-St. Lawrence River system should not be pursued at this time.*

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction to the International Upper Great Lakes Study

Chapter 1 presents an overview of the major factors affecting water levels in the Great Lakes and background on the regulation of Lake Superior outflows. It also describes the origin, objectives and organization of the International Joint Commission's International Upper Great Lakes Study.

1.1 Introduction

In the heart of North America sits the largest surface freshwater system on the planet: the Great Lakes, created 10,000 years ago at the end of the last period of continental glaciation.

Today, these waters meet many diverse needs for the estimated 45.3 million people who live in the Great Lakes region in Canada and the United States (CDM, 2010): from drinking water to electrical power generation, from industrial manufacturing to food crop irrigation, from recreational boating to commercial shipping. The waters maintain rich wetlands and fisheries. They are central to the lives of many Native American communities and First Nations. They shape beautiful, iconic shorelines and landscapes.

Prehistoric geological records and modern-day monitoring confirm that the water levels of the Great Lakes continually change in response to both natural forces and human activities. These changes can have a profound effect on the lives and livelihoods of the people who live in the region and on the ecosystems that are sustained by the waters of the Great Lakes.

All interests affected by water level changes – governments, companies and individuals – must be aware of these changes and respond to them as best they can. Yet in the entire vast territory of the upper Great Lakes basin, stretching upstream of Niagara Falls to the headwaters of Lake Superior, water levels can be regulated at only one site: where the St. Marys River flows out of Lake Superior at the twin cities of Sault Ste. Marie in Ontario and Michigan (Figure 1-1).

What will happen to upper Great Lakes water levels in the future? What forces are causing these levels to change? What will these changes mean to people who live along the shorelines, to the industries that depend on these waters, and to the fragile ecosystems that help make this area so special? And most importantly, what can and should be done in response?

This report, ***Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels***, seeks to provide answers to these critical questions.

***Figure 1-1* Lake Superior Regulation Control Structures**

Outflows from Lake Superior at the St. Marys River have been regulated since 1914 under Orders of Approval issued by the International Joint Commission. Today, the control structures consist of three hydropower plants and a gated dam at the head of the rapids known as the compensating works.

The report represents the culmination of the five-year **International Upper Great Lakes Study** (the Study). It is the product of a close cooperative effort by more than 200 scientists, engineers, planners and technical experts from both the United States and Canada from all levels of government, academia and the private sector, undertaken at the direction of the International Joint Commission (IJC). The IJC was founded in 1909 under the *Boundary Waters Treaty* to prevent and resolve potential disputes regarding many of the lakes and rivers along the border between the two countries.

The Study's research, analysis and conclusions, summarized here, have significantly increased understanding of how the upper Great Lakes function – how powerful forces are shaping water levels in the lakes and what realistic options are available for addressing the prospect of changing water levels in the future.

1.2 Great Lakes Water Levels and Flows

1.2.1 The Upper Great Lakes Basin

The upper Great Lakes basin, the focus area of the Study, stretches from the headwaters of Lake Superior all the way downstream to Niagara Falls, an area of about 686,000 km^2 (265,000 mi^2) (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data [CCGLBHHD], 1977). The area encompasses lakes Superior, Michigan, Huron (including Georgian Bay) and Erie, their drainage basins, and the connecting channels of the St. Marys River, the Straits of Mackinac, the St. Clair River system (including Lake St. Clair and the Detroit River), and the upper Niagara River above the Falls (Figure 1-2).

For the purposes of the Study, lakes Michigan and Huron were considered a single lake because they have the same surface water elevation due to their shared connection to the broad and deep Straits of Mackinac. In addition, Lake Erie was included in the Study, given its importance in determining the water levels in Lake Michigan-Huron.

Of the more than 45 million people who live in the Great Lakes region of the United States and Canada, about 25.7 million are in the upper Great Lakes basin (CDM, 2010).

Figure 1-2 ***The Upper Great Lakes Basin***

About one-third of the upper basin area consists of the water surfaces of the upper Great Lakes and their connecting channels. Figure 1-3 shows the general water surface profile of the Great Lakes – St. Lawrence River System.

Measurement Units Used in the Report

Metric units are presented first in this report, given that most of the collection, modelling and analyses of data undertaken in the Study used the metric system. The equivalent United States customary system units are provided. A table listing the conversion factors between the two systems of units is included in the inside back cover of the report.

1.2.2 Factors Affecting Upper Great Lakes Water Levels

The water levels of the Great Lakes depend on the storage capacities of the lakes, the outflow characteristics of the outlet channels, and the amount of water supply received by each lake.

Water can enter lakes by way of overlake precipitation, runoff from the drainage basin and inflow from the lake upstream. Water can leave lakes by way of evaporation and outflow to the downstream lake. Water from snowmelt or rain either seeps into the soil as temporary groundwater storage or moves over the surface as runoff to streams, wetlands and small lakes in the basin. Most groundwater flow is generally assumed to be captured as part of the runoff component, but some groundwater also flows into or out of the lakes directly. Water also flows into and out of the lakes through diversions.

Role of Connecting Channels

Despite their short length, the upper Great Lakes connecting channels play a vital role in influencing fluctuations of water levels and flows of the Great Lakes.

Great Lakes outflows depend on the water levels of the lakes – in general, the higher the level (such as during periods of high water supplies), the higher the outflow. Similarly, low lake levels produce low flows. The immense storage capacities of the Great Lakes in combination with their restricted outflow channels make the lakes a highly effective naturally-regulated water system (International Great Lakes Levels Board, 1973). Large variations in water supplies to the lakes are absorbed and modulated to maintain outflows that are remarkably steady. This essentially self-regulating feature helps keep lake levels within typical ranges over long periods.

In addition, the size of the Great Lakes and the limited discharge capacity of their outflow rivers mean that extremely high or low levels and flows can persist for a considerable time after the factors that caused them have changed.

1.2.3 Variability in Water Levels

The Great Lakes basin is highly dynamic, characterized by changes in lake levels as a result of both natural and human factors operating on time scales from hours to decades to centuries (International Great Lakes Levels Board, 1973; Nicholas, 2003). Three general types of water level fluctuations occur on the Great Lakes:

- *Short-period fluctuations* (lasting from less than an hour to several days) can occur when sustained high winds blow over a lake producing a wind set-up or storm surge on the downwind shore of the lake. This results in lower water levels at the opposite shore of the lake. Such large events are almost always followed by seiches (oscillations) that can disturb water levels for two to three days. Differences in barometric pressure can also cause short-period water level fluctuations.

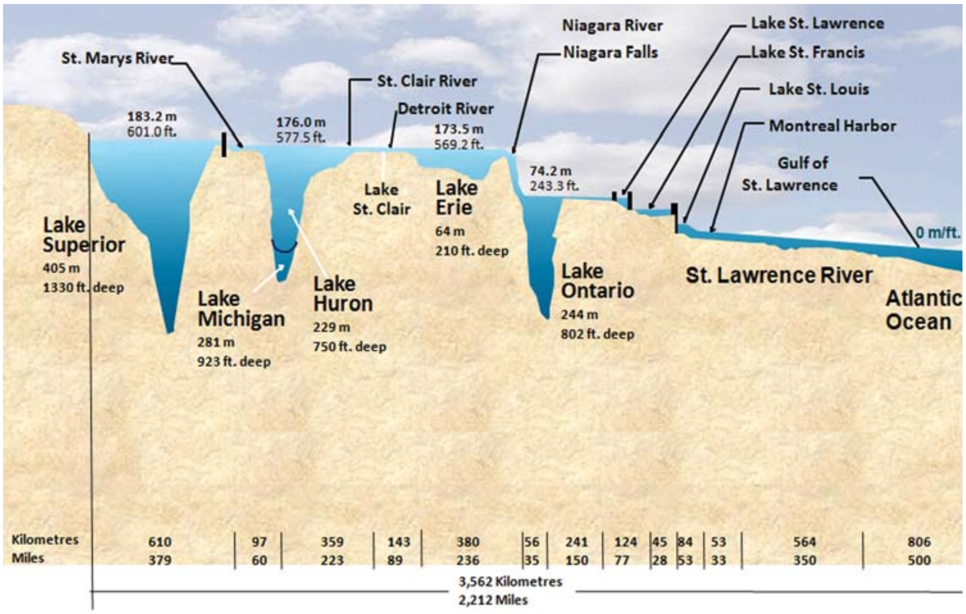
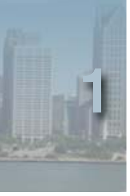


Figure 1-3 ***Water Surface Profile of the Great Lakes System***

Note: Water surface elevations are at chart datum on IGLD (1985).

Source: Modified from Great Lakes Commission and U.S. Army Corps of Engineers (1999)



- *Seasonal fluctuations* of the Great Lakes levels generally correspond to the basin's annual hydrological cycle. The cycle is characterized by higher net basin supplies[1] (NBS) during the spring and early summer as a result of snowmelt and spring rainfall, and lower NBS during the remainder of the year. Much of the seasonal decline the lakes experience each fall and early winter is due to the increase in evaporation from their surfaces when cool, dry air passes over the relatively warm water of the lakes.
- *Long-term fluctuations* in the levels of the Great Lakes are the result of persistent low or high water supply conditions within the basin, which in turn lead to extremely low or high water levels in the lakes.

Chapter 4 provides a detailed analysis of long-term trends in the variability of water levels in the upper Great Lakes, including a comparison of low and high water conditions in pre-1900 and more recent periods.

1.3 Regulating Lake Superior Outflows

Lake Superior outflows have been regulated at the St. Marys River control structures since 1914. This section provides a brief overview of the evolution of this regulation, the current regulation plan, and the challenges that must be addressed in the development of any new plan.

1.3.1 *Boundary Waters Treaty of 1909* and the IJC

About 43 percent of the 8,900-km (5,500 mi) border between Canada and the United States is water – more than 300 lakes and rivers are part of or cross the international boundary, forming 14 distinct transboundary basins (IJC, 2009). These basins stretch from the Alaska-Yukon border, to the Coastal Mountain watersheds of British Columbia and Washington, across the continent to the Great Lakes and St. Lawrence River – the largest of the transboundary basins –and beyond to the St. Croix River basin in New Brunswick and Maine.

More than 100 years ago, Canada and the United States recognized the need to cooperatively manage their shared water resources. The result was the *Boundary Waters Treaty of 1909*.[2] In the immediate term, the Treaty settled two disputes regarding the use of boundary waters at that time, one on the Niagara River and the other along the Montana-Alberta border. Over the last 100 years, however, the real legacy of the Treaty is that it established sound rules and principles that the two countries agreed would be followed to resolve future disputes. Under the Treaty, the two governments created the IJC to help prevent and resolve future disputes relating to the use and quality of boundary water and to advise them on boundary waters issues.

The Treaty's rules and principles remain vital to this day:

- Under **Article I** of the Treaty, both countries agree that the navigation of all navigable boundary waters shall forever continue free and open for the purposes of commerce to the inhabitants and to the ships, vessels, and boats of both countries.
- **Article III** and **Article IV** specify that, unless there is special agreement between the two countries, no further uses or obstructions or diversions of boundary waters on either side of the line, affecting the natural level or flow of boundary waters on the other side of the line shall be permitted except by authority of the two countries and with the approval of the IJC.
- **Article VIII** specifies that no further use shall be permitted which tends materially to conflict with or restrain any other use which is given this order of precedence:
  - uses for domestic and sanitary purposes;
  - uses for navigation, including the service of canals for the purposes of navigation; and,
  - uses for power and for irrigation purposes.

  Article VIII also states that the foregoing provisions shall not apply to or disturb any existing uses of boundary waters on either side of the boundary.
- Under **Article IX**, either one or both governments may refer matters related to boundary waters to the IJC for examination and report.

1.3.2 IJC Orders of Approval

The IJC rules upon applications for approval of projects affecting boundary or transboundary waters, such as dams and hydroelectric power stations. It can regulate the terms and conditions of such projects through Orders of Approval to maintain specific targets with respect to water levels and flows in the lakes and connecting channels. Supplementary Orders can be issued to address changing conditions, accommodate new information or data, or to better meet the needs of the interests in the upper Great Lakes system.

1 Net basin supply (NBS) is the net amount of water entering each Great Lake resulting from precipitation falling directly on the lake surface, runoff to the lake from the surrounding drainage basin, and evaporation from the lake. It does not include the inflow from the upstream Great Lake or any diversions.

2 The text of the Treaty is available through the website of the IJC: www.ijc.org

1914 Orders

The IJC's first Orders of Approval were issued in 1914, in response to an application from the Michigan Northern Power Company in the United States and Algoma Steel Corporation Ltd. in Canada to use of the waters of the St. Marys River for hydropower generation and to construct a control structure with gates in the river, known as the compensating works.

The 1914 Orders issued conditions regarding construction of the works, set criteria and requirements governing their operations, and established the Lake Superior Board of Control to oversee their operations and formulate operating rules for the regulation of the outflows of Lake Superior. For example, the Orders sought to guard against unduly high Lake Superior levels in terms of frequency and magnitude, and against unduly high levels in the lower St. Marys River below the locks. In addition, the 1914 Orders required that all the approved works be operated in such a manner as not to interfere with navigation. This requirement pertaining to navigation is consistent with the terms of the *Boundary Waters Treaty of 1909* and remains in effect in all subsequent IJC Orders regarding Lake Superior regulation. The 1914 Orders established a control board to assist the IJC in implementing the Orders to ensure that the two applicants complied with the Orders.

Peaking and Ponding Operations

The IJC also has imposed requirements related to the *peaking* and *ponding* operations of the hydropower plants on the St. Marys River. Peaking operations refers to increasing the flow to generate more electricity when the value of power is high. By contrast, ponding operations refer to the process of storing (or ponding) water upstream when demand for electricity is lower or in response to flood control needs.

A 2001 study by the International Lake Superior Board of Control concluded that peaking and ponding operations have their maximum water level impacts immediately downstream of the power plants, with the impacts becoming negligible near the mouth of the St. Marys River. Peaking and ponding operations also were found to have a negligible effect on the levels upstream of the power plants at Sault Ste. Marie.

The first IJC approval of peaking and ponding under certain conditions, issued in 2001, was for a one-year period. The authority was subsequently extended on a yearly basis. In 2006, the IJC issued a new order permitting peaking and ponding operations for an indefinite period under the Board of Control's supervision, subject to a review every five years.

1.3.3 Lake Superior Outflow Regulation Plans

The first regulation plan was established in 1916 and implemented in 1921. Since that time, seven different plans have been used to regulate Lake Superior outflows. These plans:

- incorporate the specific objectives established in the IJC's Orders of Approval and Supplementary Orders;
- establish monthly outflows from Lake Superior; and,
- allocate flows to various interests, such as hydroelectric generation and fisheries.

Regulation plans have evolved considerably since the first plan was implemented more than 90 years ago. An important characteristic of that evolution has been the adoption of the *principle of balancing the needs of varying interests* in the upper Great Lakes basin – providing benefits or relief to interests affected by water levels and flows without causing undue detriment to other interests.

For example, the early plans considered only the Lake Superior level in determining the outflow and focused on the needs of domestic and sanitary water users, navigation and hydropower. More recent plans have begun to recognize the importance of other factors, such as water levels in Lake Michigan-Huron and the need to maintain fish habitat in the St. Marys River rapids.

1. The Current Regulation Plan

The current regulation plan, **1977A**, has been in effect since 1990. It specifies monthly mean Lake Superior outflows with the objective of bringing the levels of lakes Superior and Michigan-Huron to nearly the same relative position within their respective ranges of actual historical levels. The plan seeks to prevent the monthly mean level of Lake Superior from rising above or falling below the range of levels prescribed in the 1979 Supplementary Order (*i.e.*, between 182.76 and 183.86 m [599.6 and 603.2 ft]). It also provides for a fixed minimum monthly release to:

- maintain the ecosystem in the St. Marys River rapids;
- provide water for ship locks and municipal/industrial uses; and,
- keep the hydropower plants operating, particularly to avoid freezing in winter.

The International Lake Superior Board of Control allocates the monthly flow first to:

- meet the needs of municipal and industrial water uses;
- operate the navigation locks; and,
- provide sufficient flow at the compensating works to maintain the aquatic habitat of the St. Marys River rapids.

The remainder of the monthly Lake Superior outflow, which is the majority, is allocated equally between the United States and Canada to generate electricity. If the amount of water available for hydropower generation exceeds the capacities of the hydropower plants, the excess is released by opening more gates at the compensating works.

2. Deviations from the Regulation Plan

The IJC may approve deviations from the regulation plan on the advice of the Control Board. Deviations typically involve outflows less than specified by the regulation plan to accommodate short term activities such as undertaking repairs at the hydropower plants or compensating works and trapping sea lamprey. These deviations can be offset by higher flows during the remainder of the month or the following month.

Larger scale deviations have been approved, on rare occasions, to allow reconstruction of the hydropower plants, or in an attempt to provide relief to shore property interests on the upper Great Lakes during unusual water level conditions.

1.3.4 Challenges to Developing a New Regulation Plan

Regulation plans must be reviewed periodically to ensure that they continue to comply with the criteria and requirements of the IJC, and to incorporate the latest information, science and technology. In recent years, two issues have emerged that raise important challenges to the development of any new plan to regulate Lake Superior outflows.

1. Can the regulation plan effectively handle the range of changing – though difficult to predict – water level conditions in the future?

As noted, water levels in the upper Great Lakes basin are continually changing, over both the short-term and long-term. In addition, it is now recognized that two powerful forces are significantly affecting water supplies and levels in the upper Great Lakes, introducing a high degree of uncertainty in any prediction of future conditions in the basin.

Climate Variability and Climate Change

The major factors affecting the water supply to the lakes – precipitation, evaporation and runoff – vary naturally over time and cannot be controlled. However, in addition to natural climate variability, there now is the risk that climate change – a longer term change in climate patterns attributed directly or indirectly to human activities that have altered the composition of the global atmosphere – is introducing a high level of uncertainty to predicting likely future water levels across the basin.

According to recent global climate models, for example, the climate in the upper Great Lakes basin over the next 30 years is likely to be characterized by increases in water temperature and evaporation and uncertainty about changes in precipitation. This could lead to considerable uncertainty about future lake levels.

The likely trends in climate variability and climate change in the upper Great Lakes basin and the associated impacts on water levels are considered in detail in **Chapter 4**.

Glacial Isostatic Adjustment

A second force affecting water levels is the adjustment of the earth's crust, known as glacial isostatic adjustment (GIA). During the last period of continental glaciation, which ended in North America about 10,000 years ago, the tremendous weight of ice that covered most of the Great Lakes region depressed the earth's crust underneath. The weight also caused the crust beyond the edge of the ice sheet to bulge upwards (this area is known as the "forebulge.")

When the glacier retreated, the crust, relieved of the weight, began to rebound. The northern and eastern portions of the basin, where the glacier was thicker and remained longer, now is rising relative to the centre of the earth (the geocentre). At the same time, areas in the southern and western portion of the basin are falling relative to the geocentre, as the former forebulge area subsides. This differential adjustment of the earth's crust has the effect of gradually "tilting" the Great Lakes basin over time (Figure 1-4). (For more information on GIA, see IUGLS, 2009.)

The impact of GIA is particularly noticeable along the shorelines, where features on the rising or subsiding land can be compared directly to water levels and near-shore depths. For example, the shoreline of Parry Sound, ON, in Georgian Bay, is rising at a rate of about 24 cm (9.4 in) per century relative to the outlet of Lake Michigan-Huron, such that water levels at this location appear to be falling at this rate over time. At the same time, the shoreline around Milwaukee, WI, is subsiding at a rate of about 14 cm (5.5 in) per century relative to the lake outlet, such that water levels here appear to be increasing at this rate over time.

2. Can the regulation plan find a reasonable balance among the many interests in the Great Lakes basin?

Under the *Boundary Waters Treaty of 1909*, *domestic and sanitary water uses, navigation*, and *power*[3] *and irrigation* are given order of precedence. These uses must be taken into account in the development of regulation plans.

3 In interpreting the Treaty, "power" is taken to mean hydroelectric power.

However, the Treaty does require that the IJC consider impacts on “any interests on either side of the boundary”. These others interests include ecosystems, coastal zone uses, and recreational and tourism uses. A challenge for any regulation plan, therefore, is the extent to which the needs of these evolving interests can be reasonably met, while adhering to the order of precedence of interests and other requirements established in the Treaty.

Chapter 3 provides more information on the key interests of the upper Great Lakes basin, including the likely consequences to the interests of falling or rising water levels.

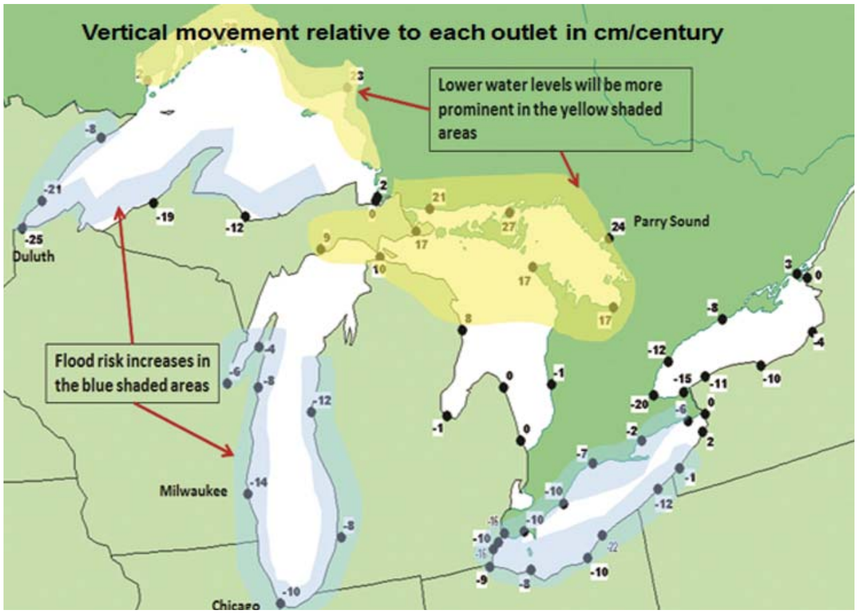


Figure 1-4 ***GIA Impacts on the Shorelines of the Upper Great Lakes***

Note: Estimates of vertical crustal velocity at water level gauge station locations relative to their lake outlets represented by water level gauges at: Cape Vincent (for Lake Ontario); Buffalo (for Lake Erie); Lakeport (for Lake Michigan-Huron); and Point Iroquois (for Lake Superior).

Source: Modified from Mainville and Craymer (2005)

The Need for a Robust Plan

With high levels of uncertainty around future water supplies and levels in the upper Great Lakes basin, it may be extremely difficult to design one regulation plan that will be optimal for all likely future water level conditions. Rather, any new regulation plan will need to be *robust* – effective and flexible enough to handle a range of future water level conditions while meeting the needs of a range of interests, all within the order of precedence constraints established under the 1909 Treaty.

Chapters 5 and 6 describe the formulation and evaluation of regulation plan options in the context of this need for robustness.

1.3.5 Additional Approaches to Addressing Changing Water Levels

While regulating Lake Superior outflows can help reduce some impacts from changing water levels on lakes Superior and Michigan-Huron, there are limits to regulation. The ability to influence high or low water levels in the upper Great Lakes through regulation at a single location is severely limited by natural climate variability, the risks that climate change could introduce more extreme conditions, GIA, and the physical geography of the lakes and connecting channels.

Longer term, therefore, there is a need to look beyond regulation at a single site to address changing water levels in the upper Great Lakes basin. The Study investigated several approaches that could be considered, either as part of or in addition to a new Lake Superior regulation plan.

1. Restoration of Lake Michigan-Huron Water Levels

Restoration involves establishing a permanent increase in the level of Lake Michigan-Huron by means of restoration structures in the St. Clair River. Examples of such structures include submerged sills or weirs, which restrict water flows and raise upstream levels.

In its first report, on the St. Clair River, the Study recommended that remedial measures to change water levels upstream not be undertaken in the St. Clair River at this time. While agreeing with the recommendation, the IJC directed the Study to conduct an exploratory analysis into restoring Lake Michigan-Huron water levels. However, the IJC did not instruct the Study to make a recommendation on whether to undertake such restoration.

Chapter 7 analyzes the feasibility and implications of raising water levels of Lake Michigan-Huron by means of restoration structures in the St. Clair River.

2. *Multi-lake Regulation*

Multi-lake regulation would involve looking beyond regulating Lake Superior outflows alone, to include using existing and new control structures to help regulate the Great Lakes-St. Lawrence River system on a system-wide basis. The general objective would be to keep the entire system within observed historical extremes on all lakes under more extreme climate conditions in the future. For example, multi-lake regulation could involve using existing control structures on the St. Marys and St. Lawrence rivers and building new regulation structures on the St. Clair and Niagara rivers.

Chapter 8 analyzes the feasibility and implications of addressing future extreme water level conditions by means of multi-lake regulation.

3. *Adaptive Management*

There are risks to property owners, companies, local governments, ecosystems and other interests whether water levels rise or decline. High water levels can cause significant damage through flooding, erosion, and loss of beaches, recreational lands and wetlands. Low levels can threaten water supplies, restrict power generation, expose mudflats, limit tourism, isolate wetlands and severely restrict navigation.

Adaptive management is a process of continuous learning – improving planning decisions as new information becomes available or as conditions in the basin change. Building the capacity in this area could involve:

- enhanced monitoring and modelling of hydroclimatic factors, such as precipitation and evaporation over the lakes and runoff to the lakes;
- improving the capacity to track and predict the physical changes in the lakes and connecting channels; and,
- distributing timely information to individuals, governments and companies in the Great Lakes so that they can better plan to reduce or cope with possible risks from changing water levels.

Adaptive management measures can be integrated into and help strengthen a new regulation plan for Lake Superior, forming part of a long-term strategy for anticipating and responding to the uncertainty of future water levels in the upper Great Lakes.

Chapter 9 considers the need for and elements of an adaptive management strategy to address future extreme water levels in the upper Great Lakes.

1.4 The International Upper Great Lakes Study

1.4.1 Origins of the Study[4]

In the mid-1980s, the upper Great Lakes were experiencing record high levels. A major IJC study completed in 1993 (Levels Reference Study Board, 1993) had focused on the question of high lake levels as well as alternative regulation plans for Lake Superior and Lake Ontario, and on potential regulation options for Lake Michigan-Huron and Lake Erie. As in previous IJC studies (IJC, 1976), the 1993 Levels Reference Study Board recommended against any regulation of Lake Michigan-Huron or Lake Erie outflows. However, this study did recommend some technical changes to the Lake Superior outflow regulation plan, and a review of the regulation criteria in the IJC Orders to ensure that they continue to reflect current and anticipated needs of the various interests in the region.

In 1998, following a nearly 30-year period of above-average water level conditions, the water levels of the upper Great Lakes began to decline. Governments and other interests became increasingly concerned about lower lake levels. As a result, the recommended technical changes to the Lake Superior outflow regulation plan were deferred pending a thorough review of the Orders and other related water level issues.

In 2001, the IJC informed the Canadian and United States governments of its intention to develop a Plan of Study to review the IJC's Orders and the regulation of the outflows from Lake Superior. The IJC set up a team to prepare the Plan of Study, invited comments on the draft directive, and held public meetings to hear views and concerns about the proposed study.

Following a period of peer review and public consultation, the Plan of Study was finalized in 2002 (Upper Great Lakes Plan of Study, 2002). This Study was designed to be conducted over five years, starting upon the completion of another major IJC study, *Options for Managing Lake Ontario and St. Lawrence River Water Levels and Flows* (International Lake Ontario-St. Lawrence River Study Board, 2006).

Low lake level conditions continued to be a concern for commercial shippers, property owners and other interests across the Great Lakes basin. In response to issues raised by an external study investigating the possible causes of low water levels in Lake Michigan-Huron (Baird, 2005), the IJC established a team to consider ways to resolve the questions surrounding possible human-induced and natural changes to the St. Clair River. On the basis of this team's

4 For a more detailed summary of the origins of the Study, see: International Upper Great Lakes Study Board (2007) and Upper Lakes Plan of Study Revision Team (2005).

recommendation, the IJC revised the 2002 Plan of Study by adding a new part to the Study to examine all the issues related to the conveyance of the St. Clair River and other factors that may be affecting Lake Michigan-Huron levels.

In 2007, the IJC issued a directive establishing a Study Board to initiate the Study. The schedule called for completion of the report on the St. Clair River in 2010 and a final report on Lake Superior regulation in 2012. At the request of the IJC, the Study Board subsequently made further adjustments to the schedule in its *Strategic Framework and Work Plan* (International Upper Great Lakes Study Board, 2007), accelerating the completion date for the St. Clair River part by nearly one year.

1.4.2 Study Objectives

The IJC launched the Study in 2007 with two major objectives:

- Examine physical processes and possible ongoing changes in the St. Clair River and their impacts on levels of Lake Michigan-Huron and, if applicable, evaluate and recommend potential remedial options; and,
- Review the regulation of Lake Superior outflows and assess the need for improvements to address both the changing conditions of the upper Great Lakes and the evolving needs of the many interests served by the system.

The Study's first report, ***Impacts on Upper Great Lakes Water Levels: St. Clair River***, addressed changes in the St. Clair River. It was submitted to the IJC in December 2009.[5]

Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels, the second and final report of the Study, addressed the second main objective.

The Study cost approximately $17.5 million (CDN) or $14.6 million (U.S.)[6] over the five years, with the second part on Lake Superior regulation accounting for about 75 percent of the total. Funding for the Study was shared equally by the governments of Canada and the United States.

Following receipt of the report, the IJC will convene public hearings to receive public comments. It also will consult with the two federal governments and state and provincial governments with an interest in the upper Great Lakes. The IJC then will select a new regulation plan for Lake Superior outflows and advise the governments of Canada and the United States. It also may undertake additional actions, based on the conclusions and recommendations of the Study.

Chapter 2 describes the Study's strategy for examining the regulation of Lake Superior outflows, future water level conditions and the impacts of those conditions on the key interests.

1.4.3 Study Organization

The organization of the Study consisted of a Study Board, the Lake Superior Regulation Task Team (Task Team) and a number of technical work groups (TWGs) responsible for specific areas of study (see Figure 1-5). Participants were drawn equally from Canada and the United States, and included experts from government agencies, as well as individuals in academia and the private sector with knowledge of Great Lakes water level issues and experience in multidisciplinary studies. All participants served in their personal and professional capacities and did not represent their employers or organizations.

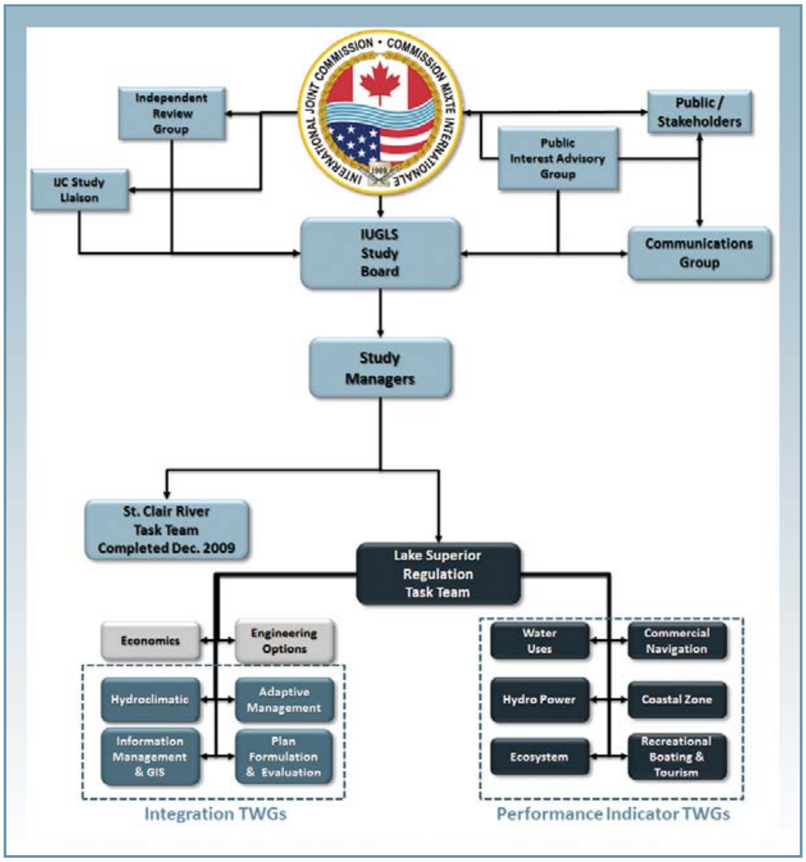


Figure 1-5 Study Organization Chart

5 Available at www.iugls.org

6 At 2005 exchange rates, when the Study's funding was established.

Many other government agencies, local governments, universities and consultants also provided data and expertise over the course of the Study.

The **Annex** lists the members of the Study Board, Task Team, and TWGs.

Study Management

The Study Board is responsible for the overall planning and management of the Study. The Study Board reports formally to the IJC on a semi-annual basis. In carrying out its mandate, the Study Board is encouraged to integrate as many relevant considerations and perspectives into its work as possible, including those that had not been incorporated to date in assessments of the upper Great Lakes system regulation, so that all significant issues may be adequately addressed.

The Study Board consisted of 10 members appointed by the IJC. The two Study Directors serve as the co-chairs and provide leadership in planning and implementing the Study Board's activities. The co-chairs of the Study's Public Interest Advisory Group (PIAG) also were members of the Study Board. The IJC assigned two co-managers to oversee the Study's day-to-day financial and administrative operations in their respective countries, and two of its technical staff to act as liaisons.

Lake Superior Regulation Task Team

The Task Team provided the strategic direction and management oversight for the numerous applied research projects undertaken to address various elements of the question of water levels in the upper Great Lakes. The Task Team consisted of the co-leads of each of the TWGs, as well as two co-chairs (one each from Canada and the United States), appointed by the Study Board.

The Task Team was responsible for:

- developing, implementing and overseeing the analytical strategy for answering the Study's science questions related to Lake Superior outflow regulation issues;
- directing development of work plans and budgets as input to the Study planning process;
- coordinating the work and schedules of the technical work groups to ensure the timely completion of tasks on budget;
- planning and directing scoping exercises, workshops and symposia to seek input and provide results of investigations;
- participating in forums and public meetings held by the Study Board and PIAG to explain the Study process, seek input and discuss results; and,
- coordinating analytical results and information with the independent expert reviewers.

Technical Work Groups

The Task Team worked directly with 10 TWGs. Each TWG was formed to examine specific issues related to the development of regulatory options. TWGs were responsible for conducting the applied research projects recommended by the Task Team and approved by the Study Board, as well as reviewing existing literature.

Six TWGs addressed the interests within the upper Great Lakes affected by water levels and flows. These TWGs identified and described baseline conditions and trends, and determined how the particular interest adapts to changing water levels and how it may be affected by various regulation plans. These TWGs addressed the following interests:

- Domestic, municipal and industrial water uses;
- Commercial navigation;
- Hydroelectric generation;
- Ecosystems;
- Coastal zone; and,
- Recreational boating and tourism.

Three *integration* TWGs were tasked with assessing and incorporating relevant information provided by the interest group TWGs to guide the development and evaluation of alternative regulation plans for review by the Study Board:

- The *Hydroclimatic* TWG worked to determine the relative contribution of NBS to water levels in the upper Great Lakes and addressed the potential impacts from climate change and climate variability. **Chapter 4** provides the results of this TWG's analysis.
- The *Plan Formulation and Evaluation* TWG developed evaluation criteria, performance indicators and baseline scenarios against which various alternative plans were formulated and evaluated; this work included receiving input from other TWGs and the PIAG to develop a transparent modelling framework to assist in the evaluation and comparison of alternative plans; the TWG applied a *shared vision model* that allows participants to review and evaluate various criteria and learn about potential impacts on water levels and flows and the various interest groups under different regulation plans. **Chapters 5 and 6** present the results of this TWG's analysis.

- The *Adaptive Management* TWG developed a strategy to help individual, private sector and government decision makers better understand, anticipate and cope with the impacts from changing water levels. **Chapter 9** presents the results of this TWG's analysis.

A fourth *integration* TWG was responsible for developing an information management strategy to allow for data sharing among the Study's researchers and to ensure that the Study's literature and data remain available for researchers and managers involved in Great Lakes water management beyond the Study. The Study Board purchased a dedicated server and information management software to provide for the sharing of information and data across all the TWGs, the two Task Teams and the Study Board. The Study's scientific and technical reports and accompanying data also have been archived and are accessible to interested individuals and organizations.[7]

1.4.4 Public Interest Advisory Group

Article XII of the *Boundary Waters Treat of 1909* requires that the public "be given a convenient opportunity to be heard." This strong commitment to public engagement has been a hallmark of the decision-making and joint fact-finding processes that the IJC has developed and improved throughout its 100 years of work under the Treaty. The views of the public play an important role in helping the IJC and its advisory bodies strengthen policy recommendations so as to increase the likelihood such recommendations will be understood, accepted and implemented.

Reflecting this commitment, and recognizing the many interests concerned with the future of water levels in the upper Great Lakes, the IJC appointed a bi-national advisory group, the PIAG, at the start of the Study. The **Annex** lists the members of the PIAG.

The PIAG was mandated to provide advice to the Study Board on issues related to the Study and advice and support regarding opportunities for interested individuals and groups to learn about the Study and to provide input regarding their views.

PIAG members were drawn from a wide range of public groups with an interest in the Great Lakes. The PIAG's Terms of Reference allowed for 10 members from each country to be appointed for two- or three-year terms and also for the appointment of *ad hoc* members for specific topics for a defined shorter duration. Throughout the course of the Study, members assisted the Study Board in organizing and conducting public meetings and workshops, and in preparing newsletters and related public information documents. Members also served as liaisons to TWGs that addressed issues in which they had a particular interest.

7 Available at www.iugls.org

In addition, the co-chairs of the group, one from Canada and one from the United States, served as members of the Study Board.

The PIAG was assisted by a Public Information Officer and a Communication Liaison from the IJC throughout the Study.

Chapter 10 of the report provides details on the activities and results of the comprehensive public information and engagement program undertaken during the Study with the support and advice of the PIAG.

1.4.5 Independent Expert Review

At the outset of the Study, the IJC and Study Board recognized the need to ensure that the Study was scientifically credible and transparent, given the diverse public and private interests concerned about Great Lakes water levels and the uncertainty and debate around some of the scientific issues. As a result, much of the Study's work was subject to a high level of independent scientific scrutiny by external experts as well as extensive review by internal experts.

The expert reviewers operated independently of the Study Board and provided their views directly to the IJC. They reviewed drafts and background studies of several of the Study's scientific and technical chapters. The Study's final report also was reviewed by the co-leads of the independent expert reviewers group. Study Task Team members considered and responded to each comment from the expert reviewers. The **Annex** lists the independent expert reviewers.[8]

1.5 Organization of the Report

The balance of this report is organized into the following 10 chapters:

Chapter 2 summarizes the *strategy* developed to guide the examination of issues related to Lake Superior regulation and upper Great Lakes water levels.

Chapter 3 provides background on the *key interests* of the upper Great Lakes basin, including their socio-economic conditions and the likely consequences to the interests of falling or rising water levels.

Chapter 4 examines how *hydroclimatic processes* affect Great Lakes water supplies and water levels, with a particular focus on the possible impacts of climate variability and climate change on future water levels.

8 For more information on the independent expert review process, the reports of the independent reviewers and the responses of Study investigators, see: www.iugls.org

Chapter 5 describes the *framework and tools* developed to help the Study formulate, evaluate and rank candidate plans for Lake Superior regulation.

Chapter 6 describes how the Study evaluated and ranked a range of regulation plans and identifies a *recommended plan*.

Chapter 7 analyzes the feasibility and implications of raising water levels of Lake Michigan-Huron to compensate for past natural and human-induced changes by means of *restoration structures* in the St. Clair River.

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

Chapter 9 considers the role that *adaptive management* can play in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels. It proposes a long-term adaptive management strategy for dealing with extreme water levels in the Great Lakes-St. Lawrence River system.

Chapter 10 provides details on the comprehensive *public information and engagement* plan undertaken during the Study with the support and advice of the PIAG.

Chapter 11 presents a summary of the Study's *key findings and recommendations* to the IJC.

The report's **Annex** provides: acknowledgements/list of contributors; a list of references, by chapter; a list of common acronyms used in the report; a glossary; and, a conversion table for comparing metric and United States customary units.

The final report is primarily scientific in terms of its language, level of complexity and presentation of data and analysis. The Study has prepared a stand-alone summary report for general readers: **Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels: *Summary of Findings and Recommendations***.[9]

9 Available at www.iugls.org

1.6 Key Points

This report, ***Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels***, presents the findings and recommendations of a major bi-national study launched by the IJC in 2007 to:

- review the regulation of Lake Superior outflows; and,
- assess the need for improvements to address the changing conditions of the upper Great Lakes and the evolving needs of the many interests served by the system.

The following points can be made, based on the background information and overview presented in Chapter 1:

- Water levels in the upper Great Lakes basin are continually changing – over periods of days, seasons, and decades – in response to complex natural forces and human activities. These changes can have a profound effect on the lives and livelihoods of the more than 25 million people who live in the upper basin.
- Since 1921, the IJC has implemented regulation plans to regulate the outflows from Lake Superior to meet the needs of various interests. Plans have evolved over the years, reflecting an increasing emphasis on balancing the needs of different interests. The current regulation plan, **1977A**, has been in effect since 1990.
- Any new regulation plan will need to be *robust* – effective and flexible enough to handle a range of future water level conditions while meeting the needs of a wide range of interests, all within the order of precedence and other requirements established under the *Boundary Waters Treaty of 1909*.
- The ability to influence high or low water levels in the upper Great Lakes through regulation at a single location is limited by natural climate variability, the risks that climate change could introduce more extreme conditions, GIA, and the physical geography of the lakes and connecting channels. There is a need to consider other approaches to addressing changing water levels, such as restoration, multi-lake regulation and adaptive management.
- Public involvement has been an important part of the Study. The PIAG played a major role in identifying Study issues and in coordinating the Study's comprehensive public information and engagement effort.
- To ensure that the Study was scientifically credible and transparent, much of the Study's work was subject to a high level of scientific scrutiny by both internal and external expert reviewers.
- The Study's work, undertaken over the last five years, has significantly increased understanding of how the upper Great Lakes function – how powerful forces are shaping the lakes and what realistic options are available for addressing the prospect of changing water levels in the future.

Chapter 2

Study Strategy

Chapter 2 summarizes the mandate of the Study and the strategy developed by the Study Board to guide the examination of issues related to Lake Superior regulation and upper Great Lakes water levels. It provides an overview of the analytical frameworks used to address future hydroclimatic and water level conditions and to guide the formulation and evaluation of options for a new regulation plan.

2.1 Study Approach

2.1.1 Defining the Problem

The International Upper Great Lakes Study (the Study) was established to examine a recurring challenge in the upper Great Lakes system: *how to manage fluctuating lake levels in the face of uncertainty over future water supplies to the basin while seeking to balance the needs of those interests served by the system*.

The Study is the most recent reflection of the ongoing effort by the International Joint Commission (IJC) to incorporate new knowledge, data and modelling strategies to address the challenge of managing water levels in the upper Great Lakes. As described in **Chapter 1**, in the large territory of the upper Great Lakes basin, water levels can be affected by regulation at only one location upstream from Niagara Falls: the control structures in the St. Marys River at the twin cities of Sault Ste. Marie in Ontario and Michigan. The release of water from Lake Superior has been regulated at this location by the IJC since 1914 under the first Orders of Approval. Since 1921, seven regulation plans have been implemented, each incorporating new information and understanding of water supplies and the potential impacts on various interests. The current regulation plan, **1977A**, was implemented in 1990.

As the third comprehensive assessment of Great Lakes water levels in the past 40 years, the Study was able to build on the accumulation of knowledge and refinement of management principles of previous studies (International Great Lakes Levels Board, 1973; Levels Reference Study Board. 1993).

2.1.2 IJC Directive to the Study

In 2007, the IJC launched the Study with two key objectives:

1. Examine physical processes and possible ongoing changes in the St. Clair River and their impacts on levels of Lake Michigan-Huron and, if applicable, evaluate and recommend potential remedial options; and,
2. Review the regulation of Lake Superior outflows and assess the need for improvements to address both the changing conditions of the upper Great Lakes and the evolving needs of the many interests served by the system.

The Directive established the International Upper Great Lakes Study Board (Study Board) to undertake the necessary studies and provide recommendations for the IJC's consideration. In carrying out its mandate, the Study Board was encouraged to integrate as many relevant considerations and perspectives into its work as possible, including those that have not been incorporated to date in assessments of the Upper Great Lakes System regulation, to assure that all significant issues were adequately addressed.

The Study Board's first report, ***Impacts on Upper Great Lakes Water Levels: St. Clair River***, submitted to the IJC in December 2009, examined the physical processes and possible ongoing changes in the St. Clair River.[1] The Study Board concluded that the conveyance of the St. Clair River has changed since the last navigational dredging work in 1962 but that the river bed has not undergone any significant, general erosion since at least 2000. The Study Board also concluded that the decline in the head difference between

1 Available at www.iugls.org

International Joint Commission Directive to the International Upper Great Lakes Study Board

Signed February 7th, 2007

"Pursuant to the Boundary Waters Treaty of 1909 (Treaty), the International Joint Commission has an ongoing responsibility for assuring that projects it has approved continue to operate in a manner that is consistent with the provisions of the Treaty as interpreted by the Commission and the governments of Canada and the United States (governments). In carrying out this responsibility, the Commission has prepared and submitted to the governments The Upper Lakes Plan of Study for the Review of the Regulation of Outflows from Lake Superior (Plan of Study), dated October, 2005. The Plan of Study describes the work for the Upper Great Lakes system from Lake Superior downstream through Lake Erie required to: examine physical processes and possible ongoing St. Clair River changes and its impacts on levels of Lake Michigan and Huron; review the operation of structures controlling Lake Superior outflow in relation to impacts of such operations on water levels and flows, and consequently affected interests; assess the need for changes in the Orders or regulation plan to meet the contemporary and emerging needs, interests, and preferences for managing the system in a sustainable manner, including under climate change scenarios; and evaluate any options identified to improve the operating rules and criteria governing Lake Superior Outflow regulation. Additionally, depending on the nature and extent of St. Clair River changes and impacts, recommend and evaluate potential remedial options. In reviewing the Order and Regulation plan, and in assessing their impacts on affected interests, the Commission will be seeking to benefit these interests and the system as a whole, consistent with the requirements of the Treaty."

Lake Michigan-Huron and Lake Erie is not the result of any single factor; rather, several physical forces have contributed to the decline: an increase in the conveyance of the St. Clair River; glacial isostatic adjustment (GIA); and shifts in climate patterns.

This second, and concluding, report of the Study Board focuses primarily on the question of Lake Superior regulation. Under the IJC Directive, the Study Board was directed to:

- review the operation of structures controlling Lake Superior outflow in relation to impacts of such operations on water levels and flows, and consequently affected interests;
- assess the need for changes in the Orders of Approval or regulation plan to meet the contemporary and emerging needs, interests, and preferences for managing the system in a sustainable manner, including under climate change scenarios; and,
- evaluate any options identified to improve the operating rules and criteria governing Lake Superior outflow regulation.

2.1.3 Overview of the Strategy

The IJC's Directive to the Study Board called for an examination of the changing conditions in the water levels of the upper Great Lakes system, an understanding of the key interests served by that system, and the identification and evaluation of options to regulate water levels while balancing the needs of the interests. Addressing these closely related issues required a thorough analysis of past, present and possible future hydrological conditions in the system and an effective approach to testing regulation options in relation to impacts on water levels and flows on the affected interests. The Study Board's strategy to address this mandate evolved considerably during the course the Study.

Figure 2-1 illustrates the major elements of the Study Board's overall strategy:

- *hydroclimatic modelling* that informed the formation and evaluation of regulation plan options (see **Chapter 4** for details);
- a comprehensive approach to *regulation plan formulation and evaluation* based on a *shared vision planning* process that sought to ensure a balancing of the many interests served by the upper Great Lakes system (**Chapters 5 and 6**);
- consideration of *restoration* and *multi-lake regulation* as potential alternatives for dealing with extreme conditions beyond those addressed by Lake Superior regulation alone (**Chapters 7 and 8**); and,
- a focus on the potential for *adaptive management* to help the interests better anticipate and respond to extreme water levels in the future (**Chapter 9**) and on an *information management plan* to ensure that the data and other information collected and generated by the Study remain available for future researchers, planners and decision makers.

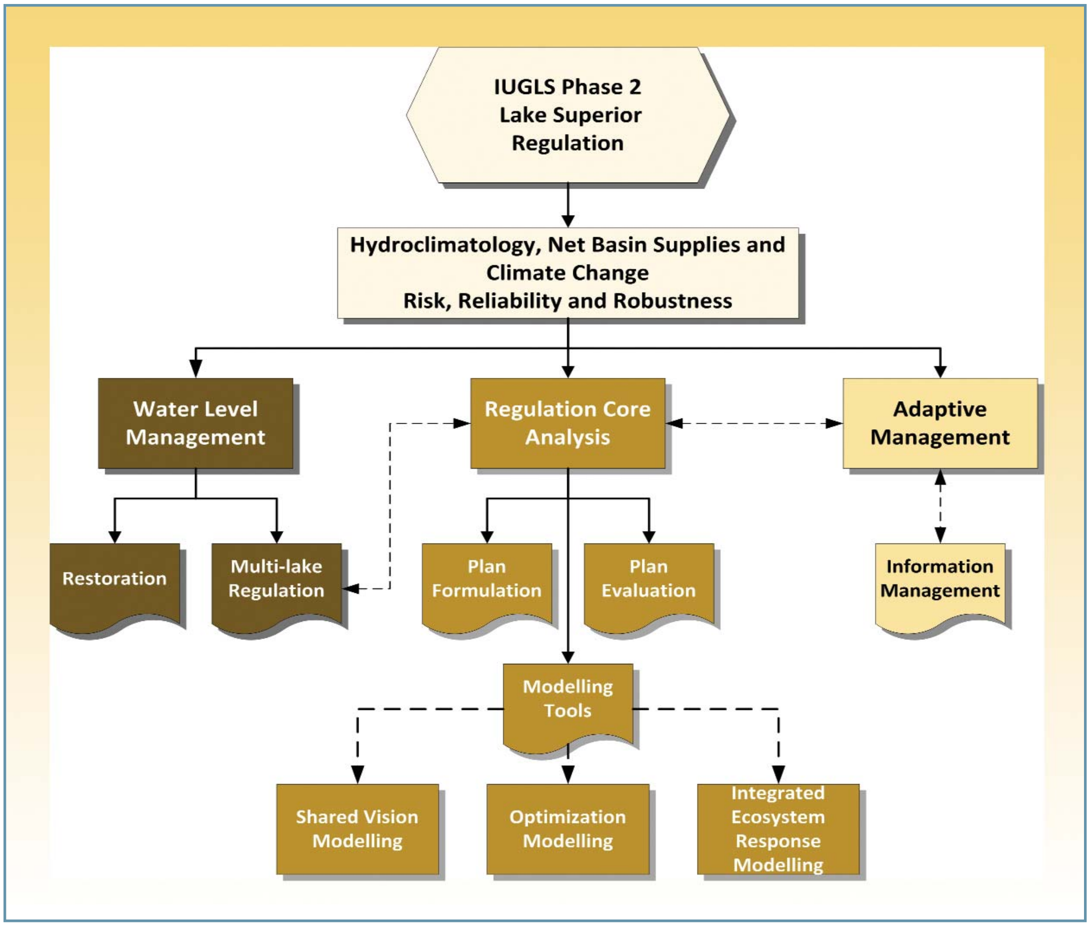


Figure 2-1 **Overall Study Strategy**

Strategy Development Documents

The Study's strategic approach was thoroughly vetted, and the following independently peer-reviewed reports[2] served to guide the Study:

- *Plan of Study* (International Upper Great Lakes Study [Upper Lakes Plan of Study Revision Team], 2005);
- *Strategic Framework and Work Plan for the International Upper Great Lakes Study* (International Upper Great Lakes Study Board, 2007);
- *Hydrology and Climate Modelling Strategy* (IUGLS, 2008);
- *The Formulation and Evaluation of Lake Superior Regulation Plans for the International Upper Great Lakes Levels Study* (IUGLS, 2009a);
- *Socio-Economic Sector Evaluations of Lake Superior Regulation Plans for the International Upper Great Lakes Levels Study* (IUGLS, 2009b); and,
- *The Ecological Evaluation of Lake Superior Regulation Plans for the International Upper Great Lakes Levels Study* (IUGLS, 2009c).

Peer review of these planning documents provided important independent insight and feedback very early on in the Study, allowing the Study Board to refine and strengthen its overall approach to addressing its mandate.

Initial Strategy

Initially, the strategy focused on the specific issues related to Lake Superior outflow regulation. In the 2005 Plan of Study, the Study's objectives were identified as:

- reviewing how Lake Superior outflow regulation and the operation of the control structures affect water levels and flows in the upper Great Lakes system;
- identifying potential updates and improvements to the criteria, requirements, operating rules and outflow limits as well as incorporating operating experience to the regulation plan;
- reviewing current institutional arrangements governing Lake Superior outflow regulation; and,
- testing regulation plan performance under climate variability and climate change scenarios.

2 Available at www.iugls.org

Inherent in the first objective are the physical impacts from water levels and flows, the associated economic benefits and costs, and resulting environmental improvements and degradations. Similarly, the last objective requires a sound understanding of future climate variability and change so as to better estimate possible water supply conditions in the basin. Thus, the Study Board determined that the Study should address both economic and environmental impacts along with the possible implications of climate variability and change on water levels and flows.

Large-scale water management studies often require a relatively long planning horizon of 30 to 50 years, particularly when evaluating potential impacts arising from climate change and climate variability. Historical hydroclimatic and water level records are used as a demonstrated basis for developing relationships between climate, water supplies, and water level regulation. In addition, projections of future climate and hydroclimatic conditions have several uncertainty components. Thus, the availability of information of climate studies by others has a strong bearing on setting a planning horizon.

In the case of Great Lakes climate change studies, the Study found that the time focus of information typically was between the years 2040 and 2090. Initially, the Study was also considering economic and ecosystem impacts over a similar timeframe. Furthermore, the life of a typical regulation plan is from 20 to 30 years. Considering these factors, the Study Board at the outset decided to develop a regulation plan with a planning horizon to the year 2040.

Balancing of Interests

Under the *Boundary Waters Treaty of 1909*, *domestic and sanitary water uses, navigation*, and *power*[3] *and irrigation* are given order of preference. These uses must be taken into account in developing regulation plans. In light of the IJC's Directive to consider the "evolving needs of the many interests served" by the upper Great Lakes system, the Study Board determined that in evaluating regulation plan options, the Study would take into account the needs of all Great Lakes interests, including those not explicitly referenced in the 1909 Treaty. These include ecosystems, coastal zone and recreational boating and tourism interests, all of which are now recognized as being important users of the system. **Chapter 3** provides more details, focusing on the implications of changing water levels and flows on these key upper Great Lakes interests.

The fundamental objective with regard to the needs of the interests would be the *principle of balancing* that now characterizes the IJC's approach to water management – that is, providing benefits or relief to interests affected by water levels and flows without causing undue detriment to other interests.

3 In interpreting the Treaty, "power" is taken to mean hydroelectric generation.

Key Considerations

The Study's strategy evolved as the limits to Lake Superior outflow regulation became clearer in the preliminary analysis. Through the development of the fencepost plans, in which a single interest or lake was favoured at the expense of other interests (see **Chapter 5** for details), the Study's analysis demonstrated that the existing Lake Superior regulation plan has limited ability to affect the levels of Lake Michigan-Huron. As a result, the Study Board concluded that any changes to regulation were more likely to be relatively minor and that major tradeoffs among interests and regions would not be a significant issue in the development of a new regulation plan.

In addition, through expert workshops, the Study Board recognized that the impacts of climate change and climate variability on future water levels would introduce considerable uncertainty to any regulation effort. This uncertainty, together with the limited influence of any Lake Superior regulation plan, particularly on Lake Michigan-Huron water levels, necessitated a reassessment of the strategy. 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[4], and consider alternative approaches for managing and adapting to uncertain future water level conditions.

Alternative Approaches: Multi-lake Regulation and Restoration

In October 2009, the Study Board sought direction from the IJC on the extent to which the Study should address *multi-lake regulation* – the possibility of operating regulation structures to benefit the Great Lakes-St. Lawrence River system *as a whole*. The IJC responded in a letter to the Study Board in April 2010, after consulting with governments. The IJC gave its approval for the Study to conduct the examination of climate change impacts on water levels and 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."*

Chapter 8 outlines the Study's analysis of the feasibility and implications of addressing extreme high and low water levels by means of multi-lake regulation.

In August 2010, the IJC provided further guidance to the Study Board by asking it to investigate methods and impacts of restoring Lake Michigan-Huron water levels as potential compensation for past lowering caused by natural and human-induced changes in the St. Clair River. The restoration analysis would include a description of possible structures

4 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.

that would be capable of restoring Lake Michigan-Huron water levels by various amounts, as well as the implications on interests throughout the Great Lakes-St. Lawrence River system. The IJC did not request that the Study Board make any recommendation as to implementing a particular restoration option. Rather, it directed that the restoration analysis: *"… provide Governments and the public with extremely valuable information and insight to help form the basis for rational and scientifically-based decision making"*.

The IJC's Directive regarding the restoration analysis emphasized the exploratory nature of the evaluation and the need for public engagement on the subject. The Study Board was also directed to include the findings in its final report. While exploratory in nature, the restoration analysis required the consideration of several components and integrating them into meaningful conclusions. **Chapter 7** outlines the Study's analysis of the feasibility and implications of raising water levels of Lake Michigan-Huron by means of restoration structures in the St. Clair River.

Adaptive Management

The initial analysis establishing the limits of Lake Superior regulation delivered two important conclusions. First, given climate variability, the limits of regulation, and the need to balance the needs of a wide range of interests, a new regulation plan would be able to provide only small improvements over plan **1977A** in terms of addressing water level risks in the upper Great Lakes. Second, a significant portion of the risks associated with changing water levels and flows would not be addressed unless a coordinated complementary adaptive management plan was implemented.

This finding led to a third key change in the Study Board's strategy. The Study Board sought and received the IJC's support to expand the scope of the Study's work to include a more comprehensive consideration of adaptive management. **Chapter 9** outlines the Study's analysis of the role that adaptive management can play in addressing future extreme water levels.

2.2 Analytical Frameworks

This section provides an overview of the analytical frameworks the Study Board used to address future hydroclimatic and water level conditions and to guide the formulation and evaluation of options for a new regulation plan.

2.2.1 Hydroclimatic Analytical Framework

Chapter 4 presents the analysis and findings of the Study's work on the hydroclimatic conditions of the upper Great Lakes basin, with a particular focus on the possible impacts of climate variability and climate change on future water levels.

The hydroclimatic analysis of the Study addressed two primary science questions:

- *What are the historical estimates of net basin supplies*[5] *(NBS) in the upper Great Lakes and how have any potential changes to the water balance components affected the level of the lakes?*
- *What potential impacts could natural variations in the climate system and anthropogenic (human)-induced climate change have on any future regulations of the upper Great Lakes?*

Analysis of hydroclimatic data and generation of future water supply conditions in the basin were the core initial elements of the Study. The results of this work formed the basis for the balance of the Study's work on regulation plan formulation and evaluation and consideration of alternative approaches to addressing uncertainty in future water levels and flows.

Figure 2-2 illustrates the three themes that were central to Study Board's analytical framework for conducting the hydroclimatic analytical and modelling studies:

- **understanding the water balance of the Great Lakes;**
- **assessing the reliability of historical recorded and estimated data, and increasing understanding of potential water supply conditions through the use of paleo[6]-information and stochastic[7] analysis; and,**
- **addressing the plausibility and scope of climate change impacts on water supplies through new modelling work.**

Understanding the Water Balance of the Great Lakes

The first science question was addressed through investigation and evaluation of existing methodologies used in the determination of contemporary estimates of the water balance. A water balance is an accounting of all water entering and leaving a given body of water, for a given period of time. This can be expressed as "*inflow equals outflow plus change in storage*." A water balance is quantified through the evaluation and accounting of these three major components.

The Study first undertook an assessment of contemporary estimates of the water balance, their uncertainty and methodological approaches. When this assessment was

5 Net basin supply (NBS) is the net amount of water entering each Great Lake resulting from precipitation falling directly on the lake surface, runoff to the lake from the surrounding drainage basin, and evaporation from the lake. It does not include the inflow from the upstream Great Lake or any diversions.

6 *Paleo* – A combining form meaning "old" or "ancient," especially in reference to former geologic time periods, used in the formation of compound words, as in *paleo-hydrology*.

7 *Stochastic* – Statistics involving or showing random behaviour. In a stochastic simulation, a model is used to create a new 'synthetic' series of plausible flows and lake levels, based on historical data. The synthetic series will, on average, preserve important properties of the historical record, such as the mean and standard deviation, while generating new combinations of high and low flow conditions that could represent more severe conditions than those seen in the past.

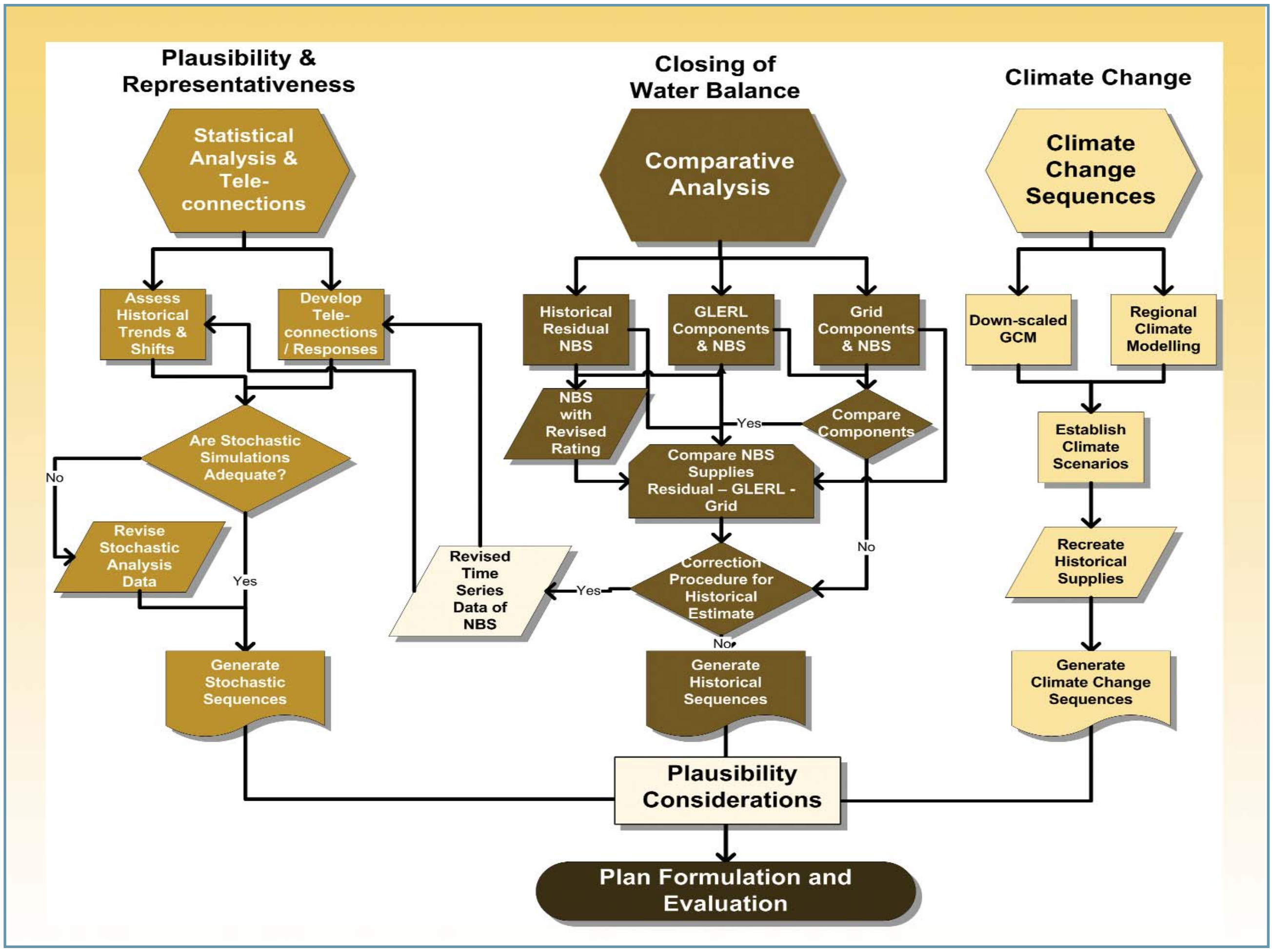


Figure 2-2 **Hydroclimatic Analytical Framework**

completed and the best estimates of the water balance established, the next task was to attribute changes in water supplies to lake levels, quantifying the level of uncertainty. Trend analyses and teleconnection studies[8] were performed to assist in identifying the causative factors related to any changes in the upper lakes water supplies. Finally, the analysis:

- described the uncertainty of the water balance components relative to one another;
- assessed the impact of uncertainty on the attribution of water supply changes to lake levels; and,
- determined the effect of NBS on the change in lake level relationship.

Assessing the Reliability of Historical Recorded and Estimated Data

The physical basis for understanding possible future water level extremes has largely been derived from analysis of climate change and climate model simulations. However, the Study Board determined that scientific approaches in addition to modelling should be explored to provide information relative to possible future events. This would provide a greater range of possible conditions for consideration and alert investigators to any inconsistencies between model projections and the climates of the past. Two important approaches were paleo-investigations and stochastic analysis:

- Paleo-water supply sequences extending back in time prior to the past 109 years for which recorded data are available provide valuable information with regards to possible climate extremes. The Study's investigation focused on existing paleo-data, primarily tree ring and beach ridge data.
- Stochastic models generate water supply sequences that reproduce key statistical characteristics of historical observations, resulting in alternative plausible sequences of water supplies, including rare and potentially catastrophic events, not seen in the brief historical record. These sequences can be used in statistical analysis and regulation plan evaluation.

8 The study of climate anomalies related to each other over large distances, typically thousands of kilometres.

Plausibility and Scope of Climate Change Impacts

Anthropogenic forcing of the climate system due to increasing concentrations of carbon dioxide and other greenhouse gases increases the probability that future conditions in the upper Great Lakes basin will be outside the envelope of conditions that have been historically observed (IPCC 2007). As such, the Study employed a number of approaches to address the possible impacts of climate change on future hydrological conditions in the basin.

Two regional climate models were utilized to down-scale possible global climate scenarios and derive and assess current and possible future water supply sequences. The method used to accomplish this was a standard nested modelling approach forcing the established United States and Canadian regional climate models (Coupled Hydrologic Atmospheric Research Model – CHARM and the Canadian Regional Climate Model – CRCM, respectively) by using several Global Climate Models (GCMs[9]) to provide boundary conditions. In this way, the interaction between the lakes and the atmosphere can be taken into account in interpolating the GCM results, as opposed to statistical methods to derive important climate forcing that will impact the water cycle. A set of possible future states of the climate system was derived using these methods.

2.2.2 Regulation Plan Analytical Framework

Chapters 5 and **6** present the analysis, findings and recommendations of the Study's work to formulate and evaluate new regulation plans for Lake Superior outflows. Figure 2-3 illustrates the Study Board's analytical framework for this task.

The Study Board determined that any change to the IJC's Orders of Approval and regulation plan for Lake Superior outflows must:

- be based on the *best assessment of impacts* that can be done given the relatively small effect that Lake Superior regulation has on water levels, and the length of shoreline of the Great Lakes relative to the budget available for assessment studies;
- address, to the extent possible, *ecological, economic, and social impacts* associated with the regulation of outflows from Lake Superior;
- *balance the needs of the various interests*, specifically by minimizing disproportionate losses to all interests and regions, including disproportionate water level changes on one lake at the expense of another; and,
- provide *robustness, or flexibility in design*, so that the International Lake Superior Board of Control and the IJC can respond to unusual or unexpected conditions affecting the Great Lakes system.

Evaluation Framework

The Study developed an evaluation framework in which regulation plan options were quantitatively evaluated by measuring the success in meeting stated goals and objectives. These steps were followed iteratively to develop a wide range of metrics that the Study Board used to gauge progress towards meetings its plan objectives:

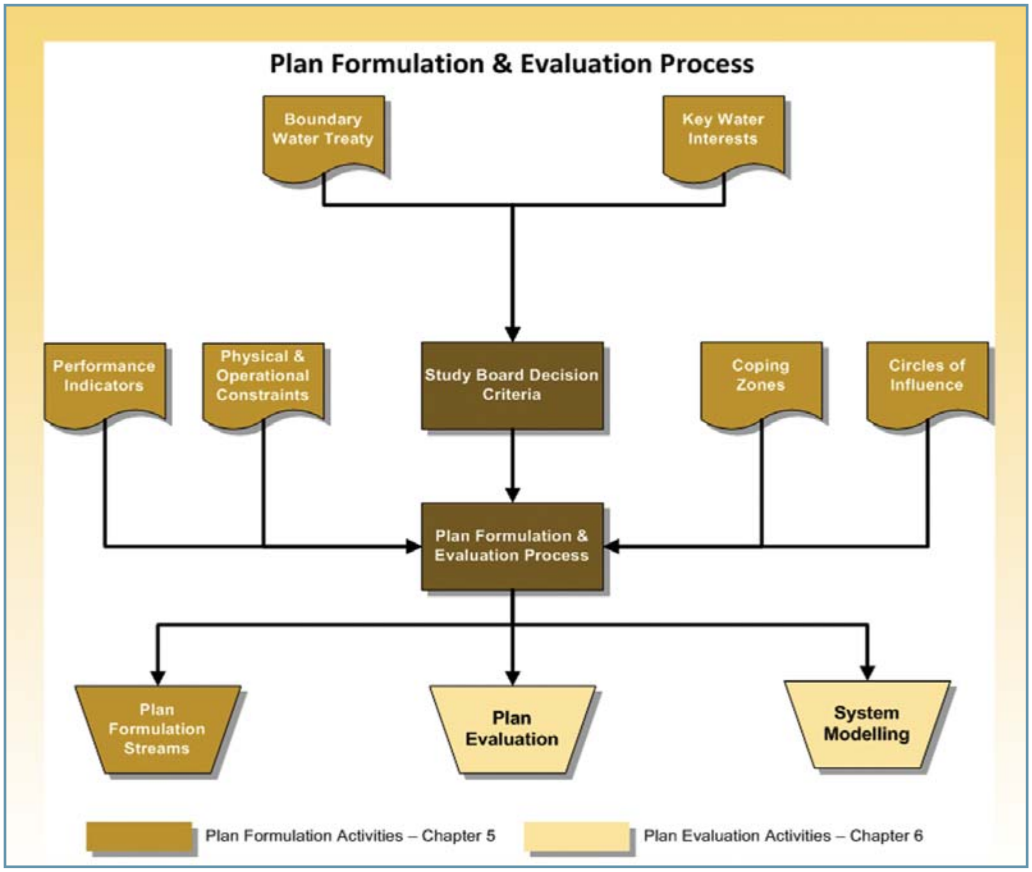


Figure 2-3 ***Regulation Plan Analytical Framework***

9 Also known as General Circulation Models and Global Circulation Models.

- articulation of Study planning objectives and review of existing criteria;
- identification of water level and flow metrics;
- identification of *performance indicators* (PIs) for each interest;
- review of functional relationship between PIs and selected hydrological attributes;
- generation of time series of PI values;
- establishment of a method for generating composite values of the simplest hydrological metrics to express areal extent, frequency, severity, duration and persistence;
- establishment of a method for the summation, display and comparison of composite PI values; and,
- establishment of *coping zones* for each water interest to help assess impacts.

Performance Indicators

The evaluation framework focused on relating lake level fluctuations and critical threshold levels directly to economic productivity. This was accomplished through the use of PIs, conventional economic information and metrics routinely used for traditional benefit-cost analysis. These PIs were then used to compare and evaluate the relative performance of each economic sector or interest (*e.g.*, hydropower, commercial navigation, recreational boating and tourism) under the range of historical and anticipated lake level fluctuations across all sectors and lakes.

Each of the six interest-specific TWGs was responsible for identifying specific PIs to be applied in measuring plan performance relative to its interest. Not all of the PIs were required to be quantifiable in dollar terms, but all needed to be significant to the interest they represent, measurable, and sensitive to changes in a regulation plan.

It was recognized that data limitations would be a problem in analyzing impacts on several of the interests. For example, data were readily available for hydropower and commercial navigation interests to support the development of appropriate PIs (*e.g.*, the estimated quantity and the projected present value of hydroelectric energy produced at the St. Marys River plants, and the impacts of lake levels and flows on the efficiency of shipping). For other interests (including coastal zone, recreational boating and tourism, and municipal and industrial water supply interests), the Study Board undertook a *representative site analysis* approach, in which key areas around the lakes that most clearly reflected the range of economic activities were selected to serve as proxies for those interests. For ecosystem interests, ecosystem indicators were developed to address the integrity and sustainability of specific ecosystem components.

Coping Zones

The Study also applied the concept of *coping zones* to evaluate regulation plan options. Each TWG developed a range of coping zones for its specific interest that assessed vulnerability to water level fluctuations as well as confounding factors such as GIA, wind/waves/storm surges and precipitation patterns. Each TWG identified three levels of progressively more challenging water level conditions for the interest:

- *Zone A:* a range of water level conditions that the interest would find tolerable;
- *Zone B:* a range of water level conditions that would have unfavourable though not irreversible impacts on the interest; and,
- *Zone C:* a range of water level conditions that would have severe, long-lasting or permanent adverse impacts on the interest.

2.2.3 Shared Vision Planning and Decision Making

Shared vision planning helped the Study Board formulate and evaluate alternative regulation plans in an open manner. This planning process is of particular value in situations when there likely will be multiple decision makers with shared responsibility for a basin, and the decision possibilities more often include changes in behavior rather than investment in new construction.

Through shared vision planning, interested parties are able to consider the estimated consequences of water management decisions before any decision is made. They are able to review and evaluate various criteria and learn about potential impacts on water levels and flows on the various interest groups under different regulation plans. Shared vision planning requires the collaborative construction of a single and relatively simple model of the entire system under study, with explicit links between the experts, researchers and the decision makers' decision criteria.

In evaluating regulation plan options and developing its final recommendations to the IJC, the Study Board undertook a series of practice decisions so as to articulate its decision factors early. Study Board members were then able to refine these factors as they became more familiar with the research conclusions and the dialogue involving impacts and tradeoffs among the interests in each practice decision. As applied in the Study, these rounds of practice decisions stimulated debate about how to balance competing interests, allowed the Study Board to focus on one part of the decision at a time, and gave the Study Board the opportunity to identify the key pieces of information needed to help with its decision.

2.3 Information Management

The Study Board recognized that the Study's five years of research and analysis would generate a number of reports and large quantities of purchased, acquired and leveraged data and information, models and associated documentation. This collection represents a significant legacy of the Study. As a result, the Study Board adopted the following management goal with regard to information management:

> "*The Study Board encourages unrestricted access to data. Data collected by the International Upper Great Lakes Study will be made available on-line once it has been approved for distribution by the Study Board. Most of the data collected by the Study will be readily available to the general public by the completion of the Study, scheduled for early 2012. However, limited data will be protected and not be distributed, such as in cases of proprietary information or national security sensitivities.*" (IUGLS, 2011)

The Study Board established an Information Management Technical Work Group (TWG) to address the information management needs of the Study. This TWG was tasked with developing options and recommendations for the archiving and dissemination of the Study's data assets. Based on the TWG's recommendations, the Study Board established the Information Management and Dissemination Business System to provide external parties with access to the Study's data and information to help meet water level research and management objectives (Figure 2-4).

The Information Management TWG also developed a web-based dynamic decision-mapping system to ensure the transparency of the Study Board's decisions.

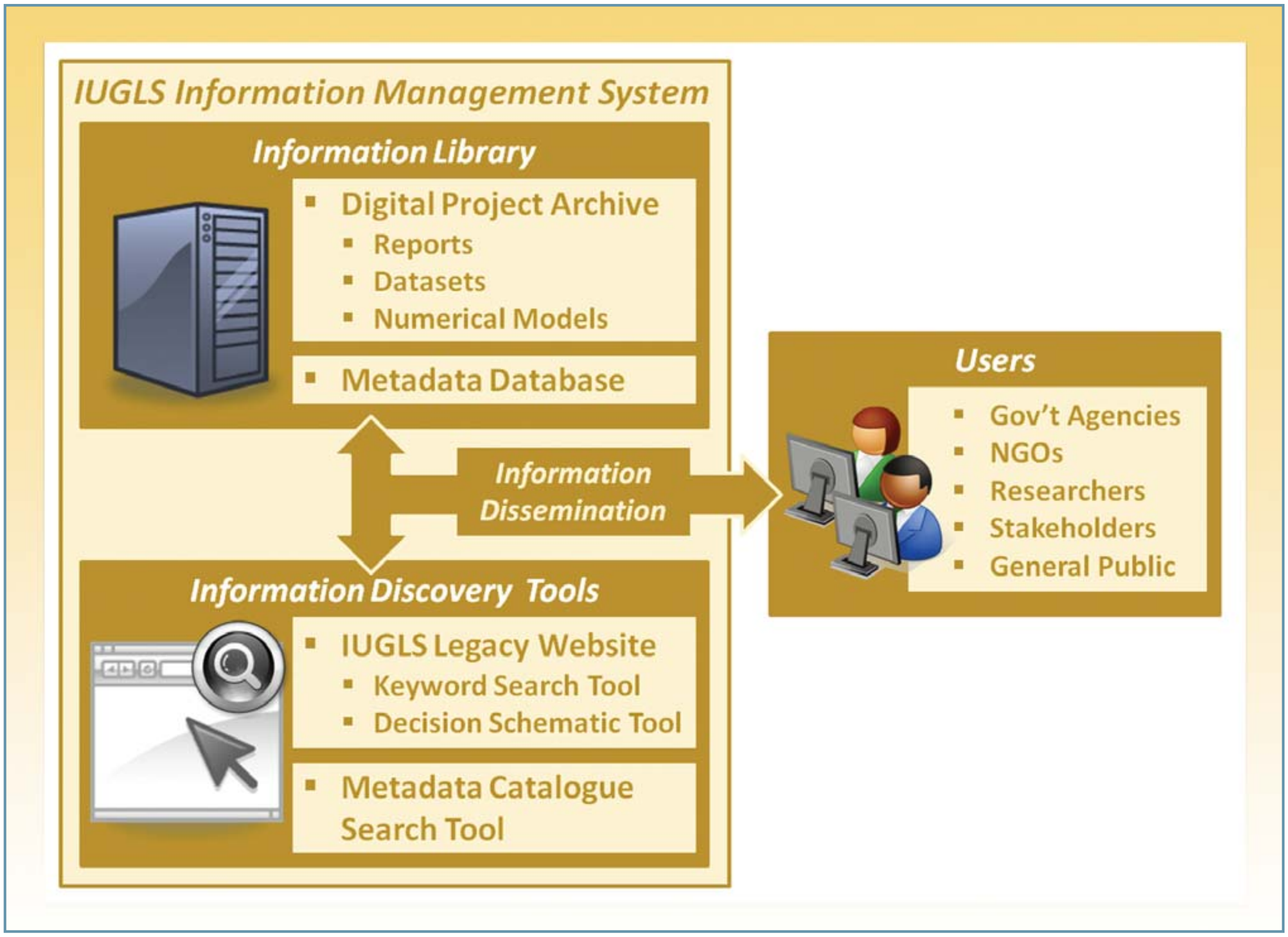


Figure 2-4 ***Overview of the Information Management and Dissemination Business System***

2.4 Key Points

With respect to the strategy applied by the Study Board to address Lake Superior regulation and upper Great Lakes water levels, the following points can be made:

- The Study was the third comprehensive assessment in the last 40 years to address a recurring challenge in the upper Great Lakes system: *how to manage fluctuating lake levels in the face of uncertainty over future water supplies to the basin while seeking to balance the needs of those interests served by the system.*
- Peer review of Study planning documents provided important independent insight and feedback very early on, allowing the Study Board to refine and strengthen its overall approach to addressing its mandate.
- The Study's strategy evolved as the limits to Lake Superior outflow regulation became clearer in the preliminary analysis. 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. These approaches included multi-lake regulation, restoration structures and adaptive management.
- Analytical frameworks were developed to address the two central tasks: understanding past, present and future hydroclimatic conditions and the associated impacts on upper Great Lakes water levels; and, formulating and evaluating alternative regulation plans.
- A planning process known as shared vision planning allowed interested parties to collaboratively consider the estimated consequences of different regulation plans before any decisions are made.
- In evaluating plan options and developing its final recommendations to the IJC, the Study Board undertook a series of practice decisions. These practice decisions allowed it refine the decision over time as it became more familiar with the research conclusions and the tradeoffs among the interests in each practice decision.
- The Study Board recognized that the Study's reports, data, models and associated documentation represent a significant legacy of the Study. The Study Board established an Information Management and Dissemination Business System to provide future researchers, water managers and other parties with access to the Study's data and information.

Chapter 3

Key Interests in the Upper Great Lakes

3

Chapter 3 provides an overview of the key interests likely to be affected by possible future changes in water levels in the upper Great Lakes basin. The chapter reviews the current and emerging socio-economic conditions of each interest and identifies the likely consequences of future extreme water levels.

3.1 Introduction

3.1.1 The Key Interests Served by the Upper Great Lakes System

Future changes in water levels in the upper Great Lakes basin will affect a complex and interrelated network of individual, institutional and commercial interests. From residents of the region who depend on the lakes for drinking water and hydroelectricity, to tourists who use the beaches and marinas, to major industries that rely on the Great Lakes fleet to move their raw commodities and finished products – all will be affected, whether future levels rise or fall.

Understanding how the region's interests may be affected by future changes in Great Lakes water levels, particularly in the context of other drivers of change, is a critical step in developing a fair and effective new regulation plan for Lake Superior and the upper Great Lakes.

Under the *Boundary Waters Treaty of 1909*, *domestic and sanitary water uses, navigation*, and *power*[1] *and irrigation* are given order of preference. These uses must be taken into account in developing regulation plans. No mention was made in 1909 of interests that are now recognized as playing an important role in supporting a healthy and vibrant Great Lakes, such as ecosystems, coastal zone uses and recreational and tourism uses. However, the Treaty does require that the International Joint Commission (IJC) consider impacts on "any interests on either side of the boundary." That is, these other interests have rights under the Treaty, as well, consistent with the IJC's balancing principle – providing benefits or relief to interests affected by water levels and flows without causing undue detriment to other interests.

1 In interpreting the Treaty, "power" is taken to mean hydroelectric power.

With this in mind, the the International Great Lakes Study (the Study) commissioned detailed analyses of the current and emerging conditions and perspectives of six key interests likely to be affected by possible future changes in water levels in the upper Great Lakes basin. The detailed analyses were prepared by technical work groups, with membership drawn from scientists, engineers and interest group representatives from the United States and Canada.

The six interests examined in the Study were:

1. **Domestic, Municipal and Industrial Water Uses**
2. **Commercial Navigation**
3. **Hydroelectric Generation**
4. **Ecosystems**
5. **Coastal Zone**
6. **Recreational Boating and Tourism.**

For each of the six interests, this chapter:

- summarizes the *socio-economic context* for the interest, including important values and perceptions; and,
- identifies the likely *consequences*, if any, for the interest of changing water levels, together with the prospects for the interest to address these risks through *adaptive behavior and response*.

The Study recognized that indigenous First Nations in Canada, Native American tribes in the United States, and Métis represent a unique perspective in the upper Great Lakes. With respect to changing water levels, their concerns cut across the Domestic Water Users, Coastal Zone and, in particular, Ecosystems interests investigated in detail. Study Board members engaged a number of First Nations and

Native American tribes through workshops and other outreach activities to identify their issues and concerns with respect to Great Lakes water levels. In addition, a member of a Native American tribe with extensive experience in Great Lakes water issues was a member of the PIAG. Section 3.8 provides an overview of the perspectives of indigenous peoples on water management in the Great Lakes basin.

The Study challenge was to address the competing needs of these different interests (Figure 3-1).

Figure 3-1 ***An Integrated View of the Interests Served by the Waters of the Upper Great Lakes***

3.1.2 Socio-economic Overview of the Study Area

Nearly 45 million people live and work in the Great Lakes region of the United States and Canada including about 25.7 million people in the Study's area of the upper Great Lakes basin (CDM, 2010). Population in the Great Lakes basin is projected to increase by about 14 percent, or 6.3 million people, between 2010 and 2040. In the United States, much of this population growth is expected to be concentrated near existing major cities along the shorelines of Lakes Michigan-Huron and Erie. Projections indicate that some rural and remote counties, including those along Lake Superior and northern sections of Lake Michigan-Huron, may experience population decreases. Similar patterns are expected along the Canadian shoreline, though comparable data projections are not available. Population also is expected to increase in some areas adjacent to the actual basin region that depend on water withdrawals from one of the lakes (*e.g.*, northeastern Illinois).

The upper Great Lakes region is undergoing an economic transition from its traditional industrial manufacturing focus. Major sectors such as automobile manufacturing and iron and steel production have declined. Total employment has slowed relative to recent trends. Household incomes and municipal taxes have declined, particularly on the United States side of the Great Lakes. These changes, in turn, affect demand for shipping, energy and recreation. Broader global economic forces are directly affecting economic activity in the region as well. For example, a shift in North American grain export markets over the past decade, away from Europe and towards Asia, has meant that more grain is being transported by rail to West Coast ports, reducing shipments through the Great Lakes.

What the region's economy transitions to would only be speculation and beyond the Study's mandate. Over the longer term, based on what are seen as dependable, readily-available water resources, the region could see the rise of new, more water-intensive industries in the upper Great Lakes, such as irrigated agriculture, biofuels, and oilsands refining.

3.2 Domestic, Municipal and Industrial Water Uses Interests[2]

Domestic, municipal and industrial water uses interest represent public and private sector organizations using water for domestic, municipal and industrial purposes, including owners/operators of water and wastewater treatment facilities, coal-fired and nuclear power stations, agricultural operations relying on irrigation, and large industrial plants, such as mines, paper manufacturers and chemical plants.

The *Boundary Waters Treaty of 1909* lists *domestic and sanitary uses* first in the order of precedence.

2 This section is based on the *Contextual Narrative Report*, Domestic, Municipal and Industrial Water Uses Technical Work Group (International Upper Great Lakes Study [IUGLS], 2011a). All data used in this section are taken from and referenced in that report.

3.2.1 Overview

Total water withdrawals in the upper Great Lakes basin are about 112,000 ML/day (29,800 Mgal/day). Four major uses account for about 98 percent of the water withdrawals in the upper Great Lakes basin: thermoelectric power generation (75 percent); industrial uses (13 percent); public supplies (9 percent); and, irrigation (1 percent). Most of this water is returned to the basin. Consumptive uses (that is, uses that do not return water to the system) account for less than 1 percent of the outflows.

No single group represents all water users. Rather, water use interests are represented by a diverse range of organizations concerned about how water use affects their own particular constituents. In the case of Great Lakes water uses, these groups include manufacturing associations, environmental groups, electric utilities, public water suppliers, wastewater managers, chambers of commerce, home builders, and companies involved in the aggregate, industrial minerals and chemical industries.

In general, population growth is expected to have only a moderate impact on water uses in the region, as per capita usage of water tends to decline with population growth. However, as urban growth continues in nearby areas not adjacent to the lakes and connecting channels, there may be increased pressure to withdraw water from these Great Lakes sources if no other viable sources of public supply are available.

Changes in energy production patterns could affect future water use. For example, from 1985 to 2005, water withdrawals for fossil fuel and nuclear thermoelectric generation decreased in the United States portion of the Great Lakes Basin. Recent projections suggest that fossil fuel thermoelectric water withdrawals may increase slightly on the United States side from 2010 to 2030, while nuclear thermoelectric water withdrawals may decrease slightly. Ontario's long-term plans to close several coal-fired power plants would reduce water withdrawals from the lakes, as well, though water consumption could increase if coal-fired plants are replaced by nuclear power plants.

The dominant value of water users along the upper Great Lakes is focused on long-term security of supply, though the nature of their perceptions varies depending on the water use:

- the majority of water users in the basin strongly support state and provincial government efforts to prohibit diversion of water out of the Great Lakes basin;
- many residents using public water supply systems believe that the water "should always be there when they turn on the tap"; and,
- owner/operators of industrial and thermoelectric facilities want to be confident that government regulations do not significantly interfere with their legal access to water; they tend to monitor lake levels closely and adjust plant operations accordingly.

3.2.2 Implications of Changing Great Lakes Water Levels

Potential Impacts

Secure access to clean freshwater has been a driver in development along the Great Lakes. Water withdrawals remain critical for metropolitan areas, customers of public supply facilities, agricultural facilities, and the general industry of the upper Great Lakes. Potential water supply interruptions, therefore, are a concern for the Great Lakes population. Even temporary interruptions can have serious health and financial implications.

Changing lake levels may impact each water withdrawal facility differently, depending, among other factors, on the location of the facility, the infrastructure of the intake, and the amount of water withdrawn.

High water conditions in the past have not been a significant problem for water withdrawal facilities in the upper Great Lakes basin. Some facilities have experienced problems with flooding of buildings, tunnels and property, as well as shoreline damages. High water conditions also can affect wastewater treatment plants by increasing the infiltration into the plant, thus increasing the demand for water and temporarily increasing treatment costs.

Lower lake levels can lead to insufficient water depths at intakes, water quality and navigation problems at water withdrawal facilities, damage to equipment, more problems with algae at intakes, and wells not being deep enough during high demand periods. These problems would be made more difficult by rising water temperatures in the changing climate.

Some facilities have been affected by short term, lower lake levels associated with seiches[3] and blockage of intakes in the winter by frazil ice[4] during low water conditions.

Adaptive Behavior and Response

Water use facilities in the region generally have adapted to varying lake levels over the past century (Figures 3-2, 3-3). However, these facilities may have to change operations or infrastructure to adapt to any changes in water levels significantly above or below historical levels.

How the various water use sectors adapt depends on how much lead time they have, how long the condition will last, the severity of the condition, and the nature of the intake structure. The risk associated with extreme events, such as wind set-up and following seiches, is significant if these events are not predicted and addressed through contingency plans.

3 *Seiche* is an oscillation of the lake surface caused by local variations in atmospheric pressure and winds resulting in temporary extremely high levels at one end of a lake and extremely low levels at the other.

4 *Frazil ice* consists of a slush-like collection of ice crystals that can adhere to and damage objects in extremely cold water.

Figure 3-2 **Water Treatment Plant – Racine, WI**

To adapt to high water conditions, some facilities can install flood-proof equipment, install a new shore shaft building at a higher elevation, add to the shorewall height, or construct flood levees.

For low water conditions, facilities may need to extend or alter intake pipe and structures, look for new water sources, reduce intake flows, install new pumps, set up an alternative supply system, or place buoys to prevent ships from hitting the intakes.

3.3 Commercial Navigation Interests[5]

Commercial navigation interests represent owners/operators of the United States and Canadian fleets of bulk carriers, tankers, barges and other commercial ships transporting goods in the Great Lakes-St. Lawrence Seaway system, as well as ocean-going cargo vessels that use the system.[6]

The *Boundary Waters Treaty of 1909* lists *navigation* second in the order of precedence.

3.3.1 Overview

The Great Lakes-St. Lawrence Seaway system for commercial navigation stretches 3,700 km (2,300 mi) from the Atlantic Ocean to the head of Lake Superior. Navigation has been facilitated by construction of the St. Lawrence Seaway, the Welland Canal and the locks at Sault Ste. Marie, MI, and by dredging and other improvements.

The system is particularly competitive in the carrying of bulk cargo. About 50 percent of Great Lakes commodity shipments pass through the Sault Ste. Marie locks. In 2007, three commodity groups accounted for nearly 88 percent of total shipments, by volume, through the locks: iron ore (54 percent); coal (24 percent); and wheat (10 percent). The locks are closed from mid-January to late March, because of winter ice conditions.

The demand for shipping is a derived demand – that is, derived from the demand for the products of the industries served by shipping. The demand for iron ore, for example, is derived from the demand for steel, which in turn, is derived from the demand for those products using steel in their manufacture, such as automobiles. Similarly, the future demand for coal shipments will depend primarily on the use of coal for electricity generation. As a result, future trends in commercial navigation in the Great Lakes

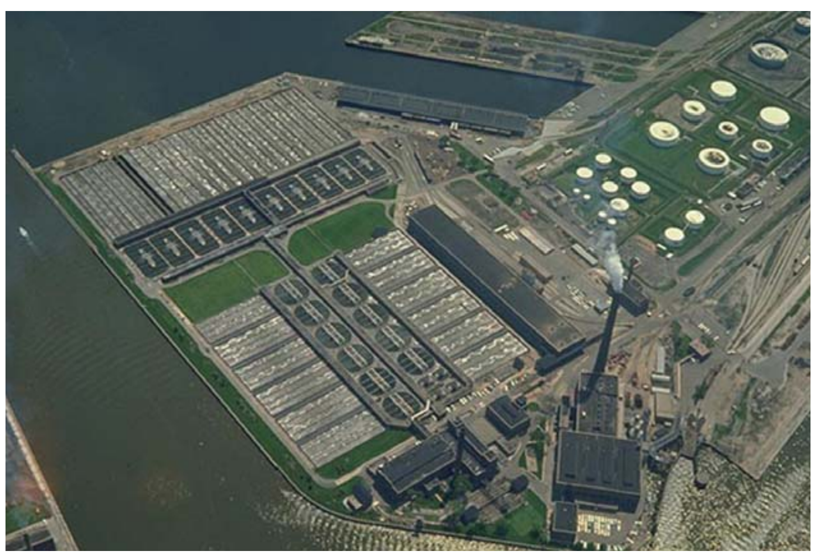


Figure 3-3 **Wastewater Treatment Plant – Milwaukee, WI**

5 This section is based on the *Contextual Narrative Report*, Commercial Navigation Technical Work Group (IUGLS, 2011b). All data used in this section are taken from and referenced in that report.

6 Note that this interest is limited to those companies and other organizations that actually move commodities on the lakes. Secondary or related navigation interests not specifically addressed here include grain, ore, steel and other commodity producers and brokers who contract with the shipping companies.

system are uncertain and will depend largely on the extent and nature of economic growth and industry demand in the region.

Three primary associations represent shipping companies operating on the Great Lakes: the Lake Carriers' Association represents United States-flag vessel operators on the Great Lakes; the Canadian Shipowners Association represents the interests of Canadian companies with domestically-flagged ships; and, the Shipping Federation of Canada represents the interests of shipping companies and their agents involved in Canada's world trade.

A core value of the commercial navigation interest is that it represents an industry essential to the economic and social well being of North America. Members of this interest believe that they provide a strategic, low cost, and environmentally sound means of transporting commodities in an economically significant and heavily populated region of North America. Given the citing of commercial navigation in the 1909 Treaty's order of precedence, there is an expectation that any future regulation plan will continue to recognize and meet the needs of the interest.

3.3.2 Implications of Changing Great Lakes Water Levels

Potential Impacts

Changing water levels have a direct and significant effect on commercial navigation interests, both in the short term and long term (Figure 3-4).

In general, lower water levels will adversely impact the interests more than higher levels. Lake vessels are built and operated to take advantage of available water depths, often operating with minimal under-keel clearances. Ocean-going vessels already typically operate in the Great Lakes and Seaway at less than their maximum cargo capacity. Reductions in water depths will force vessels to operate with reduced loads, thus increasing the number of trips and the total cost of moving a given amount of cargo. Vessel speed reductions, in addition to those currently in force, and stoppages in transit also may be necessary to avoid grounding, further increasing costs.

Higher water levels may allow increased vessel loads, reducing the costs of moving given quantities of cargo. The maximum tonnage of cargo that can be carried, however, is limited by the design capacity of vessels. Higher water levels also can damage and disable loading/unloading facilities, and impact safe operation of navigation locks if levels reach the top of approach walls or lock gates.

For many commodities, alternate modes and routes are available and would become more competitive if the cost of water transport increases. Grain exports, for example, can avoid the Great Lakes by using rail shipments to lower St. Lawrence River ports, western Canadian ports, and the port of Churchill, MB, or, in combination with barge transportation, Gulf of Mexico ports. A similar shift could occur for iron ore, which could be moved by rail or a combination of ocean transport and rail.

A reduction in ice cover as a result of climate change or climate variability may allow a longer navigation season. The resulting increased vessel utilization, reduction in stock-piling, and lower ice-breaking costs may offset some of the increase in transportation costs due to lower water levels. Conversely, if more trips are necessary, then capital expenditures on fleet additions may be required.

Adaptive Behavior and Response

Commercial navigation interests can undertake a range of adaptive measures to deal with both lower and higher water levels. The measures can take two forms: those associated with vessel operation and construction; and external actions, including infrastructure changes.

***Figure 3-4* Commercial Navigation – A Ship Entering the St. Clair River**

Measures associated with vessel operation and construction include:

- revising operating schedules and practices, such as reducing the amount of cargo carried in a vessel, scheduling additional shipments during seasonally high water levels, rerouting shipments to ports less affected by low water levels, and partially unloading at a port with no depth constraints before unloading at a port with limited depths;
- modifying existing vessels; and,
- shifting to newer types of vessels better suited to lower water levels, such as the integrated tug and barge, which are typically cheaper to construct and operate than a self-propelled vessel.

Figure 3-5 Cloverland Hydroelectric Plant – Sault Ste. Marie, MI

In addition, changes to dock facilities and other navigational infrastructure in the Great Lakes system could be undertaken to help commercial navigation adapt to lower or higher water levels. For example, the wooden supports of some docks could be damaged by exposure to air and by dry rot under lower water conditions and may need to be reconstructed. Harbours and connecting channels could be dredged in response to lower water levels (though such actions can be extremely costly and require considerable long-term planning and approval).

3.4 Hydroelectric Generation Interests[7]

Hydroelectric generation interests represent owners/operators of the three hydroelectric generating stations on the St. Marys River as well as the stations on the Niagara River and the Welland Canal.

The *Boundary Waters Treaty of 1909* lists *power* third in the order of precedence.

3.4.1 Overview

There are two hydropower generating stations located on the United States side of the St. Marys River, at Sault Ste. Marie, MI. – the United States government and Cloverland Electric Cooperative (CEC) stations (Figure 3-5). There is one station on the Canadian side, at Sault Ste. Marie, ON, owned and operated by Brookfield Renewable Power (BRP). The three stations on the St. Marys River have a combined capacity of about 115 MW. The *Boundary Waters Treaty of 1909* and the IJC's Orders of Approval govern use of water by hydropower stations along the St. Marys River (see section 1.2.3).

On the Niagara River, two plants located at Lewiston, NY have a total generating capacity of about 3,000 MW. On the Canadian side, two plants located at Queenston, ON have a total generating capacity of about 2,100 MW. These stations generate much more electricity than those on the St. Marys River because of the higher head made possible by the setting along the Niagara Escarpment and the higher flow of the Niagara River. Several smaller generating plants, with a total capacity of about 180 MW, also use the waters of the Welland Canal. The amount of water available for the plants on the Niagara River and Welland Canal depends on Lake Erie's level and its outflow as well as the institutional agreement between Canada and the United States. The *Niagara River Treaty of 1950* has the objectives of ensuring water required for domestic, sanitary and navigation purposes is available, while preserving the scenic beauty of Niagara Falls and allowing for the diversion of water for hydropower purposes. To achieve these objectives, the Chippawa-Grass Island Pool Control Structure was built above Niagara Falls, and its operations are supervised by the IJC's Niagara Board of Control.

Future demand for hydroelectric power in the upper Great Lakes basin will be dependent on a variety of socio-economic factors, including population growth and the scope and nature of future economic activity (*e.g.*, the extent to which new industries are energy-intensive or energy efficient). Policy actions in both Canada and the United States focusing on improving air quality and reducing emissions of greenhouse gases likely would favour an expansion of hydroelectric power generation.

7 This section is based on the *Contextual Narrative Report*, Hydroelectric Generation Technical Work Group (IUGLS, 2011c). All data used in this section are taken from and referenced in that report.

Hydroelectric generation interests hold several key values and perceptions. First, hydroelectric generation is seen as a preferred use of Great Lakes waters, with a long and valued history in the region. Commercial production on both sides of the border on the St. Marys River pre-dates the *1909 Boundary Waters Treat*, and is specifically cited in the 1909 Treaty as third in the order of precedence. Second, hydropower is perceived of as being a relatively less expensive, clean, reliable and renewable source of electricity that does not generate emissions of greenhouse gases.

3.4.2 Implications of Changing Great Lakes Water Levels

Potential Impacts

Water levels in the upper Great Lakes directly affect hydroelectric generation interests, as the amount of electricity that the hydropower stations produce depends on available head (*i.e.*, the difference in water levels upstream and downstream of the plants) and the amount of flow allocated to the stations. In some cases, high water conditions enable hydropower operators to increase power generation. However, very high levels and flows can have adverse impacts on their operations. For example, very high lake outflows can result in “surplus” water spilled through the spillway and thus missed opportunity to generate additional power due to lack of diversion capacity. High flows may necessitate more frequent operations of the gates at a dam (*e.g.*, the St. Marys River compensating works) cause local flooding and generate erosion concerns in power canals and tailrace, and may increase risk to structural integrity of hydropower infrastructure.

Low water conditions have more of an impact on hydroelectric generation, forcing stations to operate below capacity and reducing revenues. Over the longer term, drought, or any event that threatens the long-term, reliable supply of water, is the greatest risk to hydroelectric generation interests. Given the relatively small contribution of these hydropower stations to overall power production in the Midwest and Ontario, periods of lower production in the upper Great Lakes are not expected to adversely affect the stability of the transmission grids on either side of the international border.

Adaptive Behavior and Response

Adaptive response issues with respect to hydroelectric generation interests need to be considered in two categories: adapting to conditions within historical levels; and adapting to conditions outside historical levels.

Over the years, operators of hydroelectric generating stations have demonstrated their ability to adapt to changes in water level conditions and water supply sequences within historical ranges. Examples of these adaptive actions have included:

- maintaining or increasing generating capacity through the refurbishing of units or other electro-mechanical equipment (*e.g.*, installing more efficient runners, turbines and generators);
- promoting the establishment of stable ice formation upstream of the station, and managing frazil ice and ice jams under alternative flow conditions; and,
- modifying peaking and ponding schedules to maintain or increase the amount or value of electricity generation.

If future water levels are outside historical ranges, then the relatively routine adaptive measures cited above no longer will be sufficient. More dramatic adaptations to changing conditions will be warranted. Such measures could include deepening intake canals to increase their conveyance and modification or construction of new dams or other works.

3.5 Ecosystems Interests[8]

Ecosystems interests represent the biological components of the natural environment of the upper Great Lakes basin, together with the ecological services that the natural environment provides to the people who live and work in the region.

3.5.1 Overview

Ecosystems in the upper Great Lakes perform a wide range of economically-important ecological services. These services include: fish production to support commercial fisheries and recreational sport fisheries; waterfowl production; natural resource-based ecotourism; flood control and shoreline protection; and the provision of abundant clean water supplies for municipal and industrial uses.

Numerous non-governmental environmental service and advocacy groups are active in the Great Lakes basin. They serve to build public awareness of and action on environmental issues in the Great Lakes. Various groups promote ecosystem health by advocating for clean water, habitat protection and restoration, elimination of chemical and biological pollutants, and enlightened natural resource protection and management policies within the Great Lakes basin. Major groups active in the basin include: the National Wildlife Federation; Ducks Unlimited; Great Lakes United; the Nature Conservancy; and the Nature Conservancy of Canada.

8 This section is based on the *Contextual Narrative Report*, State of EcosystemsTechnical Work Group (IUGLS, 2011d). All data used in this section are taken from and referenced in that report.

In general, the public in the upper Great Lakes values the Great Lakes ecosystem as a unique and irreplaceable asset, and recognizes that improved water quality and ecosystem health provide overall "quality of life" and socio-economic benefits to the Great Lakes region. There also is a perception that once permanently degraded, the important ecological services and benefits to society that the Great Lakes ecosystem provides may be lost forever.

However, the important role that natural fluctuations in water levels (both short- and long-term) play in maintaining habitat diversity and critical ecological functions in the Great Lakes generally is not well understood by the public. Rather, "normal" water levels and a "static" ecosystem are viewed by many as desirable attributes of the Great Lakes, while fluctuating water levels are considered a problem. At the same time, many people appear to believe (incorrectly) that lake levels and connecting channel flows can be controlled to a great extent by existing human-built water control structures and diversions in the upper Great Lakes.

In response to public concerns regarding degrading environmental conditions in the Great Lakes, environmental oversight and regulation in the Great Lakes basin have increased significantly over the last four decades. Ecosystem interests are managed or regulated by a relatively large number of governmental agencies. Within the Great Lakes basin there are more than 19 federal agencies or commissions, 29 primary state and provincial agencies, and numerous watershed-based (*e.g.*, conservation authorities in Ontario) or local county or municipal-based agencies managing or regulating ecological resources.

Over the next several decades, land use changes – driven by population growth and public demand for coastal property – are expected to continue to alter the Great Lakes ecosystem and the important ecological services that it provides. For example, existing coastal properties could be converted into more substantial development, driven by limited availability and strong demand. Resulting changes in land use could cause increasing sediment and nutrient loads into the Great Lakes, resulting in nearshore water quality and habitat degradation, and beach closings due to increased productivity of algal blooms and other vegetation. Alteration of shoreline property, including hardening of the shoreline to protect riparian properties from damage, could result in continued loss of coastal wetlands, nearshore and coastal habitat, and diminish the ability of the ecosystem to respond to varying water level regimes.

Invasive species are expected to continue to alter the biodiversity and ecological functions within the Great Lakes. There is the added risk that warming waters will make the lakes even more susceptible to the establishment of some invasive species. Past examples of invasive species include *dreissenids* (zebra and quagga mussels), filamentous blue-green algae, purple loosestrife, and *phragmites* (reeds that can take over sandy beaches and wetlands). Introductions of new invasive species through ballast water and unprotected hydrologic connections, particularly the Asian carp, could have uncertain, though potentially significant adverse effects on Great Lakes ecosystems.

3.5.2 Implications of Changing Great Lakes Water Levels

Potential Impacts

Natural fluctuations in water levels (over both the short- and long-term) are essential to maintaining habitat diversity and critical ecological functions in the Great Lakes. Under natural conditions, coastal biological communities adapt to high and low water conditions by migrating upslope, downslope, or laterally, while maintaining biodiversity, ecological functions and benefits. Even though the Great Lakes ecosystem is dynamic and requires fluctuating water level regimes to maintain functional biodiversity, many policies and regulations are designed to maintain an ecological "status quo" (*i.e.*, a narrow range of water level and ecological conditions defined by short-term historical conditions) irrespective of changing environmental conditions.

***Figure 3-6* Wetlands in Georgian Bay, ON**

Elimination of high and low water levels (*i.e.*, range compression) due to water level regulation can result in a loss of wetland biodiversity and ecological function). Moreover, recent emerging trends may limit the ability of biological communities to adapt to changing water-level regimes. Examples include:

- Shoreline modifications and development may prevent the upslope migration of coastal wetlands, reducing the area, biodiversity, and functionality of these wetlands.
- Low water periods generally result in downslope expansion of coastal wetlands and may increase coastal wetland area and biodiversity (Figure 3-6). However, portions of these wetlands may become drier and become dominated by less diverse plant community types, which may reduce vegetative complexity and interspersion which is functionally important for both waterfowl and fish. Moreover, loss of hydrologic connectivity between the lakes, coastal wetlands, and tributaries can restrict access to both shallow water and wetland fish spawning and nursery habitats. For example, the upper St. Clair River is important spawning habitat for lake sturgeon, a threatened species (Figure 3-7).
- A rapid decline in lake water levels combined with extended periods of low water likely would provide opportunities for invasive species that could alter the biodiversity and ecological functions of Great Lakes wetlands. Protected embayments with broad shallow shorelines are particularly susceptible to the establishment of invasive species such as *phragmites*.

Figure 3-7 **Great Lakes Sturgeon**
Photo credit: Michigan Sea Grant

Adaptive Behavior and Response

Adaptive measures to protect ecosystem interests focus on changes in management policies, societal expectations, and behavior. Examples of these -regulatory adaptation measures include:

- managing flows to optimize lamprey eel capture and reduce this threat;
- building awareness of the importance and benefits to the ecosystem of water level fluctuations;
- managing newly exposed lakebeds, during low water events, as natural areas rather than as property to be developed;
- preserving native wetland plant species and aquatic organisms during high water events, to serve as a "seed bank" for re-establishment of coastal wetlands as water levels recede;
- managing fish populations to maintain diverse and balanced fish communities for anticipated water level regime conditions; and,
- preventing the introduction and establishment of invasive species into the Great Lakes basin through, for example, aggressive monitoring and eradication programs.

3.6 Coastal Zone Interests[9]

Coastal zone interests represent individuals and organizations with a direct interest in property along the shorelines and connecting channels of the upper Great Lakes (riparian property), particularly private property owners.

3.6.1 Overview

There are an estimated 93,400 properties along the upper Great Lakes shorelines and connecting channels (63,700 in the United States and 29,700 in Canada), including year-round homes, second homes and seasonal recreational properties. These riparian properties support about 233,000 full-time or seasonal residents (159,000 in the United States and 74,000 in Canada).

9 This section is based on the *Contextual Narrative Report*, Coastal Zone Technical Work Group (IUGLS, 2011e). All data used in this section are taken from and referenced in that report.

The economic importance of these riparian properties in the upper Great Lakes is estimated at between $39 and $66 billion ($U.S.), in terms of property values and taxes to local, state/provincial and federal governments. This value reflects the strong historical and sustained demand for shoreline property in the region.

The demand for shoreline properties is expected to be maintained in the coming decades throughout much of the upper Great Lakes, particularly as more people in larger metropolitan areas approach retirement age and look for full-time or seasonal retirement homes along the shoreline. It is anticipated that most of the shorelines of Lake Michigan-Huron (excluding Georgian Bay), in both Canada and the United States, will be developed as residential in 50 years. This is particularly true of land that currently is privately owned or undeveloped/non-agricultural. There likely will be no agricultural land use immediately along these shorelines and virtually no privately owned, undeveloped land.

Coastal zone interests are represented by several large organizations. The largest is the International Great Lakes Coalition, a non-profit corporation with approximately 4,000 members in both Canada and the United States.[10] The coalition represents the interests of individual coastal property owners on issues related to water levels, sediment supply and transport and coastal management.

Many riparian property owners belong to local property owner associations or ratepayer associations. In some cases, memberships in individual associations are pooled to form larger regional associations. One example of this is the Georgian Bay Association in Ontario, which consists of 22 member associations as well as concerned individuals.[11] Other riparian organizational groups have been established in recent years in response to concerns over property ownership issues and environmental and coastal management legislation that have an impact on riparian rights or activities. Examples include Save Our Shoreline in Michigan[12] and the Ohio Lakefront Group[13].

One of the core values of riparian property owners in the upper Great Lakes is a strong desire to live on the water, a desire that is generated because of the many aesthetic, recreational, spiritual and environmental benefits of living along the Great Lakes shoreline. In addition, many of these individuals have a strong historical or traditional connection to property that has been "in the family" for many generations.

Coastal and shoreline property owners also have certain expectations and preferences for water levels at their particular location, based on their own experiences and observed history of water level fluctuations and impacts in their area. Typically, these levels are neither so high as to cause excessive flood and erosion impacts, nor so low as to cause problems with boating access to their property or cause other recreational limitations.

Some riparian property owners consider regulation of activities within shoreline management zones or flood hazard zones to impinge on their property rights. In the past, for example, many owners have been hesitant to accept rigorous coastal hazard regulations, such as zoning setbacks, for fear that such regulations will limit their ability to develop their property in the future.

3.6.2 Implications of Changing Great Lakes Water Levels

Potential Impacts

Historically, the most serious impacts to riparian interests on the upper Great Lakes have occurred when water levels were extremely high. For the upper lakes, there have been four such periods in the last 60 years: the early 1950s; the early 1970s; the mid-1980s (when record highs were established on all upper Great Lakes); and, to a lesser extent, the late 1990s.

By far the most common negative impacts during these periods have been related to flood and erosion damage during storm activity, loss of land and structures from accelerated bluff or beach erosion, damage to shore protection structures, loss of beach access, and the related social and economic impacts associated with these. Damage descriptions and estimates of damages from flood and erosion impacts during high water periods are generally well documented for these periods.

For some riparian property owners, low water levels can mean wider beaches in front of coastal bluffs and sandy beach areas, and significantly reduced threats of flooding in lower lying environments. The threat of short-term bluff or beach erosion is also reduced in some areas, as is the threat of damage due to large storms. However, low water levels can negatively affect use of, or access to, property where boats are the primary means of access. Areas along the shoreline with shallow bathymetry may become exposed sand and mud flats or organic "muck" that many shore residents find aesthetically unpleasing from a visual perspective or because of odour problems. Plants and other wetland vegetation that were unable to germinate during the many years of higher water levels can rapidly sprout and grow in these flats and shallow water areas, becoming both an access and aesthetic issue for coastal zone interests.

10 www.iglc.org

11 www.georgianbay.ca

12 www.saveourshoreline.org

13 www.ohiolakefrontgroup.com

Figure 3-9 **Low Water Conditions on Lake Superior, 2007 – Goulais Bay, Near Sault Ste. Marie, ON**

Adaptive Behavior and Response

Property owners along the shorelines of the upper Great Lakes and the connecting channels have taken a variety of adaptive behaviors in the past to deal with the impacts of changing water levels. However, there has been much more experience in responding to the challenges of high levels, such as flooding and erosion (Figure 3-8), than in dealing with low level conditions (Figure 3-9).

High Water Conditions

There are regulations in place in both Canada and the United States to situate structures associated with new development above the one percent annual exceedance probability flood elevation (commonly referred to as the 1-in-100-year flood level). However, properties developed prior to these regulations, or properties that are located in areas where no formal flood level regulations or mapping exist, can still be at risk of flooding during higher water periods or storm events. Riparian owners who are threatened by flooding or wave damage can choose to adapt by elevating their home and structures above the flood level or by bringing in material to raise their lots. However, there is little evidence around the upper lakes shoreline that such adaptation of existing structures has taken place.

Rather, the most common adaptive measure under high water conditions has been to install or repair and upgrade shore protection structures to reduce bluff and beach erosion and to reduce flooding damages (*e.g.*, by constructing seawalls or dikes). Property owners frequently deal with flooding in a crisis response mode by bringing in sandbags and water pumps. Where the property is only occasionally subject to flooding, owners may experience damage several times before adapting, if they adapt at all. In the United States, flood insurance can be obtained through the National Flood Insurance Program (subject to approval based on program requirements). The program does not cover erosion losses. No comparable flood insurance program exists for property along the Canadian shoreline of the Great Lakes.

Low Water Conditions

Prior to the low levels that have occurred on Lake Superior and Lake Michigan-Huron in the past decade, there has not been an extended period of low water levels on the Great Lakes since the mid-1960s. As a result, far less is known regarding adaptation to low water levels by coastal zone interests in the upper Great Lakes compared to adaptation to high levels. Given that a large percentage of shoreline development took place following the mid-1960s low water conditions, many shoreline residents have not had to adapt to such conditions.

In addition, actions of property owners can be expected to vary considerably based on the shoreline conditions and policy and regulatory regimes in place. For example, riparian owners along coastal shorelines with erosion or flooding concerns are likely to view low water levels as beneficial and likely will not take any action. Lower water levels become more of a concern, however, for owners of property located on shallow rocky coastal environments (such as Georgian Bay), sheltered embayments or drowned rivermouth areas (*e.g.*, Saugatuck, MI) or where access to their properties is by boat. This latter group may need to extend their docks into deeper water, if possible, to retain boating access.

Figure 3-8 **Shoreline Protection Structure, 2004 – Near Michigan City, IN on Lake Michigan**

In some cases, they may be able to undertake dredging of their nearshore areas to retain access. Alternatively, they may be forced to rent boat dockage space elsewhere, or put their boats in winter storage prior to the end of what has been their "normal" fall season. In some cases (as was the experience at a number of properties on Lake Superior in 2006-2007) property owners may be unable to adapt to rapid changes in levels and have to forego boating use altogether.

Where shorelines become exposed flats and wetland vegetation takes over, property owners may choose to remove the vegetation or undertake beach grooming, subject to regulatory approvals. In prolonged periods of low water, there may be increased pressure from riparian owners to be allowed to situate closer to the water, or for new development to be sited on newly exposed shoreline sections. This may lead to the demand for the relaxation of setback and other shore management and coastal hazard regulations.

While past experiences with fluctuating water levels has provided considerable evidence of the types of adaptive responses anticipated by riparian property owners, there remains considerable uncertainty about the implementation of such approaches in the future. The role of regulatory oversight in the approvals of certain adaptive responses (including adding or modifying shoreline protection, undertaking dredging activities and removing vegetation and grooming beaches) is not uniform throughout the upper Great Lakes. While there is evidence to suggest that most applications for shoreline protection are approved, there is recognition that certain human activities along the shoreline may not be compatible with ecological features, leading to the risk of conflicts between regulatory agencies and property owners.

Figure 3-10 Tourism in the Great Lakes – Wasaga Beach, ON

3.7 Recreational Boating and Tourism Interests[14]

Recreational boating and tourism interests represent individuals, companies and associations with a direct involvement in coastal tourism (Figure 3-10), recreational boating and fishing, marinas and boat retailers (Figure 3-11), and the commercial cruise ship industry in the Great Lakes.

3.7.1 Overview

The Study considered three major components to this interest.

- ***Coastal Tourism***

  Ranging from large metropolitan areas to small towns, the upper Great Lakes coastline is lined with communities that depend upon tourism. Although these communities offer a diverse range of attractions, their common draw is the Great Lakes. In some cases, tourists actively use the lakes for recreation and in other cases the lakes merely offer a setting for a vacation experience perhaps only partially associated with the lake itself. In 2007, visitor tourism direct spending in the areas bordering the upper Great Lakes was estimated at between \$55 – \$60 billion, supporting over 650,000 jobs, and generating between \$7.5 and \$7.75 billion in local and state/provincial taxes.

- ***Recreational Boating***

  Reliable long-term data on recreational boating trends in the upper Great Lakes, particularly Canadian data, are not available. Based on projections from the limited available data, it is estimated that in 2009, up to 21 million people participated in some kind of recreational boating activity in the states and province on the upper Great Lakes. There are more than five million registered boats in the region, ranging from kayaks to large motor yachts, and of these, an estimated 1.2 million regularly operate across the upper Great Lakes region.

  Based on past studies of the spending behaviors of Great Lakes boaters, it is estimated that recreational boating on the upper Great Lakes generates up to \$3.8 billion in direct spending, which in turn supports up to nearly 50,000 full-time jobs in Canada and the United States.

14 This section is based on the *Contextual Narrative Report*, Recreational Boating and Tourism Technical Work Group (IUGLS, 2011f). All data used in this section are taken from and referenced in that report.

- ***Great Lakes Cruise Ship Industry***

  The global cruise industry is the fastest growing category within the leisure travel market, with an average growth rate in passenger numbers of more than seven percent a year since 1980. In North America alone, this segment of tourism accounted for $22.5 billion in direct expenditures in 2009. Although the growing cruise market is interested in cruises to novel locations, the Great Lakes region has yet to establish itself as a strong cruise destination. Limited data available on Great Lakes cruising suggest that cruise expenditures on the Great Lakes were a relatively modest $36.8 million in 2002. At that time, nine ships were operating on the Great Lakes, though that number decreased to only three ships in 2010.

The region is experiencing an important transition from its traditional industrial manufacturing focus. Already, the effects of these shifts are beginning to affect the tourism industry. For example, there is evidence that recreational boating is experiencing a period of stagnation or even slight decline. Since 2005, new boat sales, boat ownership and boating participation have declined from peak levels experienced in the late 1990s.

The population of the upper Great Lakes region will continue to age and become more diverse, and some population groups may not be as familiar with or interested in recreational boating and associated activities. For example, significant declines in recent years in sportfishing – by far the largest single activity in which recreational boaters engage – will likely have a negative effect on boating participation and ownership. The number of people participating in fishing in the United States portion of the Great Lakes declined by 30 percent between 1996 and 2006. Ontario saw a 27 percent decline over a comparable period.

At the same time, leisure patterns in North America are evolving, in response to broader economic and social forces. Free time for many individuals increasingly occurs in shorter durations and during the week rather than on weekends. Paid vacation time is trending downward, and in the United States, one in four workers has no paid vacation. Many older workers may postpone retirement or take part-time jobs out of financial need, reducing time available to pursue leisure activities.

Non-native and invasive species have long had an effect on the Great Lakes fisheries and recreational boating. On the positive side, the introduction of several salmonid species helped grow sportfishing and recreational boating on the Great Lakes. Conversely, the invasion of zebra mussels led to the collapse of Lake Huron's chinook salmon fishery in 2004. The collapse affected numerous coastal communities that relied on the spending of fishers. Recently, attention has focused on the prospect of Asian carp infesting the Great Lakes. Many are concerned that if this species of carp enters the Great Lakes system, it would seriously damage the existing sportfishing industry and commercial fisheries.

The primary value associated with this interest is that water-based recreation has long been a strong part of the upper Great Lakes culture and will likely remain so well into the future. Millions of people use boating experiences with family and friends on the Great Lakes to enhance the quality of their lives. The social interaction and lifelong memories created by these types of experiences create strong, intergenerational links to the Great Lakes. Tourism interests are confident that water-based tourism will evolve and survive in some form, regardless of how it must adapt to changing water levels and shifting socio-economic forces.

3.7.2 Implications of Changing Great Lakes Water Levels

Potential Impacts

- ***Coastal Tourism***

  To date, there has been little evidence linking water levels and coastal tourism. Studies have shown that tourists, for the most part, have not taken water levels into consideration when making their travel plans, and that most businesses surveyed did not see water levels as an issue that affected the performance of their business. In general, businesses indicated that lower water levels were more detrimental to tourism activities than higher water levels.

Figure 3-11 ***Recreational Boating – Marina in Gore Bay, ON***

Persistent low water levels beyond historical low levels, however, could present more serious problems to coastal tourism. For example, low water levels can affect the quality of beaches in an area and adversely damage a region's tourism image.

- ***Recreational Boating***

  Recreational boating marinas in the upper Great Lakes frequently have been affected by changes in water levels. Marinas typically are more adversely affected by low water level conditions, while high water levels are more of a nuisance than a serious problem.

  When water levels are low, some slips become unusable or unable to accommodate the size of boat for which they were designed. Low water levels also can expose and damage boating infrastructure such as docks, piers and seawalls. In some cases, low water levels can affect access to the marinas via channels that are either impassable or narrowed to the point where they create bottlenecks that increase wait times, diminish the boating experience and decrease boater activity. Finally, low water levels can increase the risk of running aground or experiencing propeller, keel or hull strikes against lake bottoms, shoals and boulders.

  In addition to marinas, nearly 500 boat launches alongside the Great Lakes and the connecting channels are affected by changes in water levels. If water levels drop below or rise above a boat launch's design specifications, there would be a systematic loss of access to the lake. With very high water levels, boat launches could be completely underwater and in some cases water could even flood parking lots.

- ***Cruise Ships***

  Potential impacts of changing water levels on the cruise ship sector are not clear, as there has been only limited experience with the industry in the basin. However, there have been incidents where cruise ships have either touched or nearly touched bottom entering certain Great Lakes ports. In those cases, ships had to find other docking sites in the region or anchor in deeper water, creating additional expenses for the cruise ship company and inconveniencing passengers who either had to be bused or brought in by life boat to the attractions in the coastal communities.

Adaptive Behavior and Response

Actions by shoreline commercial businesses to reduce the risks of changing water levels likely would be the same as private riparian property owners (see 3.6.2). For example, adaptive measures for marinas facing persistent low water conditions include: dredging; investing in more permanent adaptations, such as floating docks; and accepting only smaller boats (with a consequent loss of revenues).

Given the limited experience to date with cruise ship use in the Great Lakes, there are opportunities for the introduction of more proactive adaptive response measures, in anticipation of persistent higher or lower water conditions in the basin. Cruise lines and communities interested in dedicating resources toward becoming a cruise port of call could factor in future water level scenarios as part of their planning processes, before significant investments are committed to port infrastructure.

3.8 Perspectives of Indigenous Peoples

Indigenous peoples were the original inhabitants of the Great Lakes basin, arriving about 10,000 years ago. They developed diverse cultures that were economically self-sustaining, based on hunting, subsistence agriculture and fishing. Fishing, hunting and the harvesting of wild rice remain important resource-based activities for many Native Americans, First Nations and Métis who make their home in the upper Great Lakes basin. The rights of indigenous peoples to the fish and other natural resources in the region have been protected by various federal treaties and state/provincial agreements (Great Lakes Information Network, 2011).

Indigenous peoples' perspectives on Great Lakes water issues are strongly influenced by a world view of earth as an interconnected ecosystem, where human life is part of and not separate from that ecosystem, and where people have strong intergenerational connections both to the past and the future:

> *"When considering matters of great importance, we are taught to think beyond the current generation. We also are taught that each of us is someone else's seventh generation. We must continually ask ourselves what we are leaving for a future seventh generation …. It is our spiritual and cultural responsibility to protect our local lands and Waters in order to help protect the whole of Mother Earth."* (Tribal and First Nations Great Lakes Water Accord, 2004).

Indigenous peoples have long had a close and spiritual connection to the waters of the Great Lakes (Figure 3-12). For thousands of years, and continuing into the present, many Native American communities and First Nations have relied on the natural resources of the Great Lakes to meet their economic, cultural and spiritual needs:

> *"Like other Ojibway in the upper Great Lakes, the Batchewana First Nations has exercised its responsibility to use, possess and protect the waters, lands and resources from time immemorial. The Creator placed our people at Bawahting (the rapids at what is now called Sault Ste. Marie) with laws and responsibilities to live in harmony with all*

Creation. Our elders have told us when the Creator told the crane to choose a homeland, the crane flew around and settled at Bawahting where there was an abundance of fish." (Batchewana First Nations Notice, 2011)

A recent agreement among several Native American tribes and First Nations in the Sault Ste. Marie area calls the St. Marys River "the life blood for the region which supports each of our collection Nations." (Sault Ste. Marie Tribe of Chippewa Indians *et al.*, 2006)

Indigenous peoples have asserted their rights to resources, resource-sharing and resource management within their traditional territories, including waters and watersheds. Within this context, indigenous peoples are strongly committed to "protect our water supplies, to promote proper wastewater treatment, to promote conservation actions and to strengthen and continue our sacred duties and ceremonies." (Indigenous Water Forum, 2011).

A fundamental ongoing concern of indigenous peoples is the extent to which they are involved in the decisions of federal and state/provincial governments in the United States and Canada with regard to the Great Lakes. Some Native American tribes and First Nations in the upper Great Lakes basin have stated that given their rights of self-determination and property rights within their traditional territories:

> *"… It is our right, our responsibility and our duty to insist that no plan to protect the Great Lakes Waters moves forward without the equal highest-level participation of Tribal and First Nations governments with the governments of the United States and Canada."* (Tribal and First Nations Great Lakes Water Accord, 2004).

Other concerns of indigenous peoples related to Great Lakes waters include:

- bulk groundwater withdrawals and large-scale diversions from the Great Lakes basin (Indigenous Water Forum, 2011);
- impacts of toxic substances on water quality, fisheries and waterfowl (Sault Ste. Marie Tribe of Chippewa Indians *et al.*, 2006); and,
- the impacts of invasive species on ecosystems (Sault Ste. Marie Tribe of Chippewa Indians *et al.*, 2006).

Figure 3-12 ***Water Ceremony – Kagawong, 2011, Manitoulin Island, ON***

3.9 Key Points

With respect to the key interests likely to be affected by possible future changes in water levels in the upper Great Lakes basin, the following points can be made:

- Under the *Boundary Waters Treaty of 1909*, *domestic and sanitary water uses, navigation*, and *power and irrigation* are given order of preference. These uses must be taken into account in developing regulation plans.
- Today, it is recognized that other interests, such as ecosystems, coastal zone uses and recreational and tourism uses have rights under the Treaty, consistent with the IJC's balancing principle, which provides for benefits or relief to interests affected by water levels and flows without causing undue detriment to other interests.
- All the interests investigated in the Study are experiencing major change as a result of broad, underlying economic, social and environmental forces. The decline in heavy industry and manufacturing in the region has put into motion changes such as declines in income, population, and municipal taxes, which in turn affect demand for shipping, energy and recreation. At the same time, the region's economic transition could see the rise of new, more water-intensive industries, such as irrigated agriculture, biofuels and oilsands refining.
- All the interests have a long-established presence in the upper Great Lakes basin, and all represent significant economic value to the region. There are clear expectations across all the interests that water levels will be maintained in the future to support their needs.

- All the interests investigated in the Study can be adversely affected by both high and low water conditions. Table 3-1 summarizes the vulnerabilities, by interest.
- Most of the interests have demonstrated their capacity to adapt to changes in water level conditions that have been within historical upper or lower ranges. However, persistent future water levels that are outside these historical ranges would require some interests to carry out more comprehensive and costly adaptive responses than any undertaken to date.
- First Nations in Canada, Native Americans and Métis represent an important perspective in the upper Great Lakes. Their concerns cut across the Domestic Water Users, Coastal Zone and, in particular, the Ecosystems interests investigated in the Study. Study Board members engaged a number of First Nations and Native Americans through, for example, workshops and other outreach activities to identify their issues and concerns with respect to Great Lakes water levels.

Table 3-1: Interests in the Upper Great Lakes: Summary of Vulnerabilities to Water Level Fluctuations

Water Using Interest	Vulnerabilities
Domestic, Municipal and Industrial Water Uses	Impacts at extreme water levels can include unusable or compromised water intakes, sedimentation problems, increased operations and maintenance requirements, and reductions in water quality
Commercial Navigation	Adverse impacts generally associated with low water levels; *e.g.*, vessels forced to operate with reduced loads
Hydroelectric Generation	Can be adversely affected by high water conditions; *e.g.*, temporary local flooding, erosion concerns in power canals Persistent low water conditions can have greater impact, forcing stations to operate below capacity and reducing revenues
Ecosystems	Natural fluctuations in water levels (over both the short- and long-term) are essential to maintaining habitat diversity and critical ecological functions in the Great Lakes Coastal, protected and riverine wetlands, beaches and dune systems, tributary connections and their estuaries, islands, and other coastal margin environments are particularly sensitive to fluctuations in levels
Coastal Zone	Highly sensitive to water level changes and can suffer the greatest individual losses during extremes water level events Historically, the most serious impacts to riparian interests have occurred when water levels were extremely high, such as flood and erosion damage during storm activity Low water levels also can negatively affect use of or access to property; *e.g.*, low lying, gently sloping shorelines/bays/river mouths can become exposed
Recreational Boating and Tourism	Can be adversely affected by both high and low water conditions; *e.g.*, persistent low water levels can affect the quality of beaches in an area, as well as limit the use of some marinas and limit access to the lakes; high water levels can flood some boat launches

Chapter 4

Hydroclimatic Conditions: Past, Present and Future

Chapter 4 examines how hydroclimatic processes affect Great Lakes water supplies and water levels, with a focus on the possible impacts of climate variability and climate change.

4

4.1 Study Approach to Hydroclimatic Analysis[1]

A main task of the International Upper Great Lakes Study (the Study) was to assemble a broad range of hydroclimatic sequences to test the *robustness* of the candidate regulation plans – the capacity to meet regulation objectives under plausible future water level conditions – to replace plan **1977A** (**Chapter 5** and **Chapter 6**). This effort relied, in turn, on a hydroclimatic database that has been expanded and improved since the last major study of Great Lakes water levels in 1993 (Levels Reference Study Board, 1993). Despite these improvements, much of the science that underpins the plan formulation and evaluation by the Study is still challenged with uncertainties. Recognizing this challenge, the Study sought to reduce these uncertainties.

4.1.1 Science Questions

The Study examined the hydrology and climate of the upper Great Lakes, focusing on changes to the contemporary hydrology affecting the levels of the lakes and the impacts of future climate variability and change. The Study addressed two primary science questions:

- *What are the historical estimates of the net basin supplies[2] (NBS) in the upper lakes and how have any potential changes to the water balance components affected the level of the lakes?*
- *What potential impact could variations in the climate system have on any future regulations of the Upper Great Lakes?*

1 This chapter is based on peer-reviewed work undertaken by the Study's Hydroclimatic Technical Work Group (TWG). See the TWG's final report for more information on the methodology and analysis (IUGLS 2012).

2 Net basin supply (NBS) is the net amount of water entering a lake, consisting of the precipitation onto the lake minus evaporation from the lake, plus groundwater and runoff from its local basin, but not including inflow from an upstream lake. Time series of NBS are crucial as they are necessary to simulate water levels and flows and evaluate the impacts of the candidate regulation plans.

The first science question was extensively investigated in the Study's first report to the International Joint Commission (IJC), ***Impacts on Upper Great Lakes Water Levels: St. Clair River***[3], which examined the physical processes and possible ongoing changes in the St. Clair River. The Study expanded on this previous work for this final report.

4.1.2 Hydroclimatic Analytical Framework

The Study's analytical framework for conducting the hydroclimatic statistical and modelling studies consisted of three themes:

1. **understanding the water balance of the Great Lakes (section 4.2);**
2. **assessing the reliability of historical recorded and estimated data, and increasing understanding of potential NBS conditions through the use of paleo-information[4] and stochastic[5] analysis (section 4.3); and,**
3. **addressing the plausibility and scope of climate change impacts on NBS using established down-scaling techniques and - new modelling work (section 4.4).**

Figure 2-2 in **Chapter 2** illustrates these three themes in the Study's hydroclimatic analytical framework.

3 Available at www.iugls.org

4 *Paleo* – A combining form meaning "old" or "ancient," especially in reference to former geologic time periods, used in the formation of compound words, as in *paleo-hydrology*.

5 *Stochastic* – Statistics involving or showing random behaviour. In a stochastic simulation, a model is used to create a new 'synthetic' series of plausible flows and lake levels, based on historical data. The synthetic series will, on average, preserve important properties of the historical record, such as the mean and standard deviation, while generating new combinations of high and low flow conditions that could represent more severe conditions than those seen in the past.

Based on this analysis, the Study developed contemporary and future NBS scenarios. These scenarios, in turn, supported other key analyses of the Study:

- testing the performance and robustness of a wide range of candidate regulation plans (**Chapter 5** and **6**); and,
- analyzing the role that adaptive management can play in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels (**Chapter 9**).

4.2 Theme 1: Understanding the Water Balance of the Great Lakes

The first theme of the hydroclimatic analysis involved assessing the validity of existing methodologies used to determine contemporary estimates of the water balance. Although the existing conventional methodologies used for estimating water balance components have proven relatively successful in the past, questions remain regarding measurement uncertainties associated with the principal components of the Great Lakes water balance (*i.e.*, precipitation, evaporation and runoff). To address these questions, the Study sought to improve accuracy and consistency in NBS estimates, including the modification of existing models, development of new models, collection of new data, and improvement of a range of methodologies that have been used for lake level estimation. These analyses were also fundamental to ensuring that any potential future climate outcomes could be understood and attributed to past changes. This attribution required historical estimates of the water balance elements to be as bias-free[6] as possible and to have uncertainty bounds associated with each element.

4.2.1 Residual and Component NBS

The two most commonly used methodologies for Great Lakes water balance accounting are:

- the *residual method*, which is more indirect and is based on change in storage of the lake; and,
- the *component method*, which directly computes NBS by specifying the water balance through a quantification of the components of the hydrological cycle for each lake, and accounting for all inflows and diversions.

Residual NBS

The residual method of estimating NBS requires accurate records of the inflow, outflow, the net change in storage (as expressed by the change in water level over a given time period), as well as the major diversions into and out of the lake. Change in storage due to thermal expansion and contraction, minor diversions and estimates of consumptive use are normally assumed negligible when compared to the other larger elements of the water balance.

The coordinated residual Great Lakes NBS database is maintained by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD). The simplicity of the residual method, which relies primarily on water level measurements as the principal source of data, allows for residual NBS to be computed for the historical period of 1900 to present. For these reasons, residual NBS sequences have typically been used for operational and regulation planning purposes. For the Study's analysis, historical residual NBS sequences were deemed more suitable for both plan formulation and adaptive management purposes. A methodology was also developed as part of the Study to derive residual NBS supplies from historical data for the period 1860-1899 (Quinn, 2010), providing additional insight into the full range of NBS scenarios that have been experienced in the relatively recent past. The estimates of historical NBS for the period 1869 to 1899 are good only for Lake Superior, however. The NBS values for the downstream lakes cannot be estimated with confidence in view of unknown connecting channel conveyances.

Residual NBS are subject to considerable uncertainty, arising primarily from estimations of change-in-storage, inter-basin inflow and outflow, and diversions; not accounting for thermal volumetric changes, consumptive use, and minor diversions adds additional uncertainty (Neff and Nicholas, 2005; Bruxer, 2010). The amount of uncertainty depends not only on the accuracy of the methods used to estimate the different terms in the residual NBS equation, but also on the magnitude of the different quantities being measured, which varies depending on the lake. For example, the total uncertainty in the residual NBS computed for Lake Superior, where there is no connecting channel that flows into the lake and where the flow out of the lake makes up a relatively smaller proportion of the overall water balance, may be relatively small. By contrast, the uncertainty in NBS is greater for a smaller downstream lake such as Lake Erie, where the inflows and outflows are large in relation to the NBS, because relative errors in these terms are magnified (Quinn and Guerra, 1986; Neff and Nicholas, 2005; Quinn, 2009; Bruxer, 2010).

6 Bias refers to a systematic (*i.e.*, not random) difference between a quantity and a prediction of this quantity.

Furthermore, because NBS is computed indirectly using the residual method, these estimates cannot be used in the context of climate projections, where the physical processes that describe the interaction between climate and the different components of the hydrological cycle are required.

Equation for Calculating Residual NBS

$$NBS = O - I + \Delta S - \Delta ST + D_o - D_i + C_{use}$$

Where:

O: the outflow from a Great Lake;

I: inflow from an upstream Great Lake;

ΔS: change in water storage of the Great Lake;

ΔST: change in water storage caused by thermal expansion or contraction of water;

D_o : diversion of water out of the Great Lake or its basin, and D_i is diversion in; and

C_{use} : consumptive use of Great Lake water.

All terms are expressed in m^3/s-months (ft^3/s-months) (or other time periods).

Component NBS

The component method estimates NBS directly from its component contributions (*i.e.*, overlake precipitation, basin runoff, lake evaporation and groundwater). Component supplies have traditionally been calculated using methods outlined by the Great Lakes Environmental Research Laboratory (GLERL) and have served as the basis for comparison against residual supplies for many years (Croley and Hunter, 2008).

Since each primary component exhibits unique differences, relative to the methodology used for estimation, different techniques are commonly used to reduce errors and uncertainties. For overland *runoff*, computational estimates remain as one of the greatest sources of uncertainty in the calculation of component NBS for the Great Lakes. Daily streamflow information is essential for the adequate calculation of the overland runoff component as well as the management of the Great Lakes system in general. Monte Carlo analyses, in which the uncertainty of each error sources is simulated by randomly generating an ensemble of alternative and equally likely discharge, indicates that monthly runoff is slightly higher than estimates currently used to determine computed runoff. Investigations revealed that improvements in the estimates of discharge at gauge locations, application of better techniques extending discharge per unit area measured at downstream gauges to the entire watershed, and advances in determining basin-wide average discharge in gauged and ungauged watersheds could significantly reduce uncertainty in the calculation of component NBS.

Equation for Calculating Component NBS

$$NBS = P + R - E + G$$

Where:

P: overlake precipitation;

R: basin runoff to a Great Lake;

E: evaporation from the lake surface; and

G: net groundwater flux into a Great Lake[7].

All terms are expressed in m^3/s-months (ft^3/s-months) (or other time periods).

Overlake *precipitation* estimates can also introduce significant error into the overall water balance. Recent analysis has shown that estimates of overlake precipitation from the United States National Center for Environmental Prediction (NCEP) Multi-sensor Precipitation Estimates (MPE) Stage IV products can correctly identify areas of high and low precipitation for most of lakes Ontario, Erie, St. Clair, Michigan, and part of Lake Huron (DeMarchi *et al.*, 2009). These estimates can reduce uncertainty and error in determining precipitation amounts.

Until recently, *evaporation* from the Great Lakes was not measured, but rather was indirectly estimated as a residual of the long-term water or heat budgets, or modelled using meteorological data as input. The Study undertook investigations to directly measure evaporation at specific locations on Lake Superior and Lake Michigan-Huron using eddy covariance systems (Spence *et al.*, 2009), with the goal of improving overall lake evaporation estimates. Data collection began in June 2008 on Lake Superior at Stannard Rock Lighthouse (Figure 4-1), and in September 2009 on Lake Michigan-Huron at Spectacle Reef. Comparison of these direct measurements with evaporation estimates generated by models identified strengths and weaknesses in each method of lake-wide evaporation estimation. The IJC has committed to continuing field observations at different locations throughout the Great Lakes over multiple years, which will greatly improve the observational dataset and the theoretical models based on those data.

GLERL Model Estimates of NBS

GLERL model estimates of historical NBS from 1948 through 2008 were one of the component NBS estimates used by the Study. GLERL estimates each of the components using a suite of models and methods in conjunction with measured base data. Historical overlake *precipitation* is currently estimated by GLERL using observed precipitation measurements at primarily land-based gauges and

7 The groundwater component has relatively small effects on the water balance and is also well within the uncertainty of the major components. Thus, the groundwater impacts were not considered further in the Study.

Figure 4-1 **Monitoring Stations in the Upper Great Lakes**

Spectacle Reef Lighthouse, Lake Huron (left) and Stannard Rock Lighthouse, Lake Superior (right)
Insets – images of the eddy covariance and meteorological sensors.

extrapolating these point measurements to the lake surface using a weighting approach. Overland *runoff* has traditionally been computed using streamflow records at gauged streamflow stations, extrapolated to ungauged portions of the basin using area ratios of gauged versus ungauged basin area. Finally, a one-dimensional energy balance model, called the Large Lake Thermodynamic Evaporation Model, which was calibrated to surface water temperature and ice cover, is used to estimate lake *evaporation* from areal-average air temperature, wind-speed, humidity, precipitation and cloud-cover data. These approaches have been developed over many years and represent the first comprehensive attempt to quantify NBS components systematically in all the Great Lakes (Croley and Hunter, 1994).

MESH Model Estimates of NBS

To assess the current practices in simulating NBS, the Study applied another method for estimating component NBS. This approach is based on the coupled atmospheric hydrology modelling system developed by Environment Canada (Pietroniro *et al.*, 2007). Using the surface and hydrology MESH model (Modélisation Environnementale – Surface et Hydrologie) coupled to the GEM (Global Environmental Multiscale Model) atmospheric model (Mailhot *et al.*, 2005), predictions of NBS were determined by solving both an energy balance equation and a mass balance equation on a two-dimensional grid, over both land and water (Fortin and Gronewold, 2011).

Precipitation and overlake evaporation estimates were obtained from short-term forecasts (lead time of 6 to 18 hours) generated by the GEM numerical weather prediction (NWP) model. Overlake evaporation predictions were verified against observations from the Stannard Rock eddy covariance system on Lake Superior, established by the Study. Changes to the parameterization of surface roughness over water used by GEM were necessary to better fit these observations, which resulted not only in improved evaporation forecasts, but also in improved precipitation forecasts. Since a significant amount of uncertainty in NBS comes from the uncertainty in the runoff component, predicted streamflow was replaced by observed streamflow at 169 locations across the basin, corresponding to approximately two-thirds of the land portion of the Great Lakes watershed. The remaining one-third was predicted by the hydrological model WATFLOOD (WATerloo FLOOD) (Kouwen, 1988).

NBS was computed for each lake, based on estimates of overlake precipitation, overlake evaporation and runoff from the watershed. The resulting five-year hindcast (June 2004 – May 2009) of NBS for the Great Lakes were obtained and illustrated in Figures 4-2 and 4-3 as the water level responses to the cumulative effect of NBS over time.

MESH predictions of cumulative NBS (the sequence of partial sums from June 2004 to May 2009) match the cumulative sum of residual NBS very well. These data are plotted alongside the GLERL estimates. This does not prove that either estimate is correct, because each estimate was derived independently. However, it does increase confidence in NBS predictions obtained from these two methods (*i.e.*, MESH and residual NBS). However, the GLERL approach is more readily applied to long historical periods, as it requires less data, though bias corrections must be made, as discussed next.

Understanding Bias in Component NBS

The water balance analysis undertaken during the Study resulted in two existing time series of component NBS. The GLERL component NBS dataset for the 1948-2008 period was re-analyzed and updated in light of the observations and efforts over the duration of the Study. The component NBS dataset developed by Environment Canada used the MESH modelling with improved estimates from observations. GLERL's dataset extends back to 1948, which is very useful for assessing trends and detecting shifts in components of NBS, thus helping understand changes in NBS. However, while GLERL component NBS correlates well with

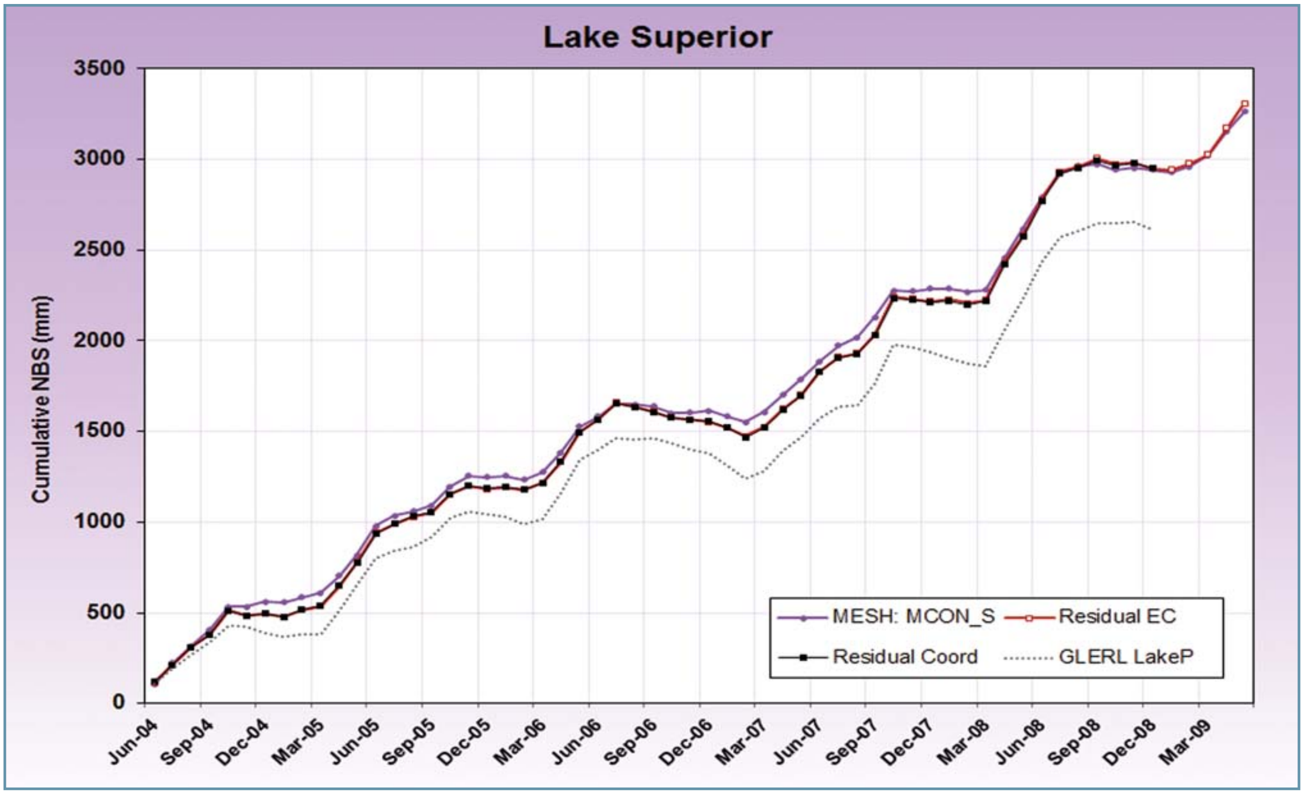


Figure 4-2 ***Cumulative NBS for Lake Superior***

in MCON_S plotted against the coordinated and provisional residual NBS, and the GLERL NBS

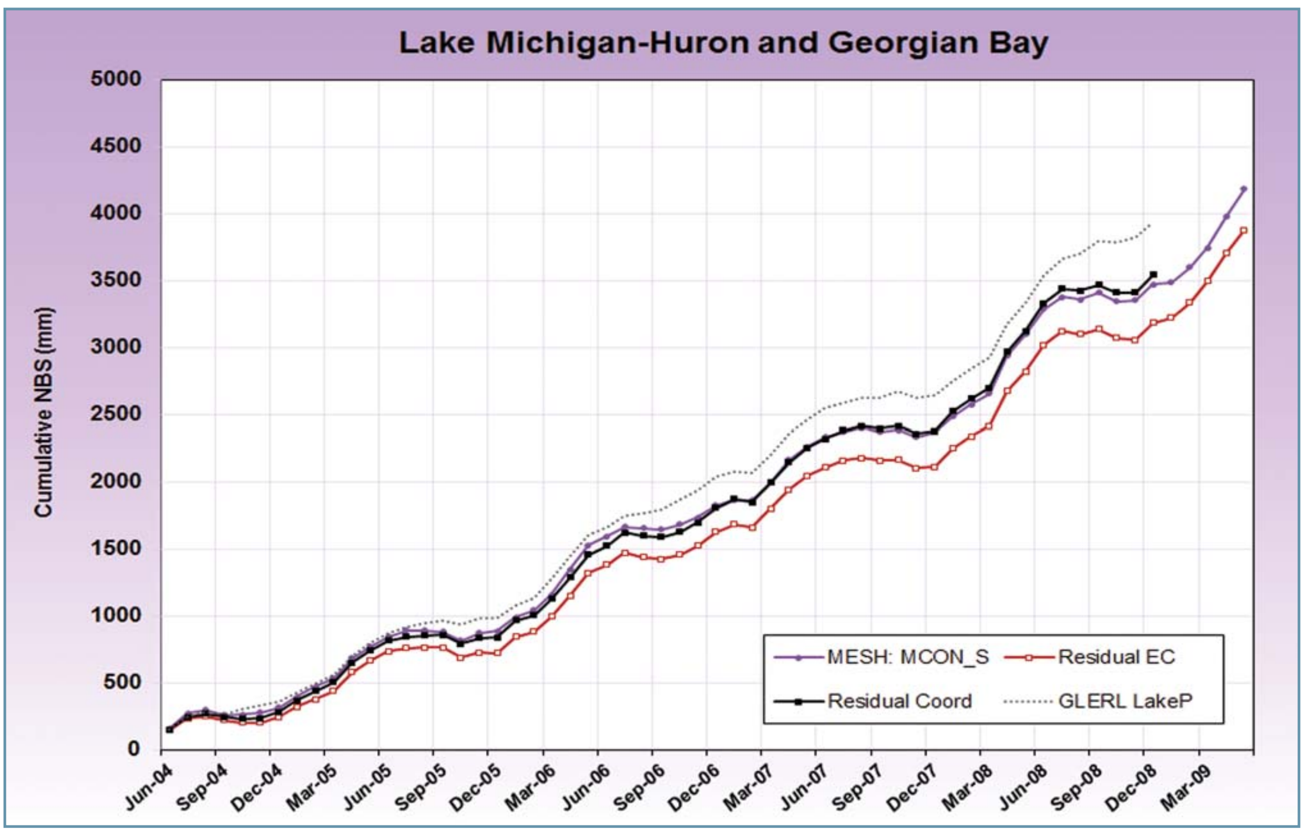


Figure 4-3 ***Cumulative NBS for Lake Michigan-Huron***

(including Georgian Bay)

in MCON_S plotted against the coordinated and provisional NBS, and the GLERL NBS coordinated residual NBS, it does not have the same long-term average. As noted above, at least over the short-term, the MESH estimates also correlate well and do exhibit less systematic bias.

Environment Canada's dataset based on the MESH model extends back only to 2004, but agrees slightly better with residual NBS than the GLERL dataset for this same period. In particular, the five-year mean of MESH component NBS is closer to the five-year mean of residual NBS for all lakes. Cumulative NBS comparisons confirm this. These results increased the confidence that the Study had in NBS estimates obtained from the MESH component and residual methods. In addition, it was also shown that compared to evaporation measured at Stannard Rock on Lake Superior, GLERL component NBS shows a significantly higher evaporation rate (Fortin and Gronewold, 2011). Furthermore, overlake precipitation estimates are obtained from near-shore stations, many of which are automated, and it is recognized that precipitation gauges are negatively-biased (Goodison *et al.*, 1998). This bias is stronger for snowfall than rainfall and much stronger at exposed sites such as near-shore stations. The GLERL uncertainty estimates for precipitation and runoff also confirmed the potential for bias (DeMarchi *et al.*, 2009). Therefore, there were reasons to believe that GLERL component NBS could be substantially affected by biases (Figure 4-3).

It was not possible within the timeframe of the Study to perform the level of analysis, revision and subsequent validation of the GLERL component NBS models that would be required to correct for all potential sources of bias, measurement error and model error, and uncertainty uncovered as a result of the Study's efforts in this area. Future scientific research and development at GLERL, including analysis and application of the latest generation of regional climate models (RCMs) will focus on these priorities (*e.g.*, Holman *et al.*, 2012; Gronewold *et al.*, 2011).

Nonetheless, by comparing GLERL and MESH component NBS estimates for the most recent period of record, it was possible to estimate a bias correction and compute a bias-corrected estimate of component NBS back to 1948. The Study referred to this third estimate of component NBS as a *back projection* of MESH component NBS (MBP). A plot of cumulative NBS, computed backward from December 2008, shows that the MBP agrees better with residual NBS than the GLERL component NBS for all lakes (Figure 4-4). These MBP data were used to show the improvement in water balance closure shown in Lake Superior and Lake Michigan-Huron.

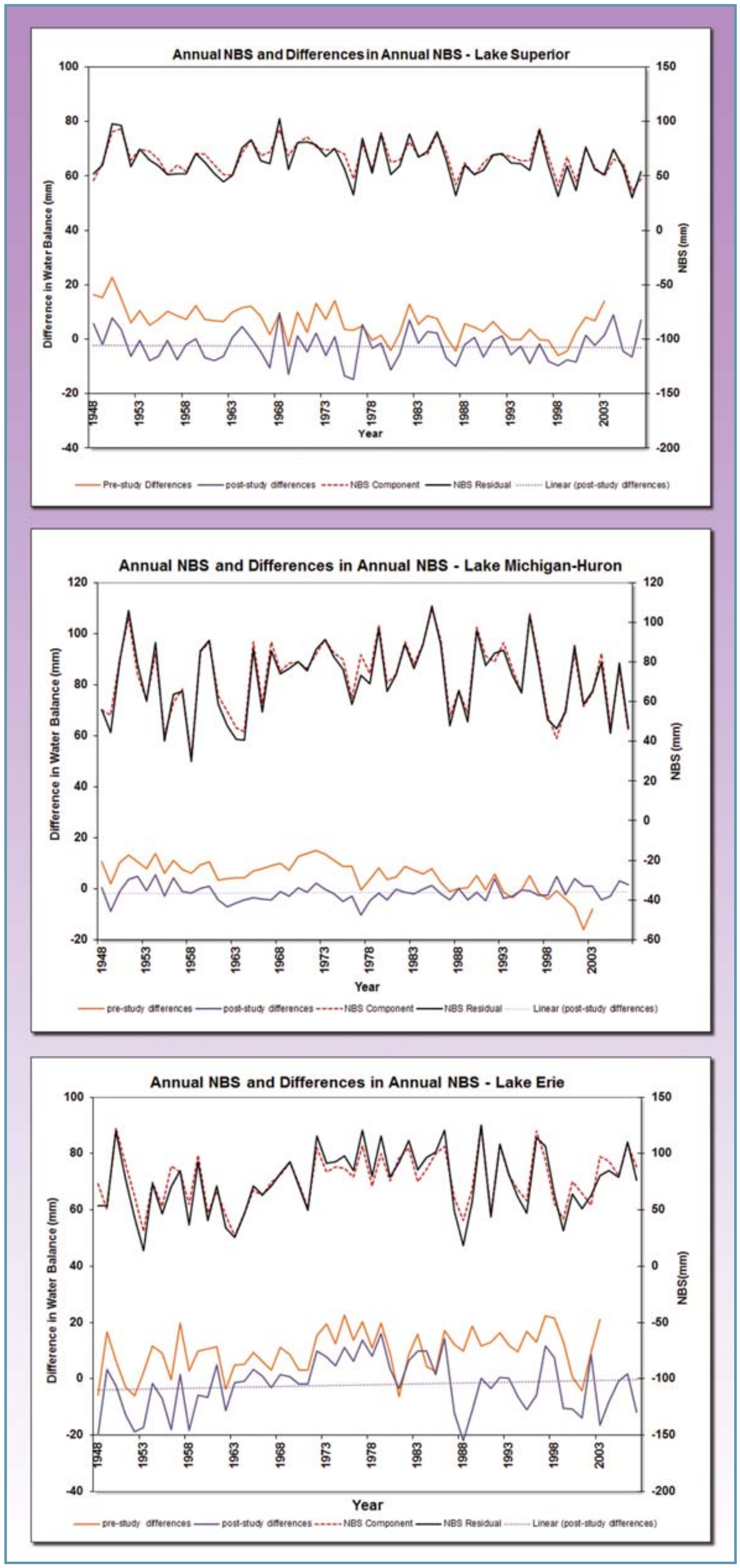


Figure 4-4 ***Sequences of Cumulative Residual NBS and GLERL Component NBS***

(before and after bias correction, 1948 to 2008)
Cumulative NBS computed backward from 2008 to 1948.

Table 4-1: Average Annual Water Balance Components of the Upper Lakes (1948-2008)

Lake	Method	Overlake Precipitation mm/year	Evaporation mm/year	Runoff mm/year	NBS mm/year
Superior	Component (GLERL)	789.2	605.6	616.4	799.2
	Component (MBP)	859.3	531.1	468.5	796.7
	Residual	n/a	n/a	n/a	774.9
Michigan-Huron	Component (GLERL)	840.8	655.1	721.1	906.8
	Component (MBP)	895.4	661.5	648.7	882.6
	Residual	n/a	n/a	n/a	860.0
Erie	Component (GLERL)	924.2	925.5	813.9	812.6
	Component (MBP)	973.1	933.8	770.1	809.4
	Residual	n/a	n/a	n/a	765.4

Using this back-projected information, a time-series of precipitation, evaporation and runoff for each of the upper lakes was generated. Table 4-1 highlights these components for the 1948-2008 period. Estimates are monthly over the surface area of the lake. The data in the table represent the current best-estimate of the mean values of the individual components. DeMarchi (2011) also derived estimates of both bias-correction and confidence intervals (uncertainty) using linear regression and Monte Carlo analysis.

Table 4-1 presents a summary of component estimates using the component and residual methods. One of the goals of the Study was to reconcile the differences in results when using the two methods. A number of observations can be made. First, there is good agreement between the two component approaches, with MBP producing slightly lower estimates. Second, there are significant differences between these approaches for each component and from lake to lake. Third, the MBP component estimates are closer to the residual method estimates.

While the NBS estimates by the GLERL and MBP methods provide reasonable convergence with the residual NBS, it is clear that efforts are still required for reconciling each of the components. It is also apparent that offsetting errors bring the overall estimates closer together. Time limitations within the Study did not allow for further analyses that could prove helpful. These include calibrating the GLERL model with the observed evaporation data in Lake Superior and Lake Michigan-Huron, and continuing the hindcast back to 1997 from 2004 using the MESH model in an effort to better understand and reconcile component estimate differences.

4.2.2 Estimating and Addressing Uncertainty in the Component NBS Sequences

The uncertainty in component NBS was assessed through the collection of new observational data, through improved model parameterizations, and through comparisons of both the GLERL and MESH component NBS estimates with the residual NBS estimates. Applying the evaporation measurements and comparing the results of complementary modelling systems, the Study sought to quantify the uncertainty in the estimates more systematically. (For more information on the methodology, see DeMarchi *et al.*, 2009; DeMarchi, 2011; and IUGLS, 2012.)

1. Lake Evaporation

Monthly level evaporation estimates from Environmental Canada's MESH model were compared with GLERL Large Lake Thermodynamic Evaporation Model for the period from June 2004 to May 2009. The distribution of the residuals between the GEM and the adjusted GLERL values is fitted with a probability distribution to determine the uncertainty band. Evaporation estimates were generally successful in replicating GEM results and bias was strongly reduced or even eliminated (IUGLS, 2012).

2. Overlake Precipitation

Nearly all precipitation gauges in the Great Lakes region are located on land, making overlake precipitation estimation difficult and susceptible to error. The lack of offshore precipitation gauges also makes a direct evaluation of overlake precipitation estimate uncertainty challenging. The strategy adopted by the Study was to compare available estimates of overlake precipitation from a number of sources and assess any differences that are identified.

GLERL overlake precipitation estimates (derived using Thiessen polygon interpolation) were compared to improved estimates of overlake precipitation that included the use of weather radar and/or forecast data, including the NCEP's MPE Stage IV product and the MESH system's CaPA product (DeMarchi *et al.*, 2009). It was shown that MPE can correctly identify areas of high and low precipitation for most of lakes Ontario, Erie, St. Clair, Michigan, and part of Lake Huron. Using these estimates can reduce uncertainty and error in determining precipitation amounts. Thus, these data may prove useful for improving GLERL overlake precipitation estimates in the future. It was also shown that there were significant differences between the GLERL precipitation estimates and those obtained from the other two precipitation estimates, which showed better agreement, suggesting a bias in the GLERL precipitation estimates.

Monthly level precipitation estimates from Environmental Canada's CaPA were compared with GLERL overlake and overland estimates for the period June 2004 to May 2009. The distribution of the residuals between the MESH and the adjusted GLERL values was fitted with a probability distribution to determine the uncertainty band. It was found that the adjusted overlake precipitations estimates succeeded in replicating the MESH results and that the bias was eliminated (IUGLS, 2012).

3. River Runoff

Computational estimates of runoff remain as one of the greatest sources of uncertainty in the calculation of component NBS for the Great Lakes. Of the three components of the Great Lakes NBS, river runoff is potentially the most accurately measured, but large portions of the lake basin are ungauged. In addition, the proportion of the basin that is ungauged has increased in recent years, notably for lakes Superior and Erie (Table 4-2). This further exacerbates the uncertainty in overall estimates of runoff from the Great Lakes basin.

Table 4-2: Percentage of Ungauged Basin Area, by Lake

Year	Lake Superior	Lake Michigan	Lake Huron	Lake Erie
1992	34 %	24%	34 %	25%
2008	40%	25%	38 %	42%

1992: modified from Lee (1992)
2008: adapted from DeMarchi et al. *(2009)*

The Study evaluated three types of errors associated with estimating basin runoff in the GLERL approach (DeMarchi *et al.*, 2009):

- errors in the observed discharge estimates at gauged locations;
- errors caused by extending the discharge per unit area measured at the most downstream gauge in a sub-basin to the remaining ungauged portion of a sub-basin; and,
- errors caused by extrapolating the lake's basin-wide average discharge per unit area in the gauged portion of the basin to ungauged sub-basins.

These sources of uncertainty were investigated using Monte Carlo analysis. This analysis indicated that not only is monthly runoff computed using this method subject to a high degree of uncertainty, but that there are systematic errors in the computed runoff. Investigations also revealed that improvements in the measured discharge estimated at gauged locations, application of more sophisticated techniques for extrapolating discharge measured at gauged locations to the ungauged portions of the drainage basin, and other advances in determining basin-wide average discharge in gauged and ungauged watersheds could significantly reduce uncertainty in the calculation of runoff and component NBS.

4.2.3 Assessing Historical Trends

An assessment of hydrological trends can provide information relative to what happened in the past, revealing changes and previously undetected events. Trend and change-point analyses conducted in the first part of the Study provided valuable insight into what had transpired within the upper Great Lakes. The analyses revealed events and apparent shifts in the hydroclimatic regime that significantly added to existing knowledge. Following this same line of analysis, the Study addressed variations and trends in component NBS.

Given annual and monthly supply sequences, it is possible to analyze the three important component NBS terms and examine for trends. As noted by Fortin and Gronewold (2011), mean annual overlake precipitation is higher than mean annual overlake evaporation. More importantly, mean annual runoff is higher than the mean annual net overlake precipitation. On an annual basis, the ratio of net overlake precipitation to NBS is, on average, about 20 percent for lakes Superior and Michigan-Huron, about 1 percent for Lake Erie and about 10 percent for Lake Ontario. As is apparent, the contribution of net overlake precipitation is much smaller than runoff. Thus, it is critical to accurately assess the runoff component. Figure 4-5 shows annual mean net overlake precipitation (precipitation minus

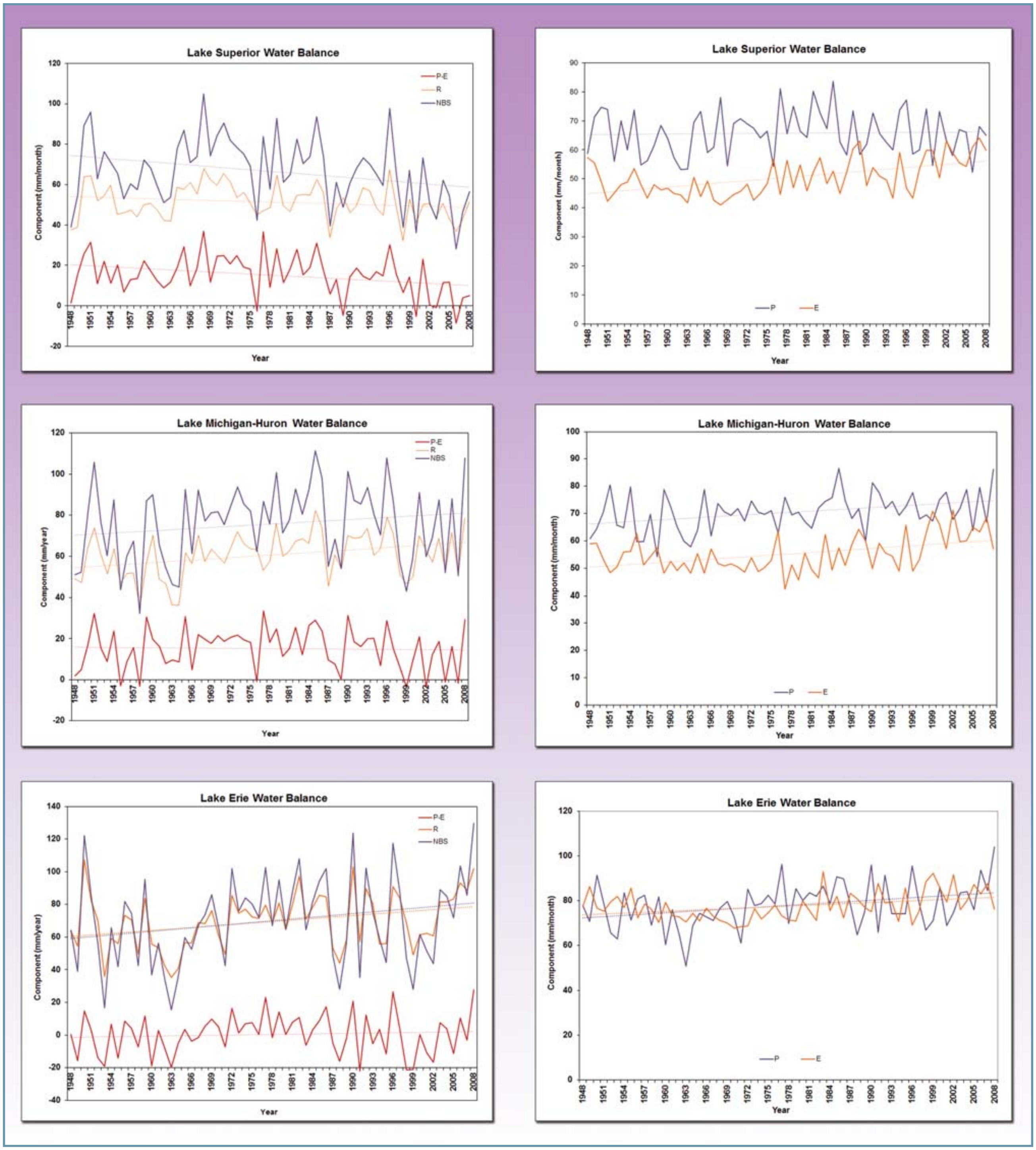


Figure 4-5 ***Annual Mean Net Overlake Precipitation, Runoff, and Component NBS***
(1948 to 2008) Note: derived from Fortin and Gronewold (2011)

evaporation, or P-E), runoff, and component NBS for each lake from 1948 to 2008. The findings indicate a general decrease in annual net overlake precipitation for lakes Michigan-Huron and Superior over the last several decades, with a noticeable increase in the frequency of negative net overlake precipitation for these two systems from roughly 2000 to 2008. On Lake Ontario, 2007 was the first year, for the period 1948-2008, with negative net overlake precipitation.

Further analysis of the net precipitation shows that overlake precipitation in all cases is generally increasing largely in step with increasing lake evaporation, leading to a small year-over-year change to the net precipitation. This is easily demonstrated when contrasting Lake Superior and Lake Michigan-Huron as show in Figure 4-5. In the case of Lake Superior, annual precipitation appears relatively steady, while there appears to be increasing evaporation.

Lake Michigan-Huron also shows an increasing evaporation trend since 1948 with what appears to be a corresponding trend towards increased overlake precipitation. This evaporation trend has been documented on a number of occasions and is largely attributed to decreasing ice-cover (Assel, 2009, IUGLS, 2009). These trends are important when trying to establish the context for future NBS sequences. The best possible unbiased estimates described earlier were used to examine the trends and they do provide an important context for the Study. In general, there is an increasing evaporation in all of the lakes since 1948. However, the Study also determined that in most cases (except Lake Superior), this is coincident with increases in precipitation over lakes. These findings appear to be consistent with estimates provided in the regional climate assessment (discussed next) and confirm that while there are changes in both precipitation and evaporation, the net impact to NBS is not as great as noted in previous studies.

Understanding the Water Balance: Summary

The first theme of the Study's hydroclimatic analysis involved addressing the need to improve understanding of the water balance in the upper Great Lakes basin.

Questions remain regarding uncertainties associated with the principal component estimates of the Great Lakes water balance (*i.e.*, precipitation, evaporation and runoff). The Study addressed this uncertainty through the collection of new observational data, improved model parameterizations, and comparisons of both the GLERL and MESH component NBS estimates.

Applying the evaporation measurements and comparing the results of complementary modelling systems, the Study sought to quantify the uncertainty in the estimates more systematically. This analysis found that:

- lake evaporation estimates were generally successful in replicating GEM results and bias was strongly reduced or even eliminated;
- adjusted overlake precipitations estimates succeeded in replicating the MESH results and that the bias was eliminated; and,
- computational estimates of runoff remain one of the greatest sources of uncertainty in the calculation of component NBS for the Great Lakes, exacerbated by the large proportion of the lakes basins that is ungauged.

Improvements in the runoff estimates at gauged locations, application of more sophisticated techniques for extrapolating discharge measured at gauged locations to the ungauged portions of the drainage basin, and other advances in determining basin-wide average discharge in gauged and ungauged watersheds could significantly reduce uncertainty in the calculation of runoff and component NBS.

In assessing historical trends in NBS, the Study concluded that evaporation has increased in all of the lakes since 1948. However, the Study also determined that except for Lake Superior, this increase in evaporation is coincident with increases in precipitation over the lakes. That is, while there are changes in both precipitation and evaporation, the net impact to NBS is not as great as noted in previous studies.

4.3 Theme 2: Assessing the Reliability of Historical Recorded and Estimated Data

In the second theme of the hydroclimatic analysis, the Study assessed the representativeness of historical variations and estimated data to provide insights into the potential impacts of climatic extremes and possible future trends. It was determined that a broad range of scientific approaches, in addition to climate modelling, should be explored to provide information relative to possible future climate scenarios. This would provide a greater range of possible conditions for consideration and alert investigators to any inconsistencies between model projections and the climates of the past. Two such approaches were paleo-investigations and stochastic hydrological analysis

4.3.1 Paleo-analyses

The Study examined paleo-sequences extending back more than 1,000 years to provide insight as to possible climate extremes in the future. Paleo-lake levels have been derived by dating submerged tree stumps and ancient beach ridges (Baedke and Thompson, 2000; Wilcox *et al.*, 2007) and reconstructed tree ring data (Quinn and Sellinger, 2006; Wiles *et al.*, 2009). Initial investigations focused on existing paleo-data, primarily tree ring and beach ridge data, as well as older measurements and climate transposition studies to examine extreme high and low lake levels that have likely occurred over the past 1,000 years. These data were used to examine potential extremes for water resource analysis and regulation studies. The information was indexed to modern reference points, such as modern chart datum levels, and the historical high and low lake levels for each of the upper Great Lakes, to the extent possible (Quinn, 2010).

The resulting analyses enabled an extrapolation of prehistoric Great Lakes water levels over the past 1,000 years. Figure 4-6 illustrates the wide range of possible lake levels (maximum and minimum) for Lake Superior, based on these findings. Comparable figures were produced for lakes Michigan-Huron and Erie, and exhibited similar ranges of levels.

Additional paleo-modelling (Brown, 2011) using a stochastic simulation framework (Prairie *et al.*, 2008) was employed to generate NBS sequences. Using this methodology, 500 sequences of 100 annual NBS values were generated.

An important facet of the paleo-simulation framework was the ability to investigate the persistence of dry and wet spell years, which is a more important factor in lake regulation than a single year maximum or minimum lake level. The replication of persistent dry and wet spells is a vital link for long-term water management. Figure 4-7 illustrates the relative frequencies of uninterrupted dry and wet years from the random 500 simulations for the upper Great Lakes (Brown *et al.*, 2011). The bar graphs generally indicate that there is a longer persistence of wet spell years than for dry spell years for all the lakes. Although the relative frequencies are not significant, a dry spell of six or seven years statistically scored the highest for each lake. For a wet spell, there are slight differences among the lakes, but generally the model's highest frequency lies between six to eight years' duration. The data also show that dry and wet periods of 10 to 15 years duration show up relatively frequently in the paleo-record, and need to be considered as part of any planning scenarios. This indicates the capability of PDSI reconstructed data to show the magnitude and duration of high and low epochs of NBS that were not observed during the period of historical record since1860 for Lake Superior. The modelling effort was able to replicate a variety of high and low sequences that have occurred in the past, based on paleo-data, and which provide a better sense of estimating the likelihood of extreme lake levels and their persistence over time.

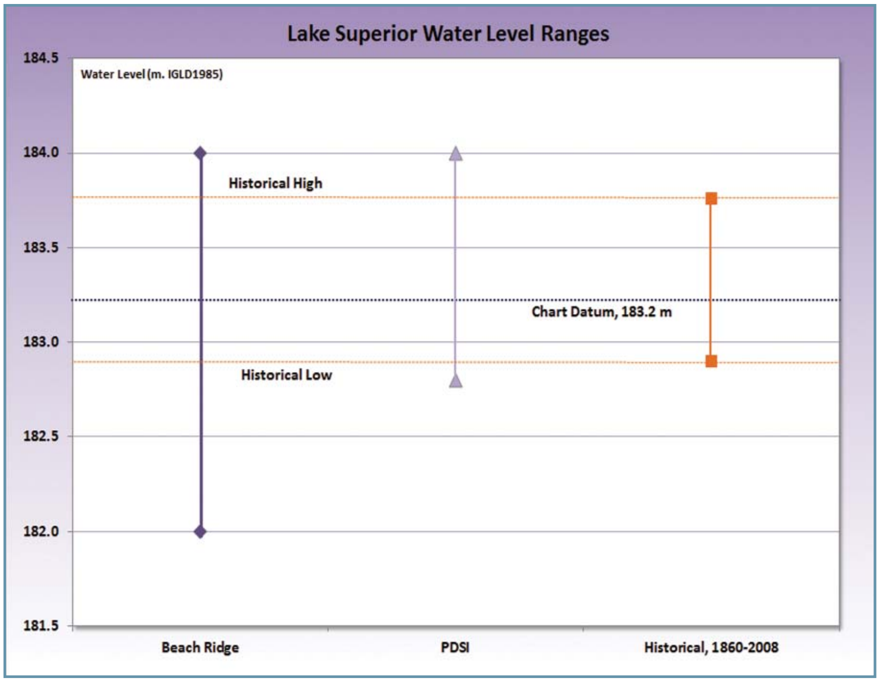


Figure 4-6 **Estimated Levels of Lake Superior, Based on Paleo-data**

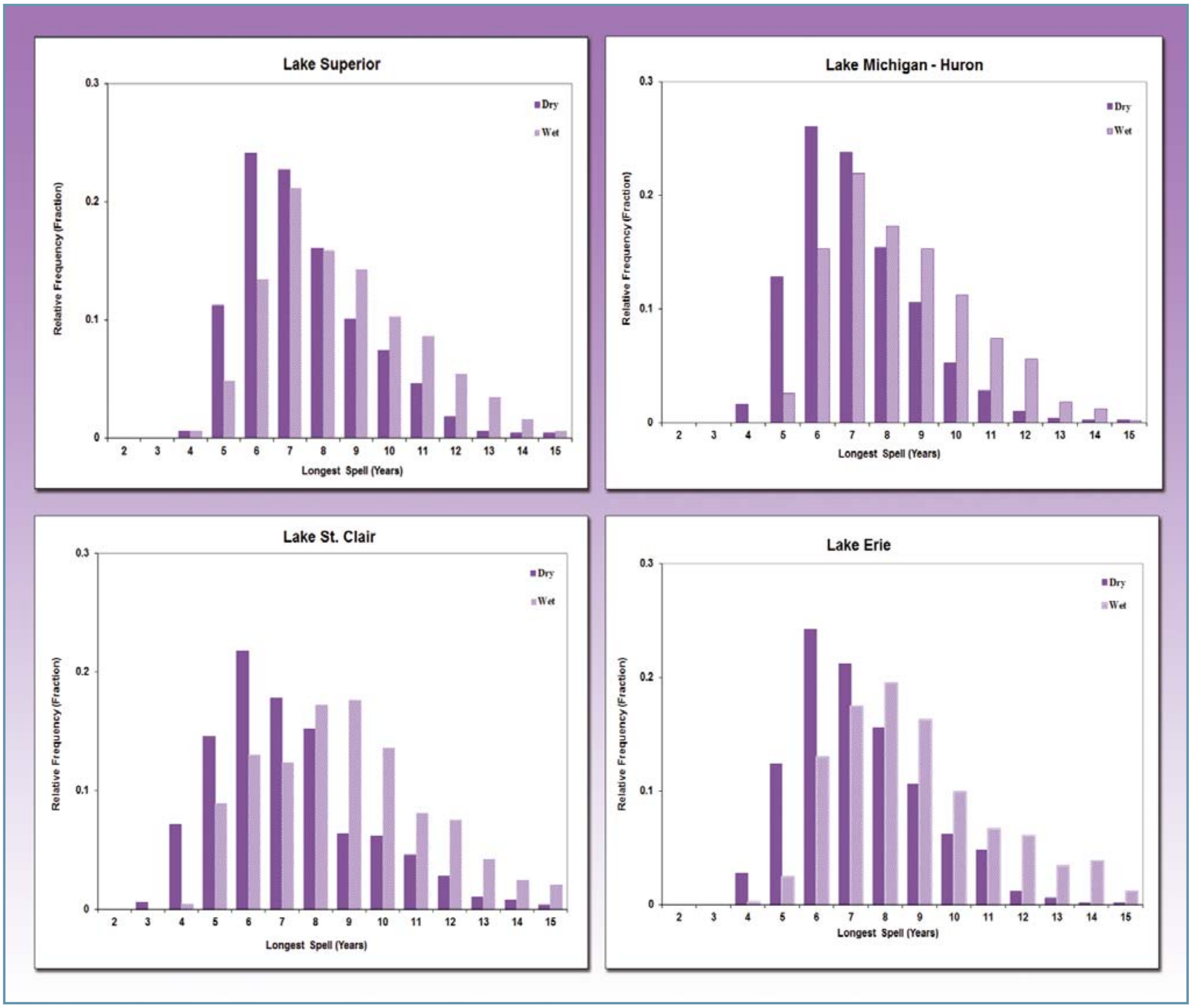


Figure 4-7 ***Relative Frequencies of Uninterrupted Dry and Wet Years, by Lake***

4.3.2 Stochastic Models

Stochastic simulation of multivariate hydrological variables is routinely used to assist in evaluating alternative designs and operation rules, particularly where the historical record is relatively short or the risk of project structural failure is relatively high. The performance of a given regulation plan can be estimated by simulating the behavior of a water resources system using sequences of inputs that are long enough to contain a large number of potential hydrological scenarios that could occur in the future, including rare and potentially catastrophic events.

To obtain a greater understanding of the long-term variability of the past, whose modes might be extended into the future, the Study developed four stochastic models for plan formulation purposes. The stochastic series produced a wide range of plausible sequences of NBS not seen in the relatively brief historical record. (For detailed information on the models, see IUGLS, 2012).

CARMA Model

An initial stochastic model of current historical climate record was developed, using the Contemporaneous Shifting Mean – CARMA Model (CSM-CARMA) at the annual level and a temporal annual-monthly disaggregation scheme. The temporal and spatial characteristics of the revised Great Lakes Residual NBS data base (1900-2008) were used with revised CSM-CARMA model parameters to generate a new data base, including all the lakes, for the Study (Fagherazzi, 2011). NBS sample statistics and the corresponding routed levels and outflows were compared with observed characteristics which verified that the generated NBS, as well as the routed levels and outflows series, reproduced the characteristics of the historical series very well. A resulting series of 55,000 annual and monthly NBS combinations, representing the randomly reconfigured statistical properties of the current climate was provided for plan formulation and evaluation.

NL-ARX Models

Two approaches combined contemporary climate data with longer-term inter-annual and decadal climate oscillations, such as the El Nino Southern Oscillation (ENSO). This was done using a non-linear auto-regressive model (NL-ARX) to develop two alternative stochastic models where the apparent shifts in the mean of annual NBS was explained using climate-related variables (Lee *et al.*, 2011). Shifts relate to a modelling assumption that the future NBS will exhibit the statistics of the past, and that the underlying process that produced the historical record is not changing over time. In this work, the shifts are presumed to be tied to climate indices. These approaches resulted in a series of 50,000 synthetic NBS values for plan formulation and evaluation.

Changed Climate NL-ARX Model

The final stochastic modelling technique utilized the stochastic NL-ARX model above to generate stochastic sequences of annual NBS with climate change-affected predictors produced by global climate models (GCMs)[8] (Seidou *et al.*, 2011). The outputs of the third generation of the Canadian General Circulation Model (CGCM3), under two climate scenarios representing moderate and high emissions of greenhouse gases, were used to calculate future values of the predictors. The model generated 500 sequences of 100 years (corresponding to years 2001-2100) for each of the two scenarios.

Assessing the Reliability of Historical Recorded and Estimated Data: Summary

The second theme of the Study's hydroclimatic analysis involved assessing the representativeness of historical variations and estimated data to provide insights into the potential impacts of climatic extremes and possible future trends.

Paleo-analyses enabled an extrapolation of prehistoric Great Lakes water levels over the past 1,000 years. The results identified a wide range of possible lake levels (maximum and minimum) for lakes Superior, Michigan-Huron and Erie.

Additional paleo-modelling was employed to generate 500 sequences of 100 annual NBS values. The modelling effort was able to replicate a variety of persistent high and low sequences that have occurred in the past, based on paleo-data, and which provide a better sense of estimating the likelihood of extreme lake levels and their persistence over time.

To obtain a greater understanding of the long-term variability of the past, four stochastic models were used to produce a wide range of plausible sequences of NBS not seen in the relatively brief historical record.

8 Also known as General Circulation Models or Global Circulation Models.

4.4 Theme 3: Assessing the Plausibility and Scope of Climate Change Impacts

Anthropogenic forcing of the climate system due to increasing concentrations of carbon dioxide and other gases are likely to lead to increased probabilities that by sometime in the 21st century the climate state in the upper Great Lakes basin will be outside the envelope of historically-observed conditions (IPCC 2007). The third theme of the Study's hydroclimatic analysis involved addressing the plausibility and scope of climate change impacts on NBS and water levels in the upper Great Lakes basin.

Figure 4-8 illustrates the Study's climate change modelling framework. As illustrated, the Study employed a number of approaches to address the possible impacts of climate change, including evaluating the validity of numerous model runs from GCMs and the applicability of utilizing the entire dataset or a subset of the runs. In addition, two RCMs were utilized to assess and derive down-scaled climate scenarios and current and future NBS sequences.

4.4.1 GCM Climate Modelling

To fully encompass estimates of the future climate of the Great Lakes, the Study first evaluated output of 565 model runs from 23 GCMs compiled by Angel and Kunkel (2010). The model runs utilized future emission scenarios B1, A1B, and A2 representing relatively low, moderate, and high emissions, respectively. Scenario A2 corresponds most closely to recent experience and International Energy Agency projections (International Energy Agency, 2007). The Study considered both the validity of the model runs and the applicability of utilizing the entire data set or a subset of the runs.

The analysis used the GLERL model to calculate NBS and lake levels for the current climate (covering the period 1970 to1999), using the input variables of maximum, minimum, and mean temperature, precipitation, humidity, wind speed, and solar radiation. For each of the GCM runs, change functions expressed as the difference between the current climate and each of the future time slices (2005-2034, 2035-2064, and 2065-2094) were calculated.

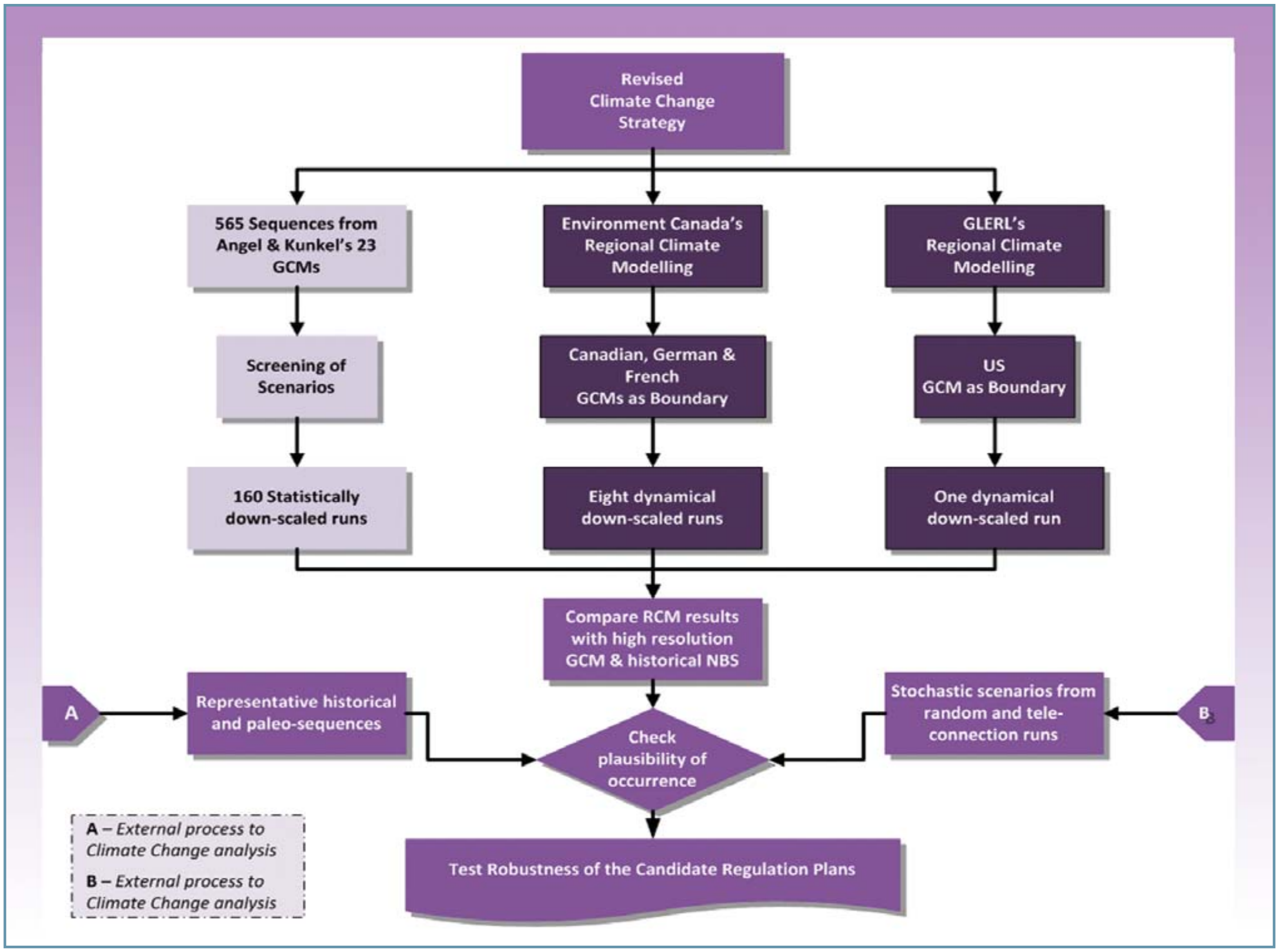


Figure 4-8 ***Climate Change Modelling Framework***

Table 4-3: Estimated Lake Level Changes for Lake Michigan-Huron at the 5th, 50th and 95th percentiles

Year	5th	50th	95th
B1 Emission Scenario			
2020	-0.60	-0.18	0.28
2050	-0.79	-0.23	0.15
2080	-0.87	-0.25	0.31
A1B Emission Scenario			
2020	-0.55	-0.07	0.46
2050	-0.91	-0.24	0.40
2080	-1.43	-0.28	0.83
A2 Emission Scenario			
2020	-0.63	-0.18	0.20
2050	-0.94	-0.23	0.42
2080	-1.81	-0.41	0.88

Source: Angel and Kunkel (2010)

Table 4-3 presents a summary of the results. The 50th percentile represents the projected change in lake levels where one-half of the scenarios predicts a greater difference while the other half predicts a lower difference for Lake Michigan-Huron. It is noted that 5 percent of the outcomes are lower than the 5th percentile and 5 percent of the outcomes are higher than the 95th percentile. Hence, these values are not the extremes.

In addition, it was noted that the results of the simulations varied widely for a single model, depending on the starting boundary conditions. Only a small number of models were run successively to determine the sensitivity and internal variability of model runs on initial conditions. These multiple runs bias the overall results shown in Table 4-3. Finally, in order to convert the precipitation forecasts for each of the models, a considerable degree of bias correction was needed, so as to convert the predictions to current values, often by a factor of five or six. The bias-corrected precipitation then had to be routed through the GLERL model and then the coordinated Great Lakes routing model. Hence the values shown in Table 4-3 are indicative rather than predictive.

4.4.2 Canadian Regional Climate Model – CRCM

The traditional approach of perturbing observed sequences of climate variables with fixed ratios or differences derived directly from GCMs in order to run conceptual runoff and evaporation models may not capture important land surface-atmosphere feedback processes, particularly for large bodies of water such as the Great Lakes (Mackay and Seglenieks, 2011).

The Study evaluated dynamical down-scaling using series GCMs boundary conditions with the Canadian RCM (CRCM) nested within these GCMs. The CRCM runs consisted of two different approaches:

- a multi-model, multi-member "ensemble" approach, based on data from eight simulations of the CRCM driven by three different GCMs; and,
- a high-resolution approach in which one of the eight simulations was further down-scaled using a variant of the CRCM known locally as the Great Lakes Canadian Regional Climate Model (GL-CRCM), developed for the Study.

CRCM Ensemble Runs

It is recognized that averaging the results of a multi-model, multi-member "ensemble" approach to analyzing the climate system – in which several simulations are generated, differing in some small way, such as through slightly perturbed initial conditions or different parameterization schemes – tends to produce better results than any individual simulation (*e.g.*, Hagedorn *et al.*, 2005; Tebaldi and Knutti 2007).

The Ouranos Climate Simulation Team[9] operationally produces CRCM simulations on the North American grid based on a number of driving GCM simulations, and archive monthly results for general use. The Study used precipitation, evaporation, and runoff data from eight of these simulations and derived estimates of NBS were inputted directly into the CGLRRM. Results were based on a 45-by-45 km (about 28-by-28 mi) horizontal resolution grid.

CRCM – High-Resolution Runs

To evaluate the GL-CRCM model performance in a future climate, it was important to evaluate the model under a current climate sequence. The most important difference running a current or future state relates to the nature of the forcing data applied at the lateral boundary conditions.

To perform climate change experiments relying on an RCM, the atmospheric lateral boundary conditions must be provided by a GCM. In the Study, the driving GCM was the Canadian CGCM3.1v2 (Scinocca *et al.*, 2008). Data were first down-scaled using the Ouranos version of the CRCM (CRCM4.2.3) over a North American grid of about 45-by-45 km (about 28-by-28 mi) horizontal resolution. This version of the CRCM did not include streamflow routing, but did have a simple lake model, which the driving GCM did not. Finally, results from the CRCM were used to drive the GL-CRCM on a 22.5-by-22.5 km (about 14-by-14 mi) horizontal resolution grid.

Bias Removal

Climate models generally simulate bias in water balance components that could have serious and lasting effects on any estimation of water level. If the nature of the bias is more or less time invariant, then the models can still be used to estimate changes in future climate with respect to present day climate. For example, if a model's simulated current climate is too wet over the Great Lakes region, and its simulated future climate is even wetter, then the model is suggesting an increase in precipitation (P) in the future: $P_{current}$ and P_{future} may be poorly simulated but $\Delta P= P_{future} – P_{current}$ might be quite reasonable and this information can be used to estimate changes in NBS and lake level. As is noted earlier, this "delta" approach is commonplace in most climate projections. In fact, all of the historical studies cited here have used this approach as a way to down-scale. The problem arises when the projected precipitation is substantially under-or over- predicted by the parent GCM, and the bias-correction requires the analyst to increase precipitation by a factor of five or more to adjust for actual present day values. This large adjustment of 500% brings into question whether this is a 'bias' or a systematic error in the GCM model.

In the Study, the bias-correction procedure made adjustments on NBS itself rather than on individual components. This approach is different from the cited literature, where typically, atmospheric forcing variable were bias-corrected using a delta approach. Mackay and Seglenieks, (2011) note the drawbacks of the more established methods and the benefits of bias-correcting NBS. The necessity for bias correction of climate model results for water resource applications is well known (*e.g.*, Wood *et al.*, 2004). However, it has been noted (Mackay and Seglenieks, 2011) that "there is no guarantee that the approach taken in these previous studies – that is, perturbing observed current climate precipitation and temperature with fixed ratios or differences deduced from simulation – does not disrupt interdependencies between these variables. Any such disruption could certainly distort water supply estimates."

9 Ouranos is a private, non-profit consortium of the Government of Quebec, Hydro Quebec, Environment Canada and Quebec universities on regional climatology and adaptation to climate change. It provides Canadian regional climate simulations and is a source of North American regional climate simulations. The GCM boundaries established by Ouranos were employed in the RCM for the Study.

By dynamically down-scaling using the GL-CRCM approach and bias-correcting the NBS rather than the individual components, two possible problems were avoided. First, one-way coupling of models (as in the approach taken by Angel and Kunkel [2010] and previous climate change studies) prevented any possibility of feedback between small-scale surface processes and the overlying atmosphere. Secondly, NBS sequences in the more traditional methods were derived from calibrated conceptual models. These calibrations may not be valid in a future climate regime, and there is no possible way to test for this. Thus, by using a two-way coupled dynamical down-scaling, modelling system, internal water balance components were at a minimum internally consistent.

4

Observed (monthly residual) and bias-corrected simulated annual NBS results for lakes Superior, Michigan-Huron and Erie are shown in Table 4-4. These differences appear to be within the range of differences of historical estimates between the GLERL and CRCMs (1948-2008).

Table 4-4: Relative Bias Between GL-CRCM and GLERL

	Superior	Michigan – Huron	Erie – St. Clair
Overlake Precipitation	5 %	2 %	10 %
Lake Evaporation	-9 %	-1 %	-9 %
Runoff	-9 %	7 %	-2 %
NBS	8 %	9 %	21 %

Observed estimates of mean annual NBS and its components (results summarized from MacKay [2008] with updated GLERL values) for 1998 – 2005. NBS = $P_L - E_L + Q$, where P_L is overlake precipitation, E_L is overlake evaporation, and Q is runoff.

To compare projected future NBS results with the present, the Study used summarized monthly means and standard deviations for the current (1962-1990) and future (2021-2050) climate periods as presented in Table 4-5. On average, the Study found that the mean monthly NBS for Lake Superior will increase by less than 1 percent, while that for Lake Michigan-Huron will decrease by about 2 percent. On the other hand, the reduction in NBS for Lake Erie is more substantial, at about 8 percent. For all the lakes, increases in monthly standard deviation are larger, ranging from 7 percent for Lake Erie to 22 percent for Lake Superior.

Table 4-5: Monthly NBS mean (standard deviation) Statistics for Bias-corrected Simulation

NBS	Observed = GL-CRCM 1962-1990	GL-CRCM 2021-2050	Change
Superior	67.9 (70.5)	68.3 (86.3)	0.4 (15.8)
Michigan – Huron	74.8 (69.7)	73.2 (79.2)	-1.6 (9.5)
Erie	82.7 (106.6)	74.9 (113.8)	-7.8 (7.2)

(1962-1990, and 2021 – 2050) (mm over lake)

To put these results in context with the previous work, water level estimates using the CCLRGM lake-routing model were also derived. Simulated lake levels for the current climate period for lakes Michigan-Huron and Erie indicated a small positive bias with respect to observed: 2 cm (0.8 in) and 7 cm (2.8 in) respectively (IUGLS, 2012). In addition, the current climate standard deviation is significantly underestimated for these lakes. Ensuring that the mean and standard deviation of simulated NBS matches the observed does not guarantee that mean and standard deviation lake levels will also agree with observed. Levels will depend somewhat on the actual sequence of NBS, which could never be captured by a climate model unless it was forced with observed data (which is not possible in a climate change experiment). However, it is possible that some of this bias could be removed with model improvements.

Table 4-6 summarizes the final bias-corrected version of the estimates NBS components for the current climate period (1961 – 1990) from the simulations. This calibration formed the basis for calculating NBS for the representing Study's design period of 2040. The annual pattern is similar for overlake and overland precipitation. The ARPEGE model is drier than the other models on a consistent basis, while the ECHAM5 model is typically wetter for lakes Superior and Michigan-Huron. The lake evaporation shows the greatest deviation between the GLERL and CRCM data. These results suggest that the eight simulations are all qualitatively reproducing the gross features of the average seasonal cycle in NBS components. Though the sample is small, it appears that results of the CRCM when driven with the ARPEGE model tend to be on the dry side, while those driven with the ECHAM5 model tend to be on the wet side, with the CGCM intermediate between the two. Nevertheless, all of the simulations show bias, which is clearly evident in the computed mean annual NBS results.

Table 4-6: Summary of Observed (GLERL) and Simulated Average Annual NBS Components for 1961-1990

Component	Lake	GLERL	CGCM	ECHAM5	ARPEGE
Lake Precipitation (mm over lake)	Superior Michigan-Huron Erie	796.5 840.7 931.8	663.3 782.5 972.6	783.6 862.3 971.5	554.2 626.4 749.2
Lake Precipitation (mm over lake)	Superior Michigan-Huron Erie	584.0 630.1 896.5	452.5 627.6 750.2	454.0 622.6 742.2	441.1 619.0 728.2
Land Precipitation (mm over land)	Superior Michigan-Huron Erie	821.1 854.5 919.7	675.4 809.1 976.6	786.6 889.1 988.7	594.6 654.9 782.0
Land Precipitation (mm over land)	Superior Michigan-Huron Erie	408.6 511.1 563.7	458.8 536.1 644.6	450.0 542.6 647.1	454.6 505.0 590.7
Runoff (mm over lake)	Superior Michigan-Huron Erie	412.5 343.4 356.1	216.8 272.8 329.8	337.6 346.0 340.6	140.5 151.5 191.8

Explanation: Simulated results are labeled by the driving GCM. Results from simulations driven by GCMs with more than one ensemble member are averaged to highlight differences in driving GCM. The values in column 3 are the average values for the GLERL based components in mm for the period of 1961-1990 representing observations. Columns 4 through 6 are based on CRCM simulations using different GCMs: CGCM (Canadian), consisting of five ensemble members; ECHAM2 (German) consisting of two ensemble members; and an experimental GCM, ARPEGE (French), with one ensemble member.

4.4.3 Coupled Hydrosphere Atmospheric Research Model – CHARM

The Study also assessed future climate variability through the use of the Coupled Hydrosphere-Atmosphere Research Model (CHARM) (Lofgren and Hunter, 2011). CHARM is a regional climate model that simulates both the atmosphere and the land and lake surfaces in the Great Lakes basin. The model includes full interaction between the surface and the atmosphere and calculates runoff on a 40-by-40 km (about 25-by-25 mi) grid. CHARM model simulation of overland temperatures, overland precipitation, overlake precipitation, surface water temperature, and evaporation revealed somewhat similar results as the CRCM analysis.

The experimental model runs involved two time slices of simulation, representing the historical years of 1964-2000 and future projections for 2043-2070. These were run under observed carbon dioxide concentrations during the historical period and under the A2 emission scenario (IPCC, 2000) in the future.

NBS simulation results are shown in Figure 4-9. The figure depicts an increase in NBS during the late spring and early summer in the Lake Superior and Lake Michigan-Huron basins. Notable increases still occur during December and January, while decreases occur during the fall in the Lake Superior basin.

Results from Lofgren and Hunter (2011) also showed that the air temperatures over the land portions of the basin increase in a highly consistent way throughout the year and in all basins. The precipitation changes (*i.e.*, the differences between future and current values) generally increase, but are variable by month and basin. One of the consistent changes is that increases in precipitation occur more strongly over the land near the lakes during the summer and directly over the lakes during the winter, shifting to the areas in which they naturally occur more during those seasons because of static instability of the atmosphere. The lake surface temperatures increase during all seasons, with the greatest increase during the summer. The evaporation from the lakes shows slight increases, governed by available energy and limited by the moistening of the atmosphere that accompanies increased evaporation. The changes in NBS due to increased greenhouse gases are generally small increases. As in the case of the CRCM runs bias-correction procedures for NBS were applied.

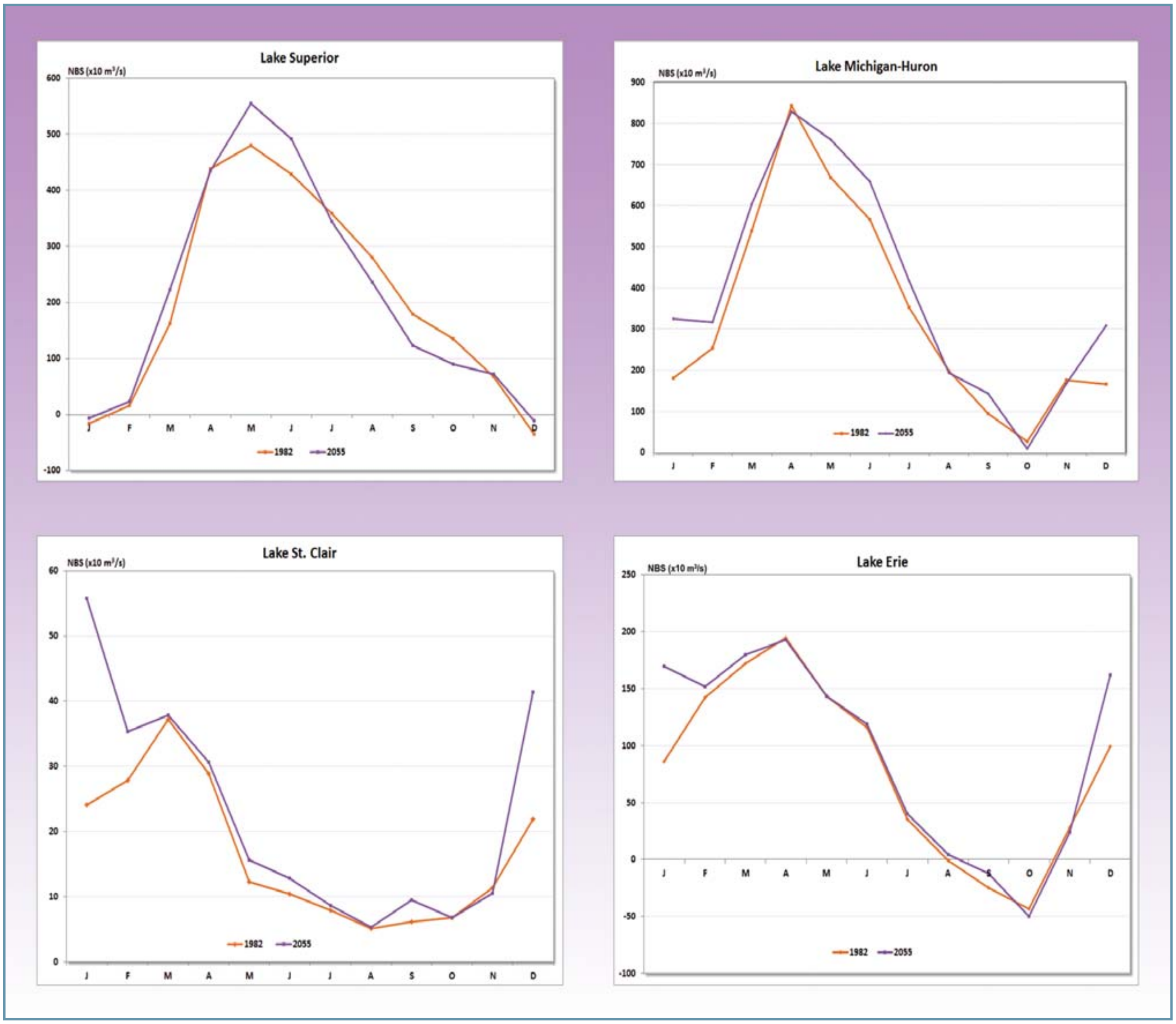


Figure 4-9 **Climatological NBS, CHARM**

4.4.4 Integration of Results

The Study's hydroclimatic analysis has advanced the understanding of climate change science and analysis in general and, in particular, the application of climate science to the Great Lakes setting. Figure 4-10 illustrates the integration of the Study's hydroclimatic analysis.

The figure shows the changes in the NBS for the design period of year 2040, comparing the results of statistically down-scaled GCMs with results of dynamical down-scaled GCM projections. The statistical modelling results are more varied for different model resolutions. For example, from the 160 different runs, the NBS of Lake Superior varies from a decrease of 245 mm (9.65 in) for a fine resolution of 1.4 degrees to an increase of 159 mm (6.26 in) for a coarse resolution of 4.53 degrees. For the eight dynamical down-scaled computations, the corresponding changes were a decrease of 135 mm (5.32 in) and an increase of 85 mm (3.35 in) at a resolution of 1.9 degrees. (Resource constraints limited the number of dynamical runs used in the analysis.)

Statistically Down-scaled GCM Projections

The GCM projections suffered from a lack of validation with the historical record. Nonetheless, the projections did inform the decision-making process. In particular, the projections described a range of possible future climates that included significant increases and decreases in mean NBS. The results were based on a future climate that is generally consistent with current understanding of the climate system and expectations of climate change.

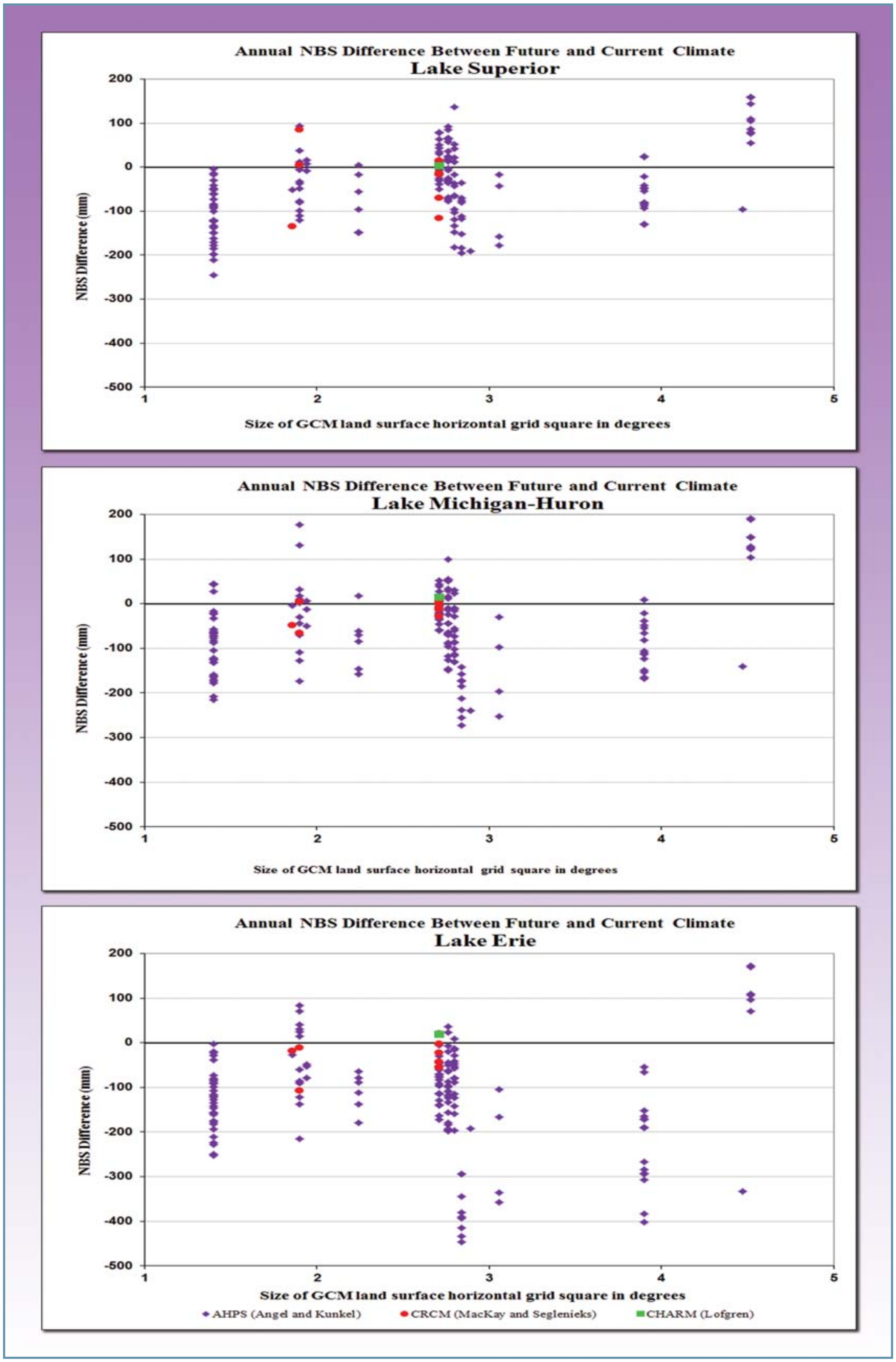


***Figure 4-10** Climatological Comparison of Statistically and Dynamical Down-scaled Model Results*

Dynamical Down-scaled GCM Projections

As noted in 4.4.2, dynamical down-scaling approaches use a RCM that takes boundary conditions from GCM projections as inputs and fully resolves the climate conditions, including local feedbacks, at a much higher resolution over a smaller area. They appear to be of particular value over the lakes because the lake dynamics (including thermal dynamics in the lakes) affecting the local climate are included in the regional models but not in the GCMs. A drawback of higher resolution is that the computational intensity of the regional simulations often limits the number of runs that can be performed and the length of those runs. The regional climate runs also exhibited differences with mean climate in historical runs with respect to NBS and the individual components. In both cases, only NBS bias corrections were applied to allow for the individual components to remain coupled to the atmospheric and land-surface dynamics being simulated by the coupled model. A statistical bias correction was required to produce realistic historical NBS values from the RCM runs, and this same correction was applied to future projections. The results showed smaller differences from statistical down-scaling from the same GCMs.

Stochastic NBS Sequences

In contrast to visions of the future provided by GCMs, stochastic or statistical approaches use the historical record of NBS as the basis for creating NBS series that are representative of the future. The stochastic NBS sequences are compromised by the reliance on an assumption of stationarity. There are clear physical reasons for doubting the validity of that assumption (Milly *et al.*, 2008). However, due to the limitations in the GCM projections for the Great Lakes region, it is clear that at present there is no satisfactory representation of future climate on that time span. A sound planning principle, therefore, is to make decisions in such a way as there is not an over-reliance on the projections of future climatic and lake level conditions of any one particular approach.

4.5 Application of the Findings

4.5.1 Knowledge and Products Gained from the Study

A major goal of the Study was to bring the best possible hydroclimatic science to bear on selecting a robust regulation plan. In working towards that objective, the Study included state-of-the-science climate projections from one of the largest ensembles of GCM runs ever assembled for a regional study, regional climate modelling from two separate national modelling centers, a variety of statistical modelling approaches and innovations in modelling of the lake system's responses to climate. In addition, paleo-climate data analysis, new observational ability in the form of two new eddy flux towers

Assessing the Plausibility and Scope of Climate Change Impacts: Summary

The third theme of the Study's hydroclimatic analysis involved assessing the plausibility and scope of climate change impacts on NBS using established down-scaling techniques and new modelling work.

Results of the GCM simulations varied widely for a single model, depending on the starting boundary conditions. Only a small number of the models were run successively to determine the sensitivity and internal variability of model runs on initial conditions. Finally, in order to convert the precipitation forecasts for each of the models, a considerable degree of bias correction was needed.

The Study evaluated dynamical down-scaling using series GCMs boundary conditions with the CRCM model nested within these GCMs.

Climate models generally simulate bias in water balance components that could have serious and lasting effects on any estimation of water level. The Study addressed this bias by making adjustments on NBS itself rather than on individual components.

The Study assessed future climate variability through the use of CHARM, a regional climate model that simulates both the atmosphere and the land and lake surfaces in the Great Lakes basin. The results showed considerable seasonal variation in NBS. NBS increases during the late spring and early summer in the Lake Superior and Lake Michigan-Huron basins. Notable increases still occur during December and January, while decreases occur during the fall in the Lake Superior basin.

In the near term (*i.e.*, 30 years) the stochastic NBS series provides a useful representation of future climate uncertainty. The current record of Great Lakes NBS appears continuingly stationary, marked by strong inter-annual and decadal variability, and showing no response that may be attributable to climate change. During the Study's planning period "natural variability" is likely to mask any forcing due to greenhouse gas emissions.

In terms of the limits of the Study's hydroclimatic analysis, perhaps most notable from the perspective of effective lake regulation is how little the lake dynamics on inter-annual and decadal timescales are understood. Despite best efforts, the lake levels remain almost entirely unpredictable more than a month ahead.

for open water evaporation measurement, new measurements of channel characteristics in the St. Clair River were incorporated into the Study. The findings represent major steps forward in improving understanding of the largest regulated freshwater system in the world.

Despite this effort, the current understanding of the Great Lakes system in terms of the factors that will affect the performance of a regulation plan can only be described as "fair." There is a long record of lake levels and a reasonable understanding of the regulation and NBS that produced those levels. There are numerous major modelling and data collection efforts. Nonetheless, the long record of historical observations is actually quite sparse spatially, because the greatest area of the basin is comprised of the lake surfaces. There are only spatially sparse and temporally short recorded observations in these overlake areas. Also, as discussed earlier, the greatest uncertainty in NBS is the runoff due to incomplete gauging of the land area. Thus, a comprehensive understanding of lake water balances remains elusive, despite major gains made in this Study.

Perhaps most notable from the perspective of effective lake regulation is how little the lake dynamics on inter-annual and decadal timescales are understood. On decadal time scales, there is clear evidence of temporal structure (*e.g.*, years of high levels followed by years of low levels) that could not be explained. Despite best efforts, the lake levels remain almost entirely unpredictable more than a month ahead (notwithstanding a finding of small prediction skill for predicting spring tendencies on Lake Superior only, from the preceding fall in years not affected by ENSO). Based on the historical record, there appears to be a specific range within which the lake levels are likely to fluctuate. However, paleo-records indicate a range that may have been greater. In terms of understanding the lakes system relative to lake levels, the unavoidable conclusion is that Great Lakes are a complex system whose dynamics are only partially understood.

This current state of understanding has its limitations for deriving predictions of the future. As described next, the Study used a variety of approaches to generate future climate scenarios. The approaches can be categorized generally as GCM-based and those based solely on the historical record (and paleo-climate analogs).

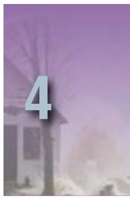


Table 4-7 summarizes the hydrological time series developed by the Study for the hydroclimatic analysis. The different approaches used by the Study were designed to provide an array of plausible future climate sequences for the other components of the Study, including formulating regulation plans and evaluating their performance under a wide range of sequences, and examining the potential for restoration structures, multi-lake regulation and adaptive management.

Table 4-7: Summary of the Study's Hydrological Time Series

Outcome	Product	Product Components
Analysis of Observations	Historical Residual NBS Sequences[1] 1860-1899	1860-1899
	Historical Residual NBS Sequences 1900-2008	1900-2008
	Historical Component NBS Sequences 1948-2006	1948-2006
Derived Sequences from Residual NBS	Stochastic Sequence of Contemporary Residual Supplies	55,000 years
	Stochastic Sequence of Contemporary Residual Supplies using ENSO indicator	50,000 years
	Stochastic Sequence of Contemporary Residual Supplies using NCEP 500 mb anomalies indicator	50,000 years
	Paleo-sequence	1000 years
Climate Model-Driven Climate Change Scenarios	Stochastic Sequence with Climate Change emission scenario A2	500 sequences of 100 years of monthly NBS
	Stochastic Sequence with Climate Change emission scenario A1b	500 sequences of 100 years of monthly NBS
	RCM Sequence	8 Ouranos 45 km runs
		2 RCM 22.5 km runs
	RCM Sequence	2 CHARM 40 km runs
	Angel and Kunkel Analysis	~500 Angel and Kunkel time slices (A2, A1B, B1 emission scenarios)

1 *The estimates of historical NBS for the period 1869 to 1899 are good only for Lake Superior. The NBS values for downstream lakes cannot be estimated with confidence in view of unknown connecting channel conveyances.*

4.5.2 Application of the NBS Sequences and Climate Scenarios for Decision Making

The Study's hydroclimatic analyses resulted in the development of NBS sequences for each of the upper Great Lakes that would reflect potential climate change impacts. These sequences served as critical inputs into the other key analyses of the Study.

Regulation Plan Formulation and Evaluation

As described in **Chapter 5**, of the hundreds of future climate change scenarios derived for the plan formulation and adaptive management studies, 13 were chosen for detailed plan formulation and evaluation. These 13 represented the full range of scenarios that would test the limits of any new proposed regulation plan. Thus, the scenarios allowed the Study Board to test candidate Lake Superior regulation plans for "robustness" – the capacity to meet particular regulation objectives under a variety of uncertain future water level conditions.

The work on plan formulation and evaluation directly related lake level fluctuations to critical threshold levels relevant to each of the key six interests served by the upper Great Lakes system. The Study applied performance indicators (PIs) to compare and evaluate the relative performance of each economic sector or interest under the range of historical and anticipated lake level fluctuations across all sectors and lakes.

Adaptive Management

The NBS sequences were inputs into the Study's analysis of the role that adaptive management can play in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels. As described in **Chapter 9**, the Study explored the relationship between future lake level fluctuations and the impacts on the key interests through the development of coping zones.

Restoration and Multi-lake Regulation

The NBS sequences developed in the hydroclimatic analysis were also available for two other areas of the Study's work, but ultimately were not used.

As described in **Chapter 7**, the Study conducted an exploratory analysis of the feasibility and impacts of non-adjustable restoration structures that would permanently raise Lake Michigan-Huron water levels. Historical residual NBS were applied to study the potential impacts of restoration over the 109-year period from 1900 to 2008. Additional scenarios were not used because of the uncertainty in future NBS and because restoration structures would have a fixed/non-adjustable effect on lake levels.

In **Chapter 8**, the Study also examined 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. This analysis required NBS sequences and evaluation points downstream from Niagara Falls, including the lower St. Lawrence River. The NBS sequences developed for the Study did not extend beyond the upper Great Lakes basin, as they were intended to support work on Lake Superior regulation. Therefore, the multi-lake regulation analysis used eight NBS scenarios chosen from the 50,000-year stochastic NBS dataset produced for the Lake Ontario-St. Lawrence River Study (International Lake Ontario-St. Lawrence River Study Board, 2006). These eight scenarios were based on the same approach used in this Study, and 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.

4.6 Key Points

The Study undertook extensive analysis to improve understanding of the hydroclimatic forces at work in the upper Great Lakes basin and their likely impacts on future water levels. It also considered how the uncertainties in the hydroclimatic analysis could influence the evaluation and decision-making framework. Based on this analysis, the following points can be made:

- The first major task of the Study was to examine the hydrology and climate of the upper Great Lakes, focusing on changes to the contemporary hydrology affecting the levels of the lakes and the impacts of future climate variability and change. Three themes were central to Study's analytical framework:
  - understanding the water balance of the Great Lakes;
  - assessing the reliability of historical recorded and estimated data; and,
  - addressing the plausibility and scope of climate change impacts on water supplies through new modelling work.
- The Study sought to improve the accuracy and consistency in NBS estimates through modification of existing models, development of new models, collection of new data, and improvement of a range of methodologies that have been used for lake level estimation. It was concluded that the improved estimates of runoff and overlake precipitation still incorporate and introduce significant uncertainty into the overall water balance. Continued efforts in modelling coupled with improved observation techniques are needed to "close the water balance" (*i.e.*, to reduce the uncertainty to as close to zero as possible).

- Perhaps most striking from the perspective of effective lake regulation is how little the lake dynamics on inter-annual and decadal timescales are understood. Despite best efforts, the lake levels remain almost entirely unpredictable more than a month ahead. In terms of understanding the lakes system relative to lake levels, the unavoidable conclusion is that the Great Lakes basin is a complex system whose dynamics are only partially understood.
- Without substantially increased confidence in historical NBS estimates for both residual and component supplies and an understanding of the uncertainty associated with these estimates, choosing plausible futures in the context of past events is highly problematical.
- In general, information from GCMs introduced more uncertainties that are very difficult to reconcile with historical data.
- Determination of climate change impacts on NBS using RCM tools provided insights into the dynamics of the hydroclimatic systems that are not possible through statistical down-scaling. Features such as local feedback and recycled evaporation are not captured in any of the GCMs. These aspects advanced scientific knowledge in this area. Due to the limited number of RCM runs, however, the full range of impacts was not assessed.
- Despite these uncertainties, it is clear that lake evaporation is increasing and likely will increase for the foreseeable future, likely due to the lack of ice-cover, increasing surface water temperatures and wind speeds. Analysis indicates that in the Lake Michigan-Huron basin, this increased evaporation is being largely offset by increases in local precipitation.
- In the Lake Superior basin, however, increasing evaporation over the past 60 years has not been compensated for by increased precipitation. As a result, NBS have been declining in general in the basin. This trend is consistent with the current understanding of climate change. Unless changes in the precipitation regime occur, which is possible, NBS in Lake Superior will continue to decline, on average, despite the possibility of higher supplies at times. It will be important to ensure that further climate analysis be undertaken to explore these dynamics and provide more certainty of future NBS estimates.
- The very short record of measured evaporation initiated by the Study suggests that earlier evaporation amounts may be over-estimated. However, regardless of differences in absolute evaporation measurements, the trends in increased evaporation rates, inferred from the earlier estimates, are thought to be reasonably reliable.
- As a result, changes in lake levels in the near-term future may not be as extreme as previous studies have predicted. Lake levels are likely to continue to fluctuate, but still remain within the relatively narrow historical range. While lower levels are likely, the possibility of higher levels at times cannot be dismissed. Both possibilities must be considered in the development of a new regulation plan.
- Beyond the next 30 years, some projections by GCMs and RCMs of more extreme water levels in the upper Great Lakes may have more validity. However, due to the limitations of these models for this region, there is, at present, no completely satisfying representation of future water balance (*i.e.*, one that takes fully into account water recycling within the basin).
- Therefore, in terms of water management and lake regulation, the best approach is to make decisions in such a way as to not overly rely on assumptions of particular future climatic and lake level conditions or specific climate model projections. *Robustness* – the capacity to meet regulation objectives under a broad range of possible future water level conditions – must be a primary attribute of any new regulation plan.
- The plausible NBS sequences and climate change scenarios developed by the Study's hydroclimatic analysis served as critical inputs into the formulation and evaluation of candidate Lake Superior regulation plans and the analysis of the role that adaptive management can play in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels.

4.7 Recommendation

The Study's comprehensive hydroclimatic analyses has established a new standard that should be used as the starting point for water level planning and related research conducted in the future. However, considerable work remains – the Study's analyses using a range of approaches showed that assessing the uncertain impacts of climate variability and change on upper Great Lakes water levels will continue to be a challenging task. The Study identified important avenues to be pursued in the near- and medium-term to improve understanding of these impacts and their implications for regulation.

In particular, the Study's strategy brought state-of-the-art modelling tools to the challenge of evaluating climate change impacts in the upper Great Lakes region. The use of RCMs with GCM-driven boundaries, while not producing differences in the final NBS estimates, provided insights into the dynamics of the hydroclimatic systems that are unavailable with statistical down-scaling. Further work on additional runs of these RCMs with GCM-driven boundaries, is needed to build on these promising preliminary results.

In its first report to the IJC, ***Impacts on Upper Great Lakes Water Levels: St. Clair River***, the Study Board identified a number of specific "legacy" recommendations regarding strengthening data collection, scientific knowledge and institutional capacity (IUGLS, 2009). In this final report, the Study Board reiterates those recommendations and in particular, notes the need for support and expansion key data collection programs (*e.g.*, evaporation gauges, International Gauging Stations). Long-term data collection continues to be essential for improving scientific understanding of how the Great Lakes system functions and how it is – and is likely to be – affected by both natural forces and human activities.

To better link this work to planning and decision-making across the Great Lakes basin, these scientific initiatives would be most effectively undertaken in a coordinated, bi-national manner. The proposed water levels advisory board, described in **Chapter 9**, could be given responsibility for this task.

Based on these findings, the Study Board makes the following recommendation:

The IJC should seek to improve scientific understanding of hydroclimatic processes at work in the Great Lakes basin and the impacts on future water levels as part of a continuous, coordinated bi-national effort. In particular, the IJC should endorse the following initiatives as priorities and strongly recommend ongoing government support:

- *strengthening climate change modelling capacity in the Great Lakes basin in light of the promising preliminary results identified in the Study; and,*
- *enhancing hydroclimatic data collection in the upper Great Lakes basin.*

Chapter 5

Framework for Developing a New Lake Superior Regulation Plan

Chapter 5 describes the framework and the tools that were developed to help the Study formulate, evaluate and rank candidate plans for Lake Superior regulation.

5

5.1 Introduction[1]

This chapter sets out how the International Upper Great Lakes Study (the Study) approached the challenge of formulating, evaluating and ranking alternative regulation plans. **Chapter 6**, in turn, describes how the Study Board applied this framework and these tools to evaluate and rank candidate Lake Superior regulation plans, and to identify a preferred plan for recommendation to the International Joint Commission (IJC).

5.1.1 Rationale for Reviewing the Current Regulation Plan

During its 100-year history, the IJC has progressively evolved its management approach for the Great Lakes in response to changing economic, environmental and social needs across the basin. Throughout this evolution, a core set of management principles has developed through a series of updated regulation plans for Lake Superior and the Great Lakes system in general. These principles are embodied in the form of official Orders of Approval and Supplementary Orders from the IJC. Each iteration of Orders has reflected a specific need (*e.g.*, hydropower or commercial navigation) or addressed a particular problem of either high lake levels or low water conditions.

As a result, when the IJC establishes a new study to develop a new set of regulation plans that seek to improve the effectiveness of lake level management, there already exists a substantive hierarchy of management principles that can be transformed into a set of planning guidelines, plan performance objectives and evaluation criteria. In this sense, the existing plan, **1977A**, in effect since 1990, represents the culmination of nearly 75 years of lake level management experience.

Several important factors have emerged since **1977A** was implemented in 1990. Taken together, these factors provide a sound rationale for reviewing the current regulation plan.

First, as described in **Chapter 4**, there is considerable uncertainty about water supplies or net basin supplies[2] (NBS) and corresponding water levels in the Great Lakes basin in the future as a result of natural climate variability and human-induced climate change. Compounding the effects of climate variability and change is a second force affecting water levels – the adjustment of the earth's crust, known as glacial isostatic adjustment (GIA). As described in **Chapter 1**, the differential adjustment of the earth's crust has the effect of gradually "tilting" the Great Lakes basin over time. The impact of GIA is particularly noticeable along the shorelines, where features on the rising or subsiding land can be compared directly to water levels and near-shore depths. The **1977A** plan has never been tested under a variety of potential climate change scenarios, nor was it designed to take into account the effects of GIA, the importance of which has only recently been generally recognized. As a result, the IJC did not know how well **1977A** would perform under extreme conditions that are outside the historical record or in response to GIA effects.

1 This chapter is based on peer-reviewed work undertaken by the Study's Plan Formulation and Evaluation Technical Work Group (TWG) (IUGLS, 2012).

2 Net basin supply (NBS) is the net amount of water entering a lake, consisting of the precipitation onto the lake minus evaporation from the lake, plus groundwater and runoff from its local basin, but not including inflow from an upstream lake.

Second, there is much better information available today than 20 years ago about the hydrology and hydraulics of the Great Lakes. Researchers have more confidence in the current models that describe how the system performs under a variety of conditions. New knowledge has also been gained through recent investigations, such as the Study's own analysis of the changes in the conveyance of the St. Clair River (IUGLS, 2009a). This improved knowledge and modelling was able to be factored into the development of a new Lake Superior regulation plan.

Finally, there is a much better information base about the different water-using sectors and public interest concerns that any new regulation plan must address. As described in **Chapter 3**, under the *Boundary Waters Treaty of 1909*, *domestic and sanitary water uses, navigation*, and *power*[3] *and irrigation* are given order of preference. These uses must be taken into account in developing regulation plans. However, the Treaty also requires that the needs of other interests, such as ecosystems, coastal zone uses and recreational boating and tourism, be taken into account, as well. This information on the various key interests served by the upper Great Lakes basin is needed to develop a sound and replicable comparative basis for impact analysis of the various plans, consistent with the IJC's principle of balancing the needs of the key interests.

5.1.2 IJC Directive to the Study

The IJC Directive to the Study dealing with the regulation of Lake Superior was to:

> "*. . . review the operation of structures controlling Lake Superior outflow in relation to impacts of such operations on water levels and flows, and consequently affected interests; assess the need for changes in the Orders or regulation plan to meet the contemporary and emerging needs, interests, and preferences for managing the system in a sustainable manner, including under climate change scenarios; and evaluate any options identified to improve the operating rules and criteria governing Lake Superior Outflow regulation*"

Figure 2-3 in **Chapter 2** illustrates the overall regulation plan formulation and evaluation analytical framework developed by the Study to address its mandate under the Directive.

5.1.3 Study Approach

The central challenge to the Study was to identify a regulation plan that performed better than **1977A** under both the historical NBS conditions and a wide range of uncertain NBS conditions resulting from climate variability and human-induced climate change. The Study's hydroclimatic analysis, described in **Chapter 4**, concluded that low NBS extremes may well occur, but high extremes are also plausible and both must be considered in the development of a new regulation plan.

The Study's approach to plan formulation, evaluation and ranking applied the following steps:

- reviewing the *historical context* for Lake Superior regulation, which can serve as the foundation for the Study Board's planning and decision making (section 5.2);
- establishing an *evaluation framework* focused on directly relating lake level fluctuations and critical threshold levels to impacts on key interests, through tools such as performance indicators and coping zones, and based on a *shared vision planning* process that supported collaborative decision making (section 5.3);
- selecting 13 *NBS sequences* from the Study's hydroclimatic analysis as representative of the range of plausible future climate change scenarios that could be used to test regulation plan options for robustness – the capacity to meet particular regulation objectives under a broad range of possible future water level conditions (section 5.4); and,
- Developing a set of nine *decision criteria* to enable the Study Board to compare the performance of each plan option against other options and for reference purposes against the existing the **1977A** plan and preproject conditions (section 5.5).

5.2 History of Regulating Lake Superior Outflows

Developing a new regulation plan that will perform better than the existing plan was a significant challenge. A useful starting point for the Study was to identify the rationale for various types of plans that led up to the development of the **1977A** plan, the characteristics of all the preceding plans and the conditions that led to changes in those plans.

Preproject Releases

The "preproject" releases from Lake Superior represent the hypothetical condition of the absence of any regulation control structures, a standard against which the impacts of any regulation plan can be measured. It is not possible to know exactly what those releases would be, as the system has not been in a natural state since about 1887 and there is little reliable information about the flows, levels or physical configuration of the controlling sections of the river at that time. However, a hydraulic equation (*i.e.*, discharge rating

3 In interpreting the Treaty, "power" is taken to mean hydroelectric power.

curve) has been developed to estimate the flows, based on some historical flow measurements from that period (see box) (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data [CCGLBHHD], 1970; Quinn, 1978; Southam and Larson, 1990).

Preproject flow releases are triggered by the existing plan when water levels become low. The preproject release rule is an important reference because it can be used to estimate what the lake levels and consequent impacts on riparian interests would have been prior to the *Boundary Waters Treaty of 1909*. It also can serve as a benchmark for estimating natural environmental conditions.

Estimating Preproject Releases

Preproject release (in m^3/s) = 824.7 × (Lake Superior water level in m - 181.43 m)$^{1.5}$

Where:

- 824.7 is a constant computational parameter related to the lake's outflow width and weir coefficient
- 181.43 m is the sill elevation at the Lake Superior outlet below which outflow will cease
- 1.5 is a power exponent to depict weir flow at the lake outlet prior to the construction of the compensating works

Evolution of Plans

As described in **Chapter 1**, the IJC issued Orders of Approval in 1914 for hydropower development on the St. Marys River and the first Lake Superior regulation plan was implemented in 1921. Since 1921, seven different regulation plans have been used to determine Lake Superior outflows:

- Sabin Rule (1921-1941);
- Rule P-5 (1941-1951);
- Rule of 1949 (1951-1955);
- 1955 Modified Rule of 1949 (1955-1979);
- Plan SO-901 ("guide" 1973-1979);
- Plan 1977 (1979-1990); and,
- Plan **1977A** (1990-present).

The early generation of regulation plans considered only the level of Lake Superior in determining the outflow, because they were designed to comply with the 1914 Orders.

In the 1940s, construction of the Long Lac and Ogoki Diversions brought an average additional 160 m^3/s (5,650 ft^3/s) supply of water into Lake Superior starting.[4] These diversions were constructed as part of WWII requirements for more hydroelectricity for industrial production and increased reliability for navigation. The additional supply of water required a change in the regulation plan because the rule curves used in the previous plan, Rule P-5, would otherwise have underestimated the release needed at any Lake Superior elevation, causing a permanent rise in Lake Superior.

Although the Rule of 1949 was intended to adjust the release to accommodate the extra water, it actually lowered Lake Superior levels. The new plan was modified in 1955 to correct these releases. This 1955 Modified Rule of 1949 Plan was used for 22 years and represents the last plan based solely on Lake Superior levels. The relevance of this plan is that it provides a useful baseline for measuring the impacts of the IJC's management principle of balancing the needs of the various key interests across the basin.

During an IJC study from 1964 to 1973 (International Great Lakes Levels Board, 1973), an experimental plan was developed that used the concept of balancing the levels of lakes Superior and Michigan-Huron. That plan, known as Plan SO-901, was used as a guide for Lake Superior outflow regulation during the mid-1970s.

Plan 1977A

In May 1977, the IJC requested that the International Lake Superior Board of Control prepare a revised regulation plan that would provide benefits to the interests throughout the Great Lakes system without undue detriment to Lake Superior interests. In September of that year, the Board of Control submitted a report on the development and evaluation of plan 1977, which was a refinement of SO-901. Plan 1977 was officially adopted in October 1979. Further improvements led to the development of **1977A**.

Plan **1977A** has a number of outflow limitations to meet the regulation criteria and requirements of the IJC Orders. For example, one outflow limit serves to prevent excessive lowering of the levels of Lake Superior, while another prevents high water level conditions in the lower St. Marys River at Sault Ste. Marie. The regulation plan also has a limit on maximum allowable outflow in the winter to reduce the risk of ice jams and associated flooding in the lower St. Marys River.

4 The Long Lac and Ogoki diversions direct southward to Lake Superior a portion of water that otherwise would have flowed north into the Hudson Bay drainage system.

In the monthly Lake Superior outflow, as specified by **1977A**, a small allocation is first made to meet the needs of municipal and industrial waters uses, operate the navigation locks, and provide sufficient flow to maintain the aquatic habitat of the St. Marys River. The remainder of the flow is allocated equally to hydroelectric facilities in the United States and Canada to generate electricity. If the amount of water available for hydropower generation exceeds the capacities of the hydropower plants, the excess is released by opening one or more of the 16 gates in the compensating works on the St. Marys River (Figure 5-1).

To meet the demand for hydroelectricity, which fluctuates over the course of the day and week, the St. Marys River hydroelectric generating plants vary their hourly flows to better match the demand. The plants will increase releases during the day on weekdays ("peaking"), when demand for electricity is higher, and reduce releases at night and on weekends ("ponding"), when electrical demand is lower, while on average equaling the monthly release allotment. These flow variations cause water levels to fluctuate downstream of the plants and in the lower St. Marys River. Peaking and ponding operations are carried out with the approval of the IJC, but they must still meet the downstream depth conditions for navigation.

The International Lake Superior Board of Control is responsible for implementing the plan and monitoring the hydrological conditions of the upper Great Lakes basin. Under certain conditions, the IJC approves deviations from the regulation plan or changes to gate settings at the compensating works on the advice of the Board of Control. These deviations may include flow changes to: accommodate repairs at the hydroelectric facilities or the compensating works; support flow measurements; allow sea lamprey trapping that typically takes place in the summer; or, deal with unusual water supply conditions. Deviations from **1977A** have been rare.

Supplementary Orders

In 1978, two Supplementary Orders permitted the redevelopment of the Canadian hydroelectric facilities at Sault Ste. Marie, ON and the protection of the St. Marys River fishery.

The 1979 Supplementary Order updated a number of the conditions governing the regulation of outflows through the structures at Sault Ste. Marie. This Order recognized that the Lake Superior water levels could not be regulated within the narrow 0.46 m (1.5 ft) range specified in the 1914 order and, while it maintained the upper level limit of 183.86 m (603.2 ft) of the 1914 order, it lowered the minimum level limit to 182.76 m (599.6 ft), near the historical minimum Lake Superior level recorded since regulation began.

Figure 5-1 ***Compensating Works on the St. Marys River***

This Order also required that the regulation plan "*provide no greater probability of exceeding elevation 183.86 m than would have occurred using the 1955 Modified Rule of 1949*" (the plan in use immediately prior to the 1979 Order) when tested with water supplies of the past adjusted for diversions into the lake. It also maintained the criteria from the 1914 Orders that required that if the Lake Superior level was below 183.40 m (601.7 ft), then flows could not be greater than those that would have occurred with the channel discharge capacities of the St Marys River of 1887, and that flows not be greater than the 1887 channel capacities if the level of Sault Ste. Marie harbour was above 177.94 m (583.8 ft). More significantly, the 1979 Supplementary Order requires that the water levels of both Lake Superior and Lake Michigan-Huron must be taken into account in determining Lake Superior outflows. This more system-wide consideration sought to provide benefits throughout the upper Great Lakes system.

5.3 Evaluation Framework

The Study Board developed an evaluation framework in which regulation plan options were quantitatively evaluated by measuring the success in meeting stated goals and objectives. The framework consisted of:

- a series of *objectives* for a new regulation plan that reflected specific statements of water management principles (section 5.3.1);
- a set of *performance indicators* for each interest to relate lake level fluctuations and critical threshold levels to economic productivity and the identification of *coping zones* for each interest to help assess the vulnerability of the various interests to water level fluctuations and other forces (5.3.2); and,
- a *shared vision model* to support collaborative and transparent evaluation and decision making (5.3.3).

5.3.1 Regulation Plan Objectives

To address all the issues set out in the IJC Directive, the Study Board first had to develop a planning process – the management goals for a new plan and the structure of the plan formulation and evaluation process. These were further refined as a set of guiding planning principles and plan performance objectives that established the desired characteristics for a new regulation plan.

Planning objectives are specific statements of water management principles – what the public, user interest groups and planners would like to have happen regarding a particular resource in a particular place over a particular period of time. The following objectives for a new Lake Superior regulation plan – and for the upper Great Lakes basin as a whole – were developed by the Study Board, based on the IJC's Directive and feedback received at public meetings:

- To maintain or improve the health of coastal and riverine ecosystems;
- To reduce flooding, erosion and shore protection damages;
- To reduce the impact of low water levels on the value of coastal property;
- To reduce shipping costs;
- To maintain or increase hydropower value;
- To maintain or increase the value of recreational boating and tourism opportunities; and,
- To maintain or enhance municipal-industrial water supply withdrawal and wastewater discharge capacity.

5.3.2 Performance Indicators and Coping Zones

To guide the evaluation of candidate regulation plans, the Study Board determined that any change to the regulation plan for Lake Superior outflows must:

- be based on the *best assessment of impacts* that can be done given the relatively small effect that Lake Superior regulation has on water levels, and the length of shoreline of the Great Lakes relative to the budget available for assessment studies;
- address, to the extent possible, *ecological, economic, and social impacts* associated with the regulation of outflows from Lake Superior;
- *balance the needs of the various interests*, specifically by minimizing disproportionate losses to all interests and regions, including disproportionate water level changes on one lake at the expense of another; and,
- provide *robustness*, so that the International Lake Superior Board of Control and the IJC can respond to changing climatic conditions affecting the Great Lakes system.

Performance Indicators

The evaluation framework focused on relating lake level fluctuations and critical threshold levels directly to impacts. Impacts were measured using hydrologic statistics, coping zone counts and through the use of PIs, especially conventional economic information and metrics routinely used for traditional benefit-cost analysis. These PIs were then used to compare and evaluate the relative performance of each economic sector or interest (*e.g.*, hydropower, commercial navigation, recreational boating and tourism) under the range of historical and anticipated lake level fluctuations across all sectors and lakes.

Each of the six interest-specific TWGs was responsible for identifying PIs to be applied in measuring plan performance relative to its interest. Not all of the PIs were required to be quantifiable in dollar terms, but all needed to be significant to the interest they represent, measurable, and sensitive to changes in a regulation plan.

Table 5-1 lists the PIs used in the analysis, by interest.

Coping Zones: Predicting the Impacts from Extreme Water Level Conditions

The Study also applied the concept of *coping zones* to help evaluate regulation plan options by allowing plan formulators to predict the impacts from extreme water levels. Each TWG developed a range of coping zones for its specific interest that assessed vulnerability to water level fluctuations as well as confounding factors such as GIA, wind/waves/storm surges and precipitation patterns. Each TWG identified three levels of progressively more challenging water level conditions for the interest:

- *Zone A*: a range of water level conditions that the interest would find tolerable;
- *Zone B*: a range of water level conditions that would have unfavourable though not irreversible impacts on the interest; and,
- *Zone C*: a range of water level conditions that would have severe, long-lasting or permanent adverse impacts on the interest.

Table 5-1: Performance Indicators (PIs), by Interest[1]

Key Interest	Primary PI	Other PIs
Domestic, Municipal and Industrial Water Uses	None used; all plans had very similar impacts in this interest, so a primary PI was not useful in plan selection	Frequency and duration of affected services and the population affected
Commercial Navigation	Net average annual change in the costs of shipping	Frequency and magnitude of navigation benefits by month
Hydroelectric Generation	Net average annual change in the value of energy at St. Marys River hydropower plants	Net average annual change in power produced at the St. Marys River plants Frequency and magnitude of hydropower benefits by month Robustness of plan benefits with various price assumptions Minimum power produced in a month Minimum value produced in a month Month-to-month and annual flow stability
Ecosystems	See Table 5-2 for primary ecological indicators	Zone C occurrences for 34 ecosystem indicators
Coastal Zone	Net average annual change in the costs of maintaining shoreline protection	Flooding: high water level statistics Low water impacts: low water level statistics Erosion: rates of erosion on lakes Superior and Michigan-Huron (but there were no significant plan differences in the erosion rates)
Recreational Boating and Tourism	None used; although plans could change the number of slips available on Lake Superior, there was no evidence that showed an unusable slip actually hindered boating	Number of slips each month that were unavailable for use Boat ramp utility score

1 For more information on the PIs, see IUGLS (2012).

Clearly, higher and lower levels would exacerbate the problems that had been experienced before. However, it was not known whether damages would grow linearly or exponentially. The clearest example of this relates to flooding damage. The historical high water levels have a return period of approximately 100 years. Floodplain management measures have been taken in most places to discourage development that could be damaged at these levels. But property just a little higher than this level could be developed and might still have the advantages of a water view and lakefront location. If water levels shifted higher under climate change, then flood damages could increase significantly, but because it is deemed safe now, little stage-damage data have been collected for development immediately above the floodplain.

With the important exception of coping zones for ecosystem interests, the coping zone tool proved to be not as meaningful as PIs for measuring the impacts of the small water level changes produced by different regulation plans.

The usable slip count and boat level ramp usability index used as recreational boating indicators provide a continuous assessment of the availability of slips and ramps, but there are no data to indicate how losses in availability actually affect recreational opportunities. In addition, counts of how frequently a plan caused Zone B or C conditions were not thought to provide useful plan evaluation information, because the difference between levels in any of the final plans was small. For example, a difference of 2.5 cm (1 in) between the Lake Michigan-Huron water levels of two plans could mean that one plan was in Zone A and the other in Zone B.

PIs for domestic, municipal and industrial uses were based on data provided by most of the largest and some of the smaller water supply and treatment plants that define the levels at which service is impacted and the levels at which service is lost, along with the numbers of people affected. The elevations provided exceed the range of water levels modelled, so these functions are applicable to extreme climate conditions. In the end, these indicators did not factor into the selection of plans, because there were no significant differences in how plans scored on these PIs. As with other interests, the Study Board's analysis showed that extreme NBS could cause problems, most of which could not be addressed through regulation of Lake Superior.

Ecosystem Indicators

Coping zones for ecosystem interests were different from ones in the other five interests in two ways. First, the high and low water levels that caused problems for coastal development, navigation, recreational boating, hydropower and municipal water systems were generally good for ecosystems. Second, ecosystem coping zone definitions were generally complex, often combining water level, time of the year and persistence. The Study Board had to place greater reliance on the definition of the ecosystem interests' coping Zone C because of that complexity. For any of the other interests, there were other measures that allowed the Study Board to track the onset of damages as water levels rose or fell (*e.g.*, the number of customers without municipal water service, economic damages for navigation and hydropower, shoreline protection structure costs, and number of unusable slips in recreational boating). But the complexity of the ecosystem indicators made it difficult for the Study Board to gain an understanding of how the levels of impacts would differ. As a result, the Study Board specified the performance indicator levels that marked the transitions from one coping zone to another.

Detailed analysis of the plan results for 34 ecosystem indicators showed the differences between plans were generally insignificant. For many indicators, there were no differences between plans when simulated with the same NBS, even though there could be great differences in ecosystem indictor metrics between two different NBS sequences regardless of which plan was used. There were numerical differences between plans in the eight ecosystem indicators in Table 5-2. In several cases, differences between plans with respect to these indicators were important.

5.3.3 Shared Vision Planning

The overall approach to the Study's strategy to address the IJC's Directive was based on shared vision planning. Shared vision planning builds on water resources planning traditions that extend back to the beginning of the 20th century (Holmes, 1979). More recently, shared vision planning has evolved for use in the types of water decisions that are more common in the 21st century – when it is more likely there will be multiple decision makers with shared responsibility for a basin, and the decision possibilities more often include changes in behavior rather than investment in new structures.

Table 5-2: Eight Primary Ecological Performance Indicators Used in the Study

PI Code	Zone C Condition	Performance Indicators	Goal is to Avoid Zone C
SUP-01	SUP-01 measures the degree to which natural **peak water level** events on Lake Superior, which occur roughly on a 30-year cycle, are lowered by regulation		Prevent/minimize range compression for Lake Superior
SUP-02	SUP-02 measures the degree to which there is a ***drawdown*** of Lake Superior following a peak water level 'event'. SUP-01 and SUP-02 scores closer to pre-project (and larger than 1977A) are better.		Prevent/minimize range compression for Lake Superior
SUP-04	Peak summertime water level rises above 184.0 m (603.7 ft) for **3 or more** consecutive years	Wild rice abundance in Kakagon Slough, near Duluth, MN	Maintain viability of wild rice population
SUP-05	Mean spring (Apr-May) water level is more than 0.67 m (2.2 ft) below the mean level for the preceding 10-year period for **7 or more** consecutive years	Northern pike habitat and population in Black Bay on the north shore of Lake Superior	Prevent significant decline in northern pike abundance
SMQ-01	Mean flow rate during June maintained below 1,700 m^3/s (60,035.5 ft^3/s) for **5 or more** consecutive years	Lake sturgeon spawning habitat	Provide suitable spawning area for lake sturgeon
SMQ-02	Mean flow rate during May-June maintained below 2,000 m^3/s (70,600 ft^3/s) for **7 or more** consecutive years	Maintenance of flushing flows in the channel into Lake George (a small lake near Sault Ste. Marie, ON)	Maintain substrate in Lake George channel
LMH-07	Mean growing season (Apr-Oct) water level is less than 176.0 m (577.4 ft) for a period of **4 or more consecutive years**	Fish and wildlife community eastern Georgian Bay wetlands	Maintain fish access to eastern Georgian Bay wetlands (current conditions)
LMH-08	Mean growing season (Apr-Oct) water level is less than 176.12 m (577.8 ft) for a period of **4 or more consecutive years**	Fish and wildlife community eastern Georgian Bay wetlands	Maintain fish access to eastern Georgian Bay wetlands (+100 yr conditions)

Overview

Shared vision planning applies advances in planning, modelling and public participation in results-oriented systems analysis (Figure 5-2). It is an iterative process built on the following steps:

- build a team and identify problems;
- develop objectives and metrics for evaluation;
- describe the baseline condition;
- formulate alternatives to the baseline;
- evaluate alternatives;
- select and implement the preferred plan; and,
- use, exercise, and update the plan.

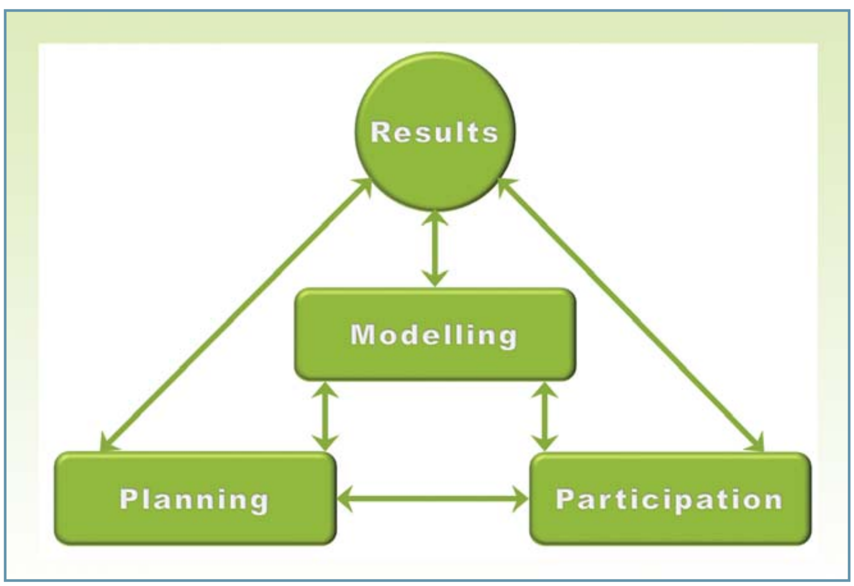


Figure 5-2 ***Results-oriented Shared Vision Planning***

The central notion of shared vision planning is that experts, decision makers and stakeholders all work together to build a unified computer model of the lake or river system – a shared vision model (SVM). SVMs are built with user-friendly, graphical simulation software, and bridge the gap between specialized computer analysis tools and the way people typically conceptualize problems and make decisions. This helps minimize disagreements about facts and shifts the debate to how to balance conflicting objectives. Given that baseline conditions are also modelled, participants in the shared vision planning exercise can better understand the implications of any regulatory decision.

Unlike traditional modelling approaches to water management planning, shared vision planning requires the collaborative construction of a single model of the entire system under study, with explicit mathematic links between the experts' research and the decision makers' decision criteria. The collaboration helps ensure that the model will be thoroughly reviewed and that there is a level of trust in the results. The explicit connections also help researchers shape their investigations to address the identified needs of decision makers.

The Study's Shared Vision Model

The Study Board used a SVM to undertake practice decisions to allow experts, stakeholders and decision makers a series of opportunities to weigh the decision as information developed. The SVM used in the Study was an EXCEL-based spreadsheet that calculates and displays the economic and environmental PIs based on water levels and flows from proposed regulation plans. (The plans were simulated in a hydraulic model, the Great Lakes Routing Model.) The SVM incorporated results from an ecological model (Integrated Ecologic Response Model) that calculates the ecosystem scores, and executable code that runs a version of the Upper Great Lakes Shore Protection (UGLSP) model that calculates shoreline protection costs. For more information on the Study's shared vision model, see IUGLS (2012).

The SVM was developed over the course of the Study as data were gathered and benefit algorithms were completed and refined, and as the Study Board's decision criteria were refined in the practice discussions. Initially, the SVM presented the results of one alternative compared to stored results for the **1977A** plan, using only the historical NBS. Later SVM outputs included multiple NBS choices and allowed comparisons of any two alternatives to real time evaluations of **1977A**. By the end of the Study, the SVM was able to compare all plans across all NBS sequences for the different criteria. The SVM was designed to operate like a website using hyperlinks to move from section to section (Figure 5-3).

5

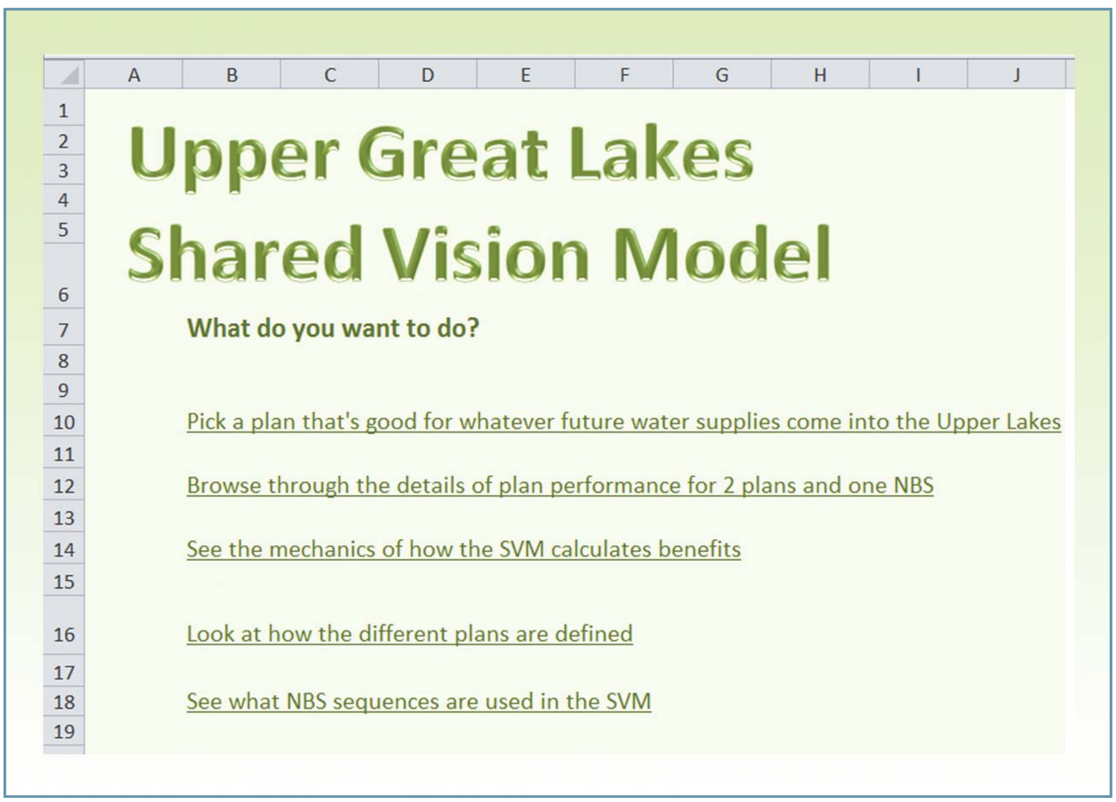


Figure 5-3 **Homepage of the Study's Shared Vision Model**

5.4 Application of the Hydroclimatic Analysis

5.4.1 Plausible Scenarios for Future NBS

As described in **Chapter 4**, there is considerable uncertainty regarding future NBS in the upper Great Lakes basin. As a result, the Study Board considered four scenarios that encompass the widest range of plausible futures. Each is based on a different hypothesis about the impact of varying climate. NBS data series from different models were selected to test plans under each scenario. For the Study Board to endorse a plan, the plan had to perform as well as any other plan for all four of the scenarios. The four scenarios are:

1. Stationary Climate (i.e., over the next 30 years, NBS will be similar to the historical NBS)

The primary argument for planning for this scenario is that climate change impacts are likely to be small over the expected life of the next regulation plan (30 years) and that the Study's statistically-estimated extreme NBS sequences provide for a sufficiently rigorous test.

2. Climate is changing, but the direction of NBS is unclear

This scenario combines the concern that climate change may already be happening with acknowledgment that there are climate model results that show changes in mean NBS ranging from wetter (increase in NBS) to drier (decrease in NBS) for Lake Superior and similar ranges for the other lakes.

3. Climate is changing and NBS is decreasing

This planning scenario is based on the hypothesis that recent Great Lakes NBS already demonstrate the impact of increased atmospheric concentrations of CO_2 and other greenhouse gases. Data show that CO_2 emissions have been increasing as fast as or faster than the "worst case" projections of the Intergovernmental Panel on Climate Change (IPCC, 2007). A slight decreasing trend in NBS is projected by many climate models.

4. Great Lakes NBS will next enter a very wet phase

In this view, Great Lakes NBS are quasi-cyclical, and the next cycle will see above-average NBS. For example, the low lake levels that have been experienced since the mid-1990s followed high NBS conditions in the 1970s and 1980s, which in turn had followed low NBS conditions in the 1960s.

5.4.2 Rationale for Selecting the Suite of NBS Sequences

The Study's hydroclimatic analysis and NBS sequences, outlined in **Chapter 4**, served as input into the work to evaluate candidate regulation plans. Of the hundreds of future climate change scenarios or NBS sequences generated by the hydroclimatic analysis, 13 were chosen for detailed plan formulation and evaluation. These 13 are representative of the range of plausible sequences that could be used to test the limits of any new proposed regulation plan. This suite of sequences allowed the Study Board to test plans for robustness.

The 13 NBS sequences that were selected came from five different scientific approaches:

1. **Historical Data:** Water management measures are most often evaluated using NBS that have occurred in the past, particularly when there is a fairly long historical record. In this case, there were 109 years of estimated NBS on which to base this dataset; more importantly, the dataset included very wet and dry sequences.
2. **Stochastic[5]:** Two stochastic supply sets, together containing more than 100,000 years of statistically-generated NBS, were generated based on the historical NBS. The stochastic datasets include much wetter and much drier supplies than any in the historical dataset. From these, seven 109 year-long sequences were used to reflect a range of future NBS conditions. To test the ability of plans to deal with extreme conditions, the seven sequences included very wet and very dry sequences that would occur only rarely. The seven stochastic sequences were selected for use by filtering with the levels produced by routing these NBS through plan **1977A**. These sequences included the:
   - 109-year NBS set that contained the highest and lowest monthly levels on Lake Superior;
   - 109-year periods with the highest and lowest monthly levels on Lake Michigan-Huron;
   - 109-year period with the highest 50-year average combined levels on lakes Superior and Michigan-Huron;
   - 109-year period with the lowest 50-year average combined levels on lakes Superior and Michigan-Huron; and,
   - 109-year period with the smallest range in 50-year average combined levels on lakes Superior and Michigan-Huron.
3. **Climate Change based on Regional Climate Model (RCM) Outputs:** Down-scaled RCMs produced two sequences, both reflecting the IPCC A2 climate change scenario[6], using two different RCM simulations. These NBS sequences produced a change in the seasonality of NBS, with increases in NBS generally occurring during

5 Stochastic – Statistics involving or showing random behaviour. In a stochastic simulation, a model is used to create a new 'synthetic' series of plausible flows and lake levels, based on historical data. The synthetic series will, on average, preserve important properties of the historical record, such as the mean and standard deviation, while generating new combinations of high and low flow conditions that could represent more severe conditions than those seen in the past.

6 As described in **Chapter 4**, Scenario A2 represents a future climate scenario characterized by high levels of greenhouse gas emissions. This scenario corresponds most closely to recent experience and International Energy Agency (IEA) projections (IEA, 2011).

winter and spring, and decreases seen in the late summer and early fall, even though the average annual values were not that much drier.

4. **Climate Change Datasets Generated with a Stochastic Model:** This enabled a shift in the mean of future NBS over time based on both direct Global Climate Model (GCM) (also known as General Circulation Models or Global Circulation Models) projections and GCM-based projections of how a variety of climate parameters might change. These datasets purport to show the onset of climate change, with the greatest effects at the end of the 109 years. Two severe periods were selected from the large stochastic set.

5. **Recent Trends:** One dataset was created statistically by assuming that any trends in NBS on each lake since 1960 reflected a linear trend rather than the dry or wet portion of a cycle. This represented one view of what NBS would be if the past decade of low water levels on the upper lakes reflects climate change.

Table 5-3 summarizes the 13 NBS sequences used in the plan evaluation. The table includes the names of sequences used in the SVM as well as a brief description of the key features of the sequences.

Table 5-3: Summary of NBS Sequences Applied in Regulation Plan Evaluation

Climate Scenario	NBS Sequence	SVM Code	Comments
1. Stationary	1. Historical	HI	The 109-year period 1900-2008 recorded NBS, adjusted to current demands and diversions. This sequence has as many as 7 consecutive years above, and 7 consecutive years below average NBS.
	2. Low Range	LR	A 109-year sequence from the stochastic NBS. The standard deviation of annual NBS is only 453 m^3/s (15,998 ft^3/s), compared to 495 m^3/s (17,481 ft^3/s) (for historical NBS).
	3. Dry	DS	A 109-year sequence from the stochastic NBS. Still representative of current climate, this is the driest stochastic sequence for Lake Superior.
2. Uncertain Change	4. High Michigan	HM	A 109-year sequence from the stochastic NBS. Based on current climate, but creates the highest Michigan-Huron levels from the stochastic datasets, with a great range between wettest and driest years.
	5. Wet (shifts mean up slightly)	WS	A 109-year sequence from the stochastic NBS. Even though it is based on current climate, it happens to reflect a higher mean NBS for the entire 109-year period.
	6. Low Michigan	LM	A 109-year sequence from the stochastic NBS. Based on current climate, but creates the lowest Michigan-Huron levels from the stochastic datasets while still producing a maximum level greater than historical. Includes 14 consecutive years of below average NBS.
	7. CC-AET	AT	A climate change sequence. One of the sequences produced by the Canadian RCM that produces higher highs and lower lows. The range of RCM projections was not large. Two NBS sequences, CC-AET and CC-AEV (Sequence 9) were chosen to represent the range of RCM projections, but the plan rankings for the two sequences were similar.
3. Change to Drier Period	8. Low Superior	LS	A 109-year sequence from the stochastic NBS. Based on current climate, but produces the lowest Lake Superior level in entire stochastic simulation.
	9. CC-AEV – **1977A** Superior min lower than stochastic min	AV	Another Canadian RCM sequence; **1977A** produces lower levels with this sequence than with any in the stochastic.
	10. Sequence A2 174	T1	One of thousands of climate change sequences in which the climate change effect becomes more pronounced over time. Plan **1977A** Superior levels drop below 182.0 m (597.1 ft) using this sequence.
	11. Sequence A2 370	T2	Another sequence that got drier over the course of the 109 years, but even more severe than sequence A2 174.
	12. Extended trend	TR	This sequence did not use climate models, but just reduced historical NBS assuming the mean would continue to decline as it has in the last two decades. This was the most severe dry test of all, and many plans could not keep water levels above 182.0 m (597.1 ft).
4. Change to Wetter Period	13. High Superior	HS	Current climate with average NBS close to historical NBS, but with the highest Lake Superior level in the stochastic set. The wettest portion of this supply sequence comes early in the simulation, as would be expected if recent dry NBS forecast a reversal to wet conditions.

5.5 Decision Criteria for Evaluating Candidate Regulation Plans

5.5.1 Role of the Decision Criteria

All candidate plans were evaluated against the performance of the **1977A** plan to show the net change that would occur if the existing plan were replaced. The Study Board wanted to clearly demonstrate that whatever plan that was put forward to the IJC improved performance over the existing plan. The focus then, was on: *what constitutes improved performance and how should it be reflected in the evaluation criteria?*

In addition, there are some comparisons to preproject conditions that were used to determine whether regulation is imposing a significant impact compared to the impacts that would have occurred without the structures in place. Comparisons to the 1955 Modified Rule of 1949 plan were also referenced because it was the last plan that did not include balancing – it compresses Lake Superior levels and allows for a wider range of Lake Michigan-Huron levels. As noted in section 5.2, this plan was in place up to 1979, when the IJC issued the Supplementary Order that required that Lake Superior levels be balanced with those of Lake Michigan-Huron.

Therefore, the Study Board's goals, objectives and principles were translated into nine decision criteria. These criteria had to be further quantified by an associated set of metrics that could be used to directly and objectively compare plan performance for each formulated plan, and against **1977A** and the preproject condition. The system of performance metrics enabled the Study Board and the plan formulators to better design plans to achieve these goals and evaluate how well these plans met the decision criteria under a variety of possible future NBS conditions as described above.

The nine decision criteria were grouped into three categories and posed as questions (Table 5-4). The regulation plan evaluations summarized in **Chapter 6** illustrate how these decision criteria shaped selection of a preferred plan.

The Study's SVM generated scores or "pass/fail" evaluations for the decision criteria. Figure 5-4 presents a summary display of the decision criteria. Each of the nine decision criteria represented in the summary displays are supported by more detailed displays so that users can more fully understand the relative performance of each plan being formulated at each stage of the planning process. This was a continuous, iterative formulation and evaluation process. New information was developed and introduced into the evaluation system, and new plans were formulated and adjusted to improve their effectiveness in meeting the evolving planning objectives and performance metrics.

Table 5-4: Decision Criteria for Evaluating Candidate Regulation Plans

Hydrological Decision Criteria

1. How well does the plan perform in keeping Lake Superior water levels between 182.76 and 183.86 m (599.6 to 603.2 ft)?
2. Does the plan maintain the historical balance of Lake Superior levels with Lake Michigan-Huron levels?
3. How much does the plan lower the highest Lake Michigan-Huron levels and raise the lowest?
4. Does the plan create fewer Lake Superior levels below chart datum for the historical NBS than preproject?

Ecological Decision Criteria

5. Does the plan enhance ecological attributes and reduce negative environmental impacts?

Economic Decision Criteria

6. Does the plan minimize disproportionate loss to any particular water interest?
7. How much does the plan reduce net shoreline protection costs?
8. How much does the plan increase benefits[1] for consumers affected by shipping costs?
9. How much does the plan increase benefits[1] for those who use hydropower generated on the St. Marys River?

1 Note: Benefits are used here in terms of benefits to the general public or consumers and not based on corporate revenue and profits.

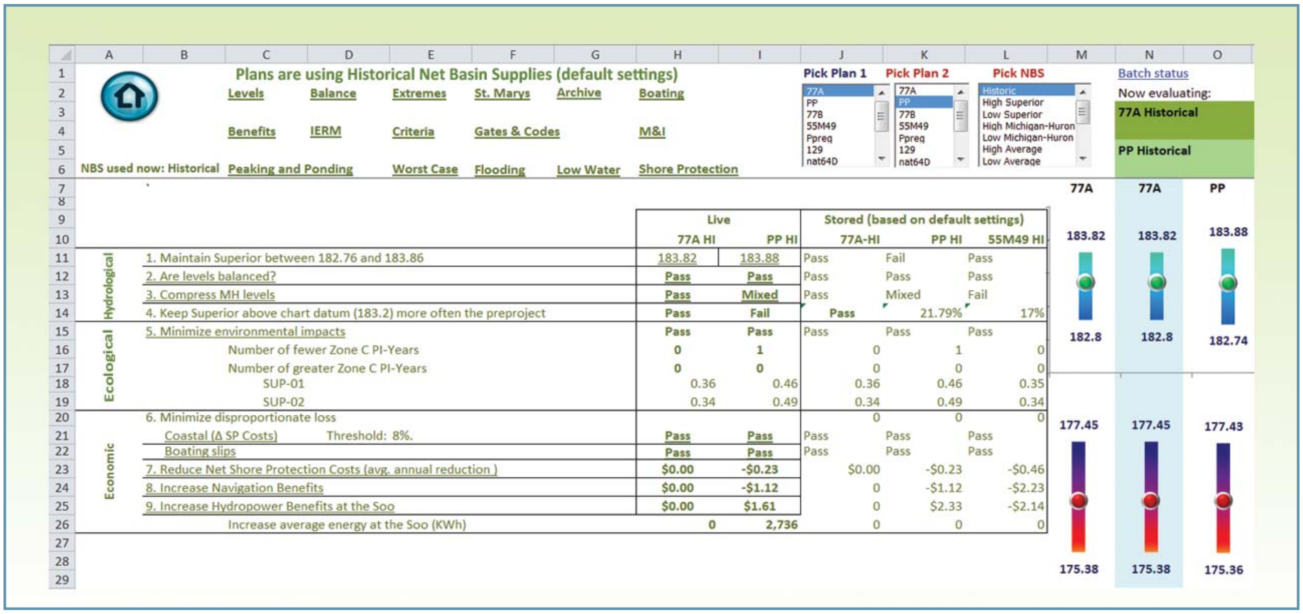


Figure 5-4 ***SVM Summary Evaluations for the Nine Decision Criteria***

Tradeoffs Among Water Interests

There were, as would be expected, competing needs among the different interests. The Study Board sought to:

- maintain or improve hydroelectric generation and commercial navigation benefits, protecting the priority given them by the Treaty;
- perform at least as well as the **1977A** plan had done in terms of impacts on ecosystem interests; and,
- reduce shoreline protection costs.

As it is very difficult to accommodate all these water interests equitably on all the lakes, tradeoffs were inevitable between achieving all the objectives on Lake Superior versus those on Lake Michigan-Huron. As a result, the Study Board imposed the IJC principle of "no disproportionate loss" to assure that the benefits for the majority were not produced at the expense of significant losses to any particular interest.

5.5.2 Hydrological Decision Criteria

Criterion 1:
How well does the plan perform in keeping Lake Superior water levels between 182.76 and 183.86 m (599.6 to 603.2 ft)?

Criterion (a) of Condition 1 of the IJC's current Orders of Approval specifies these levels as desirable maximum and minimum levels for Lake Superior. These levels are close to historical records, and similar to the levels reached by the **1977A** plan simulated with the historical NBS. The current Orders establish an absolute requirement to stay within the levels when tested with historical NBS adjusted for diversions (at least to 1979) and Lake Superior water levels must not exceed 183.86 m (603.2 ft) more often than under the 1955 Modification of the Rule of 1949 plan. The Orders include the statement "with the supplies of the past as adjusted and in such a manner as to not interfere with navigation" within Condition 6 of the Orders.

In the SVM, a "pass" score means that for the selected plan and NBS, this criterion was fully met; in other words, the maximum Lake Superior level was less than or equal to 183.86 m (603.2 ft) and the minimum was 182.76 m (599.6 ft) or more. As described in **Chapter 6**, none of the candidate plans was able to keep Lake Superior levels within this range when simulated with the more extreme NBS not experienced in the historical record (1900-2008). As a result, the pass/fail scores were supplemented by comparisons of the frequency and magnitude of the potential violation.

The SVM can generate level frequency graphs for any plan and any of the 13 NBS datasets (Figure 5-5). The graphs show how often (frequencies on the horizontal axis) the lake in question is below a certain elevation (marked on the vertical axis). The graph on the left shows the Lake Superior levels of three plans (A, B, **1977A**) under the T2 NBS sequence (a climate change scenario, sequence 11 listed in Table 5-3) and **1977A** under historical NBS (dashed line). The left-most point on the graph is the highest Lake Superior level during the entire simulation for that plan and NBS set. To the right of "Max" on the horizontal axis, there is the frequency "0.99" and the levels on the graph above that are slightly lower than the corresponding maximum for each plan and NBS. This is a depiction of the statistic that "99 percent of all Lake Superior levels simulated with this plan and NBS will be less than the level shown above 0.99".

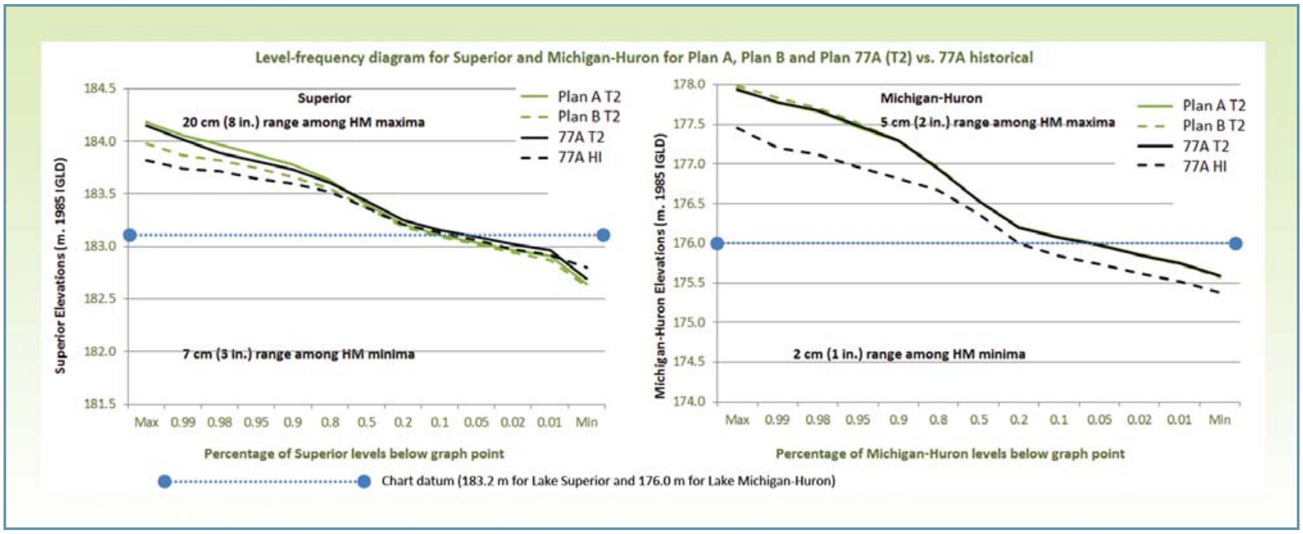


Figure 5-5 ***Comparison of Level Frequency Graphs for Lakes Superior and Michigan-Huron***

In the illustration shown in Figure 5-5, the plan under the T2 NBS sequence would lower Lake Superior high levels slightly, but would greatly reduce low levels. Among the three plans illustrated, **1977A** is worst at avoiding the lowest levels on Lake Superior.

Criterion 2:
Does the plan maintain the historical balance of Lake Superior levels with Lake Michigan-Huron levels?

The notion of balancing lake levels was provided as an objective in the Supplementary Order; a balancing formula is included in the current plan, **1977A**. In this plan, Lake Superior levels are balanced with Lake Michigan-Huron levels when each are an equal number of standard deviations above or an equal number below the long-term monthly mean for each. In **1977A**, there are fixed values for 12 monthly means and 12 monthly standard deviations for each lake based on the simulated lake levels expected with the 1955 Modification of the Rule of 1949. Figure 5-6 illustrates how this criterion was applied to compare two candidate plans.

Over time, there will be an equal number of Lake Superior levels within one standard deviation of the mean as there are Lake Michigan-Huron levels within one standard deviation of its mean. But when the distance from the mean is tested in any one month, the lakes are almost unavoidably out of balance as recognized by the existing Orders, which attempt to address this issue. For example, if Lake Superior is currently near average levels and Lake Michigan-Huron is well above average, then the existing Orders encourage a smaller release than would otherwise be made. This would raise levels on Lake Superior and lower them on Lake Michigan-Huron, bringing them closer to balance in the coming months. However, because of the huge volumes in both lakes, relative to the flow between the lakes, it would take many months to adjust the lake levels so that they were above or below their average levels by a proportional amount.

The SVM provided a pass/fail grade for this criterion. A passing grade means that the sub-criteria for assessing the degree to which the two lakes are balanced, for a particular plan and NBS, met thresholds similar to scores under the **1977A** plan. The first sub-metric was the *range of imbalance*, a measure of magnitude – how far out of balance the lakes typically were. As illustrated in Figure 5-6, a plan with a smaller range of imbalance would produce a flatter graph with all values closer to the x-axis (zero imbalance). The numerical score for the *range of imbalance* is proportional to the sum of the areas above and below the x-axis.

The other sub-metric is a *frequency bias*, which is a measure of which of lakes Superior or Michigan-Huron is more likely to be more out of balance than the other. The farther from the 50 percent mark on the x-axis that the line crosses the x-axis, the more biased a plan is with respect to one lake or the other.

Criterion 3:
How much does the plan lower the highest Lake Michigan-Huron levels and raise the lowest?

Figure 5-7 shows the highest and lowest two percent of water levels on lakes Superior and Michigan-Huron comparing two plans given historical NBS. Plan 1 is better for reducing the highs on Michigan-Huron, but results in higher highs on Superior. There is little difference in low levels between the two plans.

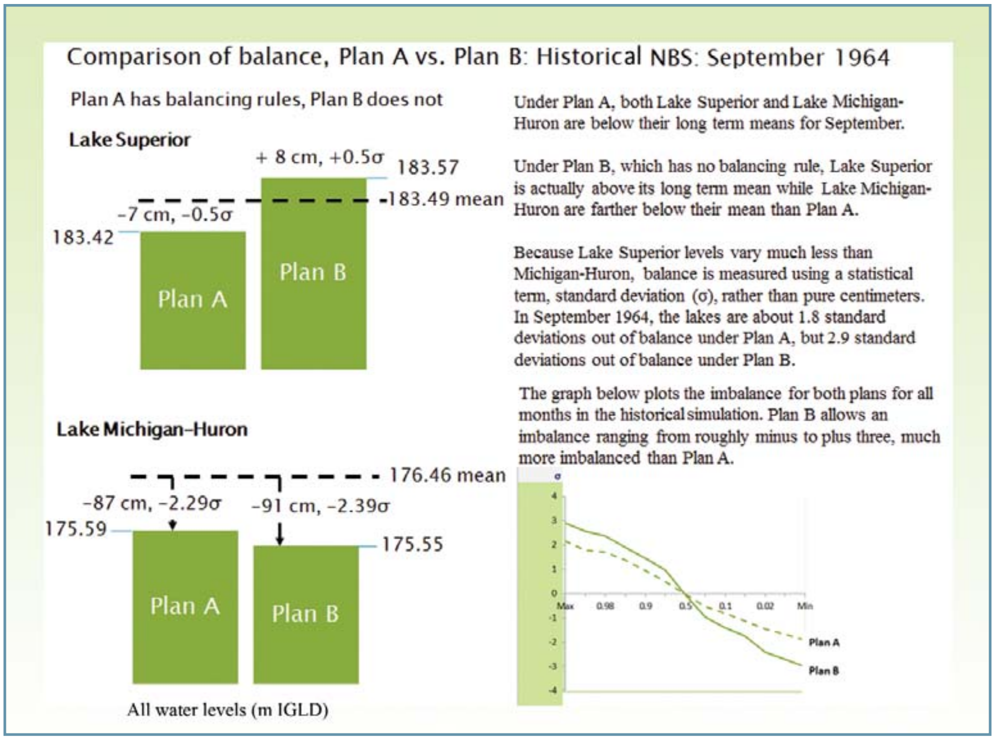


Figure 5-6 **Balance Display in the SVM**

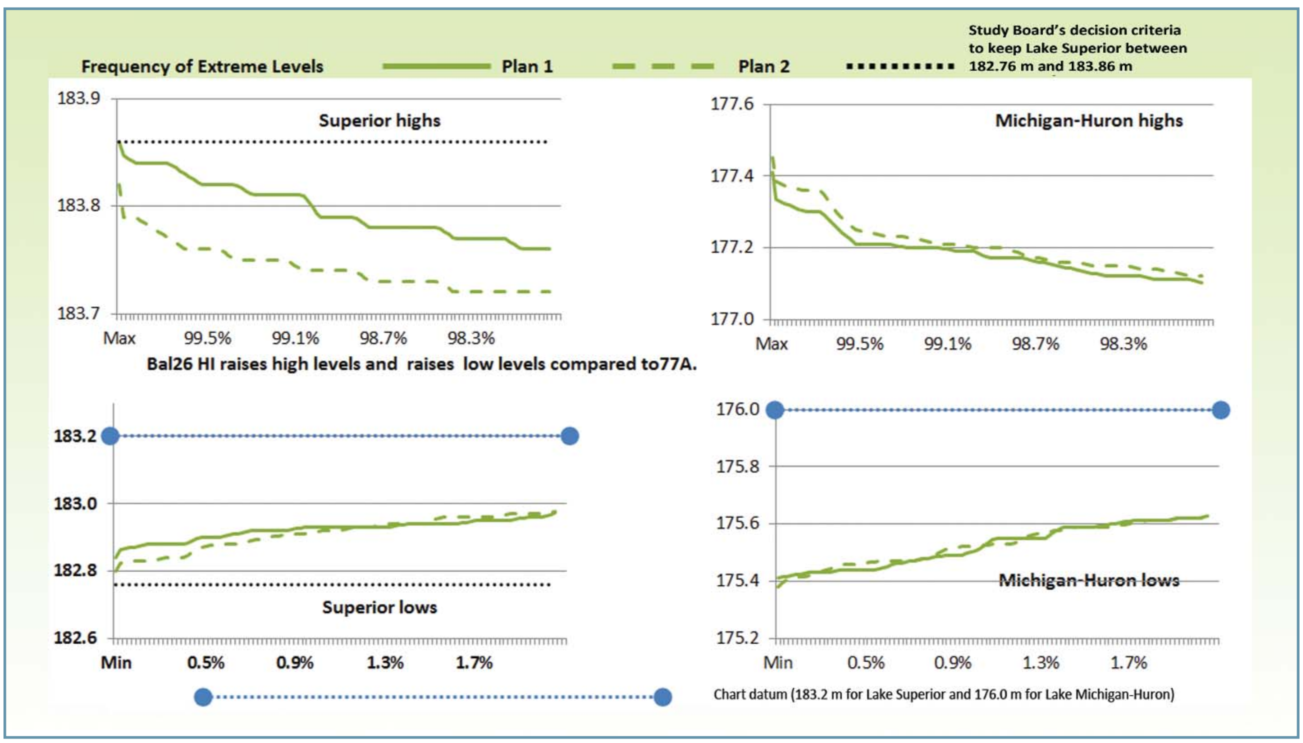


Figure 5-7 **Highest and Lowest Two percent of Water Levels, Two plans, Historical NBS**

Reducing the highest levels of Lake Michigan-Huron slows erosion and reduces flooding and shoreline protection damages. Raising the lowest levels helps provide easier access for commercial shipping and recreational boating. Homeowners also report that lower levels reduce property values of near-lake homes.

As noted previously, the ability to control Lake Michigan-Huron using Lake Superior is limited. Lake Michigan-Huron levels are driven primarily by NBS of the lake's larger watershed area and the discharge of water into Lake St. Clair. Therefore, changes in the releases from Lake Superior tend to have a much larger effect on Lake Superior than on the receiving lakes downstream.

Criterion 4:
Does the plan create fewer Lake Superior levels below chart datum for the historical NBS than preproject?

Plan **1977A** includes a provision required by **criterion c** in the 1979 Supplementary Order that when Lake Superior levels are at 183.4 m (601.7 ft) IGLD 1985[7] or lower, the plan release cannot be greater than what would have occurred with no structures (*i.e.*, the preproject release). This is one way of avoiding Lake Superior levels being lower than would have occurred before the structures were built.

5

5.5.3 Ecological Decision Criteria

Criterion 5:
Does the plan enhance ecological attributes and reduce negative environmental impacts?

Lake Superior levels under plan **1977A** are not that much different from unregulated lake levels and there is no evidence that wetlands along the coast of Lake Superior have been affected by the current regulation plan. (Georgian Bay wetlands are clearly affected by GIA and the increased conveyance of the St. Clair River, but these impacts cannot be significantly reduced through regulation of Lake Superior). The concern for Lake Superior is how NBS conditions that are significantly drier or wetter than the historical record could affect the environment.

The Study Board used metrics, developed by Study investigators, to rate new plans that attempted to reflect these relatively small changes. A coping zone metric was used to rate water level conditions (see section 5.2.4). The basic criterion was that the new plan should perform at least as well as the existing plan. The criterion used the 34 environmental performance metrics assessed within an Integrated Ecologic Response Model (IERM2) (LimnoTech, 2011) (Figure 5-8). As shown in the figure, the IERM2

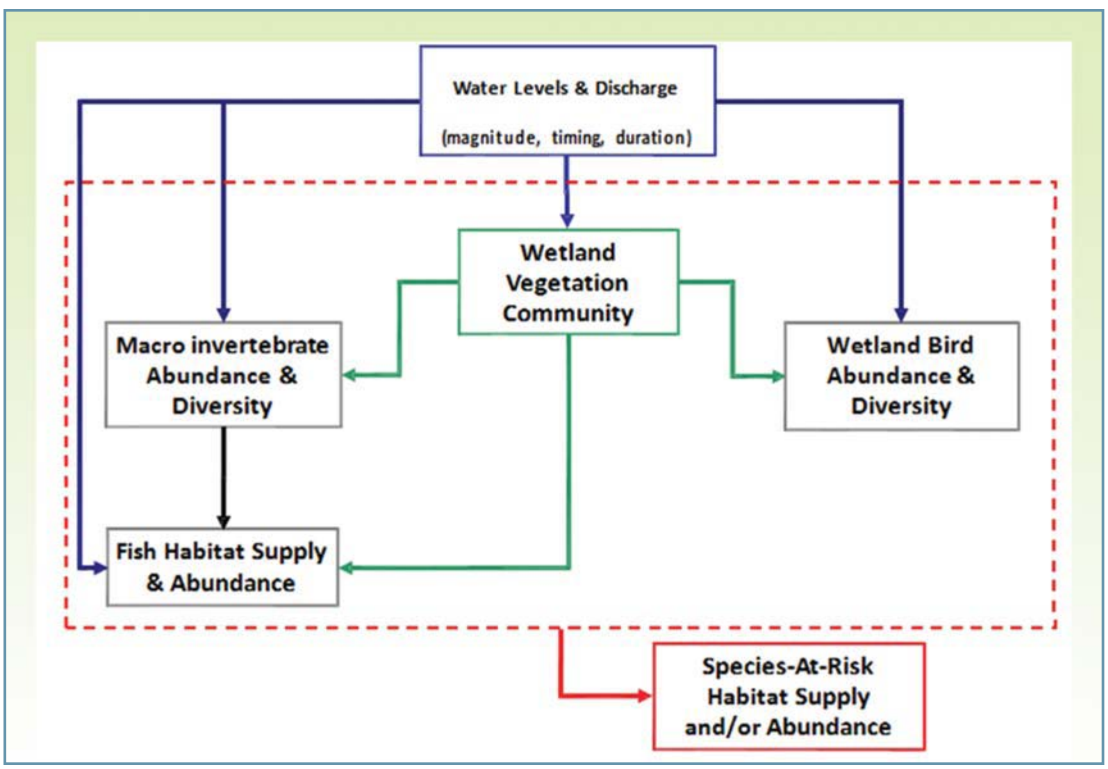


Figure 5-8 IERM2 Conceptual Linkages between Ecological Components and Sub-models

7 International Great Lakes Datum (IGLD 1985) is a fixed vertical reference used to measure water levels in the Great Lakes-St. Lawrence River system. The datum has its zero reference elevation as mean sea level near Rimouski, QC on the St. Lawrence River.

model calculated wetland vegetation indicators directly from water level characteristics, and generated other indicators based on water levels and wetland vegetation information.

5.5.4 Economic Decision Criteria

Criterion 6:
Does the plan minimize disproportionate loss to any particular water interest?

The Study Board defined disproportionate loss in terms of two interests, shoreline protection (long-term costs of maintaining existing structures) and recreational boating (changes in the availability of slips) that had potential lake-to-lake conflicts and were not addressed in other decision criteria. The Study Board flagged plan results for these two metrics if they fell outside certain bounds.

Figures 5-9 and 5-10 show the SVM displays for disproportionate loss for shoreline protection and recreational boating, respectively. In this example, Plan 1 results in slightly worse shoreline protection than **1977A** in several reaches but never by more than 2 percent, while it reduces overall shore protection costs. Similarly, as Figure 5-10 shows, both Plans 1 and 2 created very slightly higher rates of unusable slips on Lake Superior in return for slightly lower rates on Lake Michigan-Huron, a tradeoff that was not considered to create a disproportionate loss to Lake Superior boaters.

If the Study Board allowed no region to suffer any disbenefits compared to **1977A**, it could not have changed the plan. This stems from the fact that changing a **1977A** release will change levels on Lake Superior and Lake Michigan-Huron in opposite directions. The point of this decision criterion was to limit the negative impact that any one region would

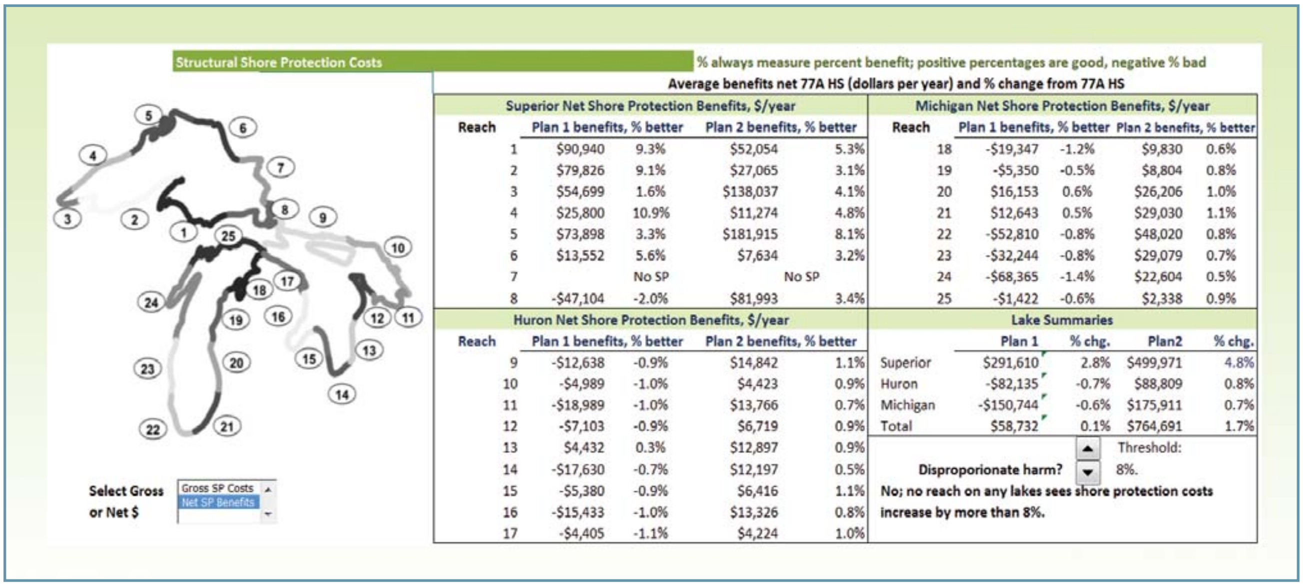


Figure 5-9 ***Check for Disproportionate Shoreline Protection Losses***

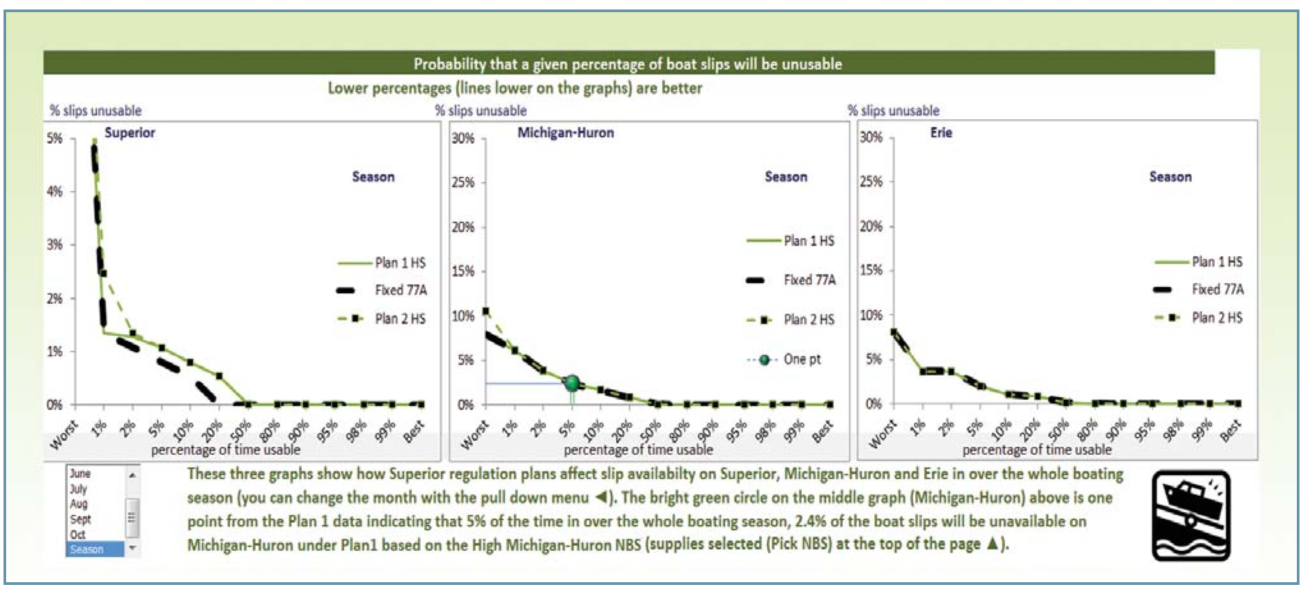


Figure 5-10 ***Changes in Slip Availability on Different Lakes***

receive from a plan that was better overall. The Study Board tried to minimize these regional impacts, and it flagged as disproportionate shoreline protection costs in any one region that increased by more than 8 percent. Figure 5-9 illustrates that the SVM identified the summary evaluation for these two plans: that "*no reach sees shore protection costs increase by more than 8 percent*".

Criterion 7:
How much does the plan reduce net shoreline protection costs?

The Study Board sought to reduce the total costs of maintaining shoreline protection on lakes Superior and Michigan-Huron, and as a minimum to not increase costs over the current plan, **1977A**. An algorithm was developed that used existing large-scale databases for structures, waves and shoreline configurations to produce the average annual costs of maintaining shoreline protection in 24 regions on the lakes (see Figure 5-9). The algorithm calculates the costs of maintaining shoreline protection for each plan in each reach in each month of the simulation, and then compares those reach-by-reach costs to the costs under **1977A**. The SVM can display either the gross costs or (as selected in Figure 5-9) the net benefit (**1977A** costs minus candidate plan costs), by reach. Lake Erie shoreline protection costs were not calculated because regulation of Lake Superior has a negligible effect on Lake Erie levels or shoreline protection costs.

Calculating Shoreline Protection Costs

The water depth at the base of a shoreline protection structure typically is the controlling influence on wave conditions that affect the structure's performance. In calculating shoreline protection costs, two primary physical processes were modelled: undercutting (erosion and scouring) of the shoreline protection structure toe; and, overtopping of the structure, when a combination of static water level and surge/wave actions drive water over and behind the structure. Lower water levels generally are beneficial to coastal structures in that both the frequency and severity of wave exposure is reduced.

The responses of the structures are estimated in the model based on statistical distributions of structure characteristics within each of the 24 shoreline reaches and on accumulated evidence of how structures respond to undercutting and overtopping. Detailed structure-by-structure inventories of shore protection from Racine County WI, Lake and Cook Counties, IL, and Collingwood-Wasaga Beach, ON were used to establish the statistical distribution of structure characteristics, which was then adapted to reflect conditions in each of the 24 reaches. As well, the variation of actual surge and wave height intensity and duration had to be simplified in the model using statistical approaches. However in the SVM, only one input variable, the static water level data series produced by the particular regulation plan and NBS, is changed. Therefore, the relative difference in estimated costs between plans represents a credible difference in their performance.

For more information on the methodology, see Coldwater Consulting Ltd. (2011).

Criterion 8:
How much does the plan increase benefits for consumers affected by shipping costs?

The Study Board preferred plans that at least preserved or even decreased shipping costs on the Great Lakes. It considered changes from plan **1977A** costs, looking at average annual, worst year and best year, and frequency-magnitude distributions of annual benefits.

Figure 5-11 illustrates a sample comparison of the impacts on commercial navigation interests of two different plans. Costs are shown for 10 routes reflecting possible combinations of shipping origins and destinations. For example, Route 1 (Lake Superior) is for shipments from one Lake Superior port to another. In this case, the levels on Lake Superior were the only levels needed to calculate these costs. Route 6 (lakes Superior-Michigan-Huron-St. Clair) included shipments between Lake Superior and Lake St. Clair ports, and the levels on lakes Superior, Michigan-Huron, and St. Clair as well as the St. Clair River and three points on the St. Marys River, were needed to calculate costs.

As indicated in Figure 5-11, the Study's SVM included "drop" menus that control basic assumptions underlying the calculations that created the values. The default assumptions were that: peaking and ponding was taking place; and, that ship operators going through the locks at Sault Ste. Marie would allow 0.6 m (2 ft) less under-keel clearance at the origin and destination than they would through the connecting channels (because they moved quickly through the channels, and because the channels have some rock-bottom areas).

The columns show the gross costs, the net improvement compared to **1977A** costs, the net improvement as a percentage of **1977A** costs, and the best and worst years in terms of net costs for each plan on each route.

Net Benefits for Plan1 and Plan2 HM

Breakdown of navigation impacts by routes and cargo

	Avg. Ann. Costs (Gross)		Avg. Ann. Benefits Net 77A		As a % of total costs		Worst Year (net)		Best Year (net)		
Routes	Plan 1 HM	Plan 2 HM	Plan 1 HS	Plan 2 HS	Plan 1 HS	Plan 2 HS	Plan 1 HS	Plan 2 HS	Plan 1 HS	Plan 2 HS	Routes
1-Sup	**$20.57**	**$20.57**	$0.00	-$0.01	-0.02%	-0.04%	1990; $-0.02	1970; $-0.03	1934; $0.01	1997; $0.01	1-Sup
2-MH	**$249.76**	**$249.91**	$0.08	-$0.07	0.03%	-0.03%	1965; $-0.31	1982; $-1.07	1979; $0.75	1907; $0.88	2-MH
3-StC	**$0.08**	**$0.08**	$0.00	$0.00	0.00%	0.01%	1906; $0	1936; $0	1900; $0	1907; $0	3-StC
4-E	**$490.15**	**$490.17**	$0.01	-$0.01	0.00%	0.00%	1965; $-0.05	1982; $-0.18	1979; $0.12	1907; $0.16	4-E
5-S-MH	**$430.45**	**$430.99**	-$0.16	-$0.71	-0.04%	-0.16%	1991; $-0.97	1970; $-3.53	1916; $0.76	1993; $0.94	5-S-MH
6-S-MH-StC	**$237.73**	**$237.80**	$0.00	-$0.08	0.00%	-0.03%	2003; $-0.09	1970; $-0.34	1903; $0.11	2007; $0.08	6-S-MH-StC
7-S-MH-StC-E	**$939.75**	**$940.54**	-$0.09	-$0.88	-0.01%	-0.09%	1992; $-1.09	1970; $-4.23	1916; $0.82	1994; $0.8	7-S-MH-StC-E
8-MH-StC	**$23.23**	**$23.24**	$0.01	$0.00	0.03%	-0.02%	2003; $-0.04	1982; $-0.11	1979; $0.06	1907; $0.09	8-MH-StC
9-MH-StC-E	**$368.17**	**$368.30**	$0.07	-$0.06	0.02%	-0.02%	1965; $-0.26	1962; $-0.9	1979; $0.71	1907; $0.77	9-MH-StC-E
10-StC-E	**$58.01**	**$58.01**	$0.00	$0.00	0.00%	0.00%	1965; $-0.01	1982; $-0.02	1979; $0.01	1907; $0.02	10-StC-E
	$2,817.90	**$2,819.62**	-$0.09	-$1.81	0.00%	-0.06%	1992; $-2.41	1970; $-6.72	1961; $2.61	1994; $1.36	

Average annual, $ millions per year

Values for Plan1 and Plan2 are based on deeper peak and shallower off-peak depths at US Slip.

**** - Costs for both plans reflect the user selected assumption that underkeel clearance at the east and west docks for ships tranisting the Soo (routes 5, 6 and 7) have been reduced by 2 ft.***

Sensitivity analysis

Model peaking and ponding
Model with no peaking

No adjustment
Add 1 ft at the docks
Add 1.5 ft at the docks
Add 2' at the docks

Just Soo
All Docks

Figure 5-11 ***Sample Comparison of Commercial Navigation Benefits***

Calculating Commercial Navigation Benefits

The estimate of shipping costs used depths available on each route each month and estimates of how shipping costs along each route would change at different depths in each calendar month. The estimate of costs was based on a Corps of Engineers model (GL-SAND) that included all 2005 Great Lakes ship transits in both countries as well as detailed cost information for the ships used to transport the material. The GL SAND model produced depth-cost curves for more than 3,000 shipments. This information was condensed in the SVM to about 275 sub-routes, each consisting of one or many shipments following the same route with same origin and destination dock depths.

For example, ships moving iron ore from harbours on the western shore of Lake Superior to steel mills in Chicago are loaded to depths that will allow safe navigation from the port in which they are loaded, across Lake Superior, through the St. Marys River, across Lakes Huron and Michigan and into the port where they are unloaded. The SVM calculates each of those depths each month and uses the minimum depth to determine the loading of all ships moving between those two ports each month. Greater water depths allow more cargo per load to be shipped, thus reducing costs. The GL-SAND model provides the depth-cost functions based on the characteristics of the actual ships and routes used in a representative year.

The modelling assumptions were reviewed with members of the Study's Commercial Navigation TWG and Great Lakes ship captains familiar with these routes. A comparison of GL-SAND and SVM cost estimates for three scenarios showed the SVM estimates of shipping cost changes between plans were valid and consistent with GL-SAND estimates. The changes in costs for any of the regulation plans and NBS were generally very small, on the order of a million dollars per year change in average annual costs, which amounts to a change of about 0.04 percent of total costs.

For more information on the methodology, see IUGLS (2009b).

Criterion 9:
How much does the plan increase benefits for those who use hydropower generated on the St. Marys River?

The Study Board preferred plans that at least preserved or even increased the value of hydroelectricity generated by the hydropower plants on the St. Marys River. In this analysis, the Study Board considered only the power plants on the St. Marys River. It was recognized that changes in the releases from Lake Superior will have a small effect on Lake Erie levels eventually, which would, in turn, affect the energy produced at power plants at Niagara Falls. However, any changes in the levels and flows driving hydroelectric power at Niagara are small and beyond the ability of existing computer models to estimate in a planning study or for operators to control effectively in practice (*e.g.*, the error in the estimate would generally be larger than the estimated change).

Calculating Hydropower Benefits

The hydropower benefit is the value to society of the power produced at the hydroelectric generating stations at Sault Ste. Marie. It has two components, the amount of hydroelectricity produced and the value per unit of energy:

- the estimates of hydroelectricity that would be produced under different plans were based on equations that relate flows and levels to energy produced at each of the plants (Fay and Fan, 2009); and,
- the estimates of energy value were based on the marginal prices of energy (Synapse Energy Economics Inc., 2011).

In comparing plan performance, the estimated net benefit from hydropower production is the product of net energy change times the marginal price of energy for the alternative plan minus the same product for the existing plan. The SVM calculates this value at each of the three hydropower plants. The energy for each month was calculated based on both peak and off-peak flows, and then energy for the month was multiplied by the estimated marginal price of energy each month to estimate the value of hydropower production. The difference in prices month-to-month reflects the difference in demand in different seasons, with the highest demand associated with peak heating and air conditioning loads.

The estimates of energy values shown in the evaluation tables in **Chapter 6** represent one set of forecasted prices for the year 2020. Numerous sensitivity analyses demonstrated that plan rankings were insensitive to the price of energy used. This was true primarily because the change in energy between plans was generally small, on the order of about 2 percent. Monthly prices were used to expose plans that generated the same amount of energy but shifted it from months of high demand to months of low demand. In some cases a plan would provide a slight increase in energy, but because the increase was more in months with low demand, produced slightly less benefit.

For more information on the methodology, see IUGLS (2009b) and Synapse Energy Economics Inc. (2011).

5

5.6 Key Points

With respect to the Study's approach to formulating, evaluating and ranking candidate plans for Lake Superior regulation, the following points can be made:

- The existing Lake Superior regulation plan, **1977A**, in effect since 1990, represents the culmination of nearly 75 years of water management experience responding to changing economic, environmental and social conditions across the upper Great Lakes basin.
- The rationale for reviewing the existing plan is based on several important factors that have emerged over the past 20 years:
  - a recognition of the considerable uncertainty about future NBS and corresponding water levels in the Great Lakes basin as a result of natural climate variability and human-induced climate change;
  - the opportunity to apply new data, modelling and knowledge about the hydrology and hydraulics of the Great Lakes system; and,
  - a much better understanding of the needs of the key interests that any new regulation plan must address.
- The historical context for Lake Superior regulation, including the rationale for and characteristics of all the preceding plans and the conditions that led to changes in those plans, served as the foundation for the Study Board's planning and decision making.
- The evaluation framework focused on directly relating lake level fluctuations and critical threshold levels to impacts on key interests, through tools such as performance indicators and coping zones. The approach was based on a shared vision planning process that supported collaborative decision making. The Study Board used a shared vision model to undertake practice decisions, allowing experts, stakeholders and decision makers a series of opportunities to weigh the results as information developed.
- Of the hundreds of NBS sequences generated by the Study's hydroclimatic analysis, 13 were chosen for detailed plan formulation and evaluation. These 13, developed through several different scientific approaches, are representative of the range of plausible NBS conditions that could be used to test the limits of any new proposed regulation plan. This suite of NBS sequences allowed the Study Board to test plans for *robustness* – the capacity to meet particular regulation objectives under a broad range of possible future water level conditions.
- The Study Board's objectives and principles were translated into nine specific decision criteria. These criteria, posed as questions under hydrological, ecological and economic factors, enabled the Study Board and plan formulators to better design plans to achieve these goals and evaluate how well these plans met the criteria under a variety of possible future NBS conditions.
- The Study Board applied the framework and tools outlined in this chapter to evaluate and rank candidate Lake Superior regulation plans, and to identify a preferred plan for recommendation to the IJC (described in **Chapter 6**).

Chapter 6

Selecting *Lake Superior Regulation Plan 2012*

Chapter 6 describes how the Study formulated, evaluated and ranked plans for regulating Lake Superior outflows. It then identifies and summarizes the advantages of a preferred plan, **Lake Superior Regulation Plan 2012*****, and describes recommended changes in the International Joint Commission's Orders of Approval.***

6.1 Overview of Study Approach to Plan Formulation and Evaluation[1]

Chapter 1 provided an overview of the history of Lake Superior regulation by the International Joint Commission (IJC). Beginning in 1921, seven plans have been implemented, each designed according to its own guiding principles and management objectives, reflecting the circumstances of that particular period. Each succeeding plan was more sophisticated in that it was designed to incorporate new data and knowledge. The current plan, **1977A**, has been in effect since 1990. **Chapter 5** provided details on the key provisions and features of the **1977A** plan.

The central challenge to the International Upper Great Lakes Study (the Study) was to identify a regulation plan that performed better than **1977A** under both the historical water supply conditions (net basin supplies[2], or NBS) and a wide range of uncertain NBS conditions resulting from changing climate conditions. The Study's hydroclimatic analysis, described in **Chapter 4**, found that beyond the next 30 years, there is considerable uncertainty regarding future NBS in the upper Great Lakes as a result of climate change – low NBS extremes may well happen, but high extremes are also plausible and both possibilities must be considered in the development of a new regulation plan.

1 This chapter is based on peer-reviewed work undertaken by the Study's Plan Formulation and Evaluation Technical Work Group (TWG). See the TWG's final report for more information on the methodology and analysis (IUGLS, 2012).

2 Net basin supply (NBS) is the net amount of water entering a lake, consisting of the precipitation onto the lake minus evaporation from the lake, plus groundwater and runoff from its local basin, but not including inflow from an upstream lake.

This chapter summarizes how the Study approached the challenge of developing and evaluating a regulation plan that performed better than **1977A**. The Study's approach was built on the following steps:

- Determine the absolute limits of how much Lake Superior regulation can affect water levels and flows through use of "fencepost" plans (section 6.2);
- Formulate a comprehensive suite of regulation plans, allowing formulators to collaboratively pursue a variety of different approaches (section 6.3);
- Evaluate and rank the plans, through a series of iterative practice decisions by the Study Board using the Shared Vision Model (SVM) and the decision criteria described in **Chapter 5** (section 6.4);
- Identify a new regulation plan for recommendation to the IJC (section 6.5); and,
- Put forward the changes that are required to make the IJC's Orders of Approval more effective and efficient (section 6.6).

6.2. "Fencepost" Regulation Plans

In the earlier stages of plan formulation, the Study highlighted three "fencepost" plans to identify the boundaries of what could be done for the key interests, such as hydroelectric generation, commercial navigation or coastal zone interests, through the regulation of Lake Superior. (**Chapter 3** provides details on the six key interests to be taken into account in Lake Superior regulation). These fencepost plans were not designed to be viable alternatives to the existing regulation plan but rather to illustrate the impacts of considering a plan that serves the specific needs of a single interest or group of like-minded interests.

6.2.1 Fencepost Plan 1: "Lake Superior for Lake Superior"

The goal for this plan was to address the interests of Lake Superior boaters and shoreline owners and the small sub-set of the commercial navigation industry that transits only between Lake Superior ports rather than passing through the locks on the St. Marys River. This interest group benefits from a compressed range of Lake Superior levels.

Figure 6-1 shows how the "Lake Superior for Lake Superior" plan was able to compress the range of Lake Superior levels, lowering the **1977A** high by 3 cm (about 1 in) and raising the **1977A** minimum by 35 cm (13.8 in) thus keeping the extremes within the optimal range for navigation and shoreline interests on that lake. The compression of Lake Superior levels, on the other hand, has minimal impact on levels on Lake Michigan-Huron, as shown in Figure 6-2.

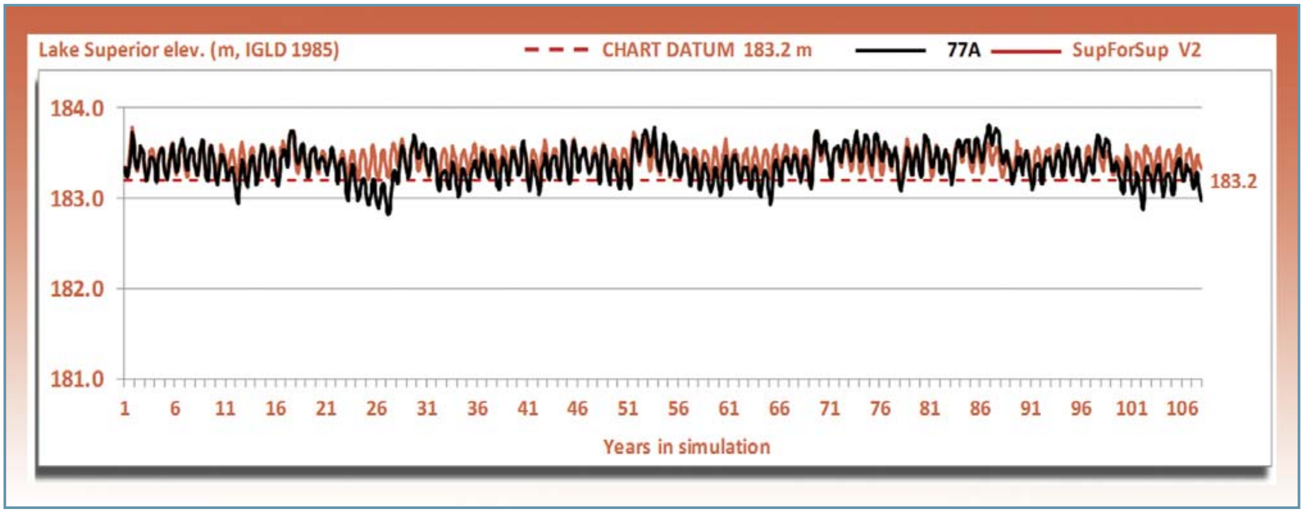


Figure 6-1 ***Comparison of Lake Superior Levels under Fencepost Plan 1***
*Historical NBS with **1977A** (black) and the Fencepost Plan (brown)*

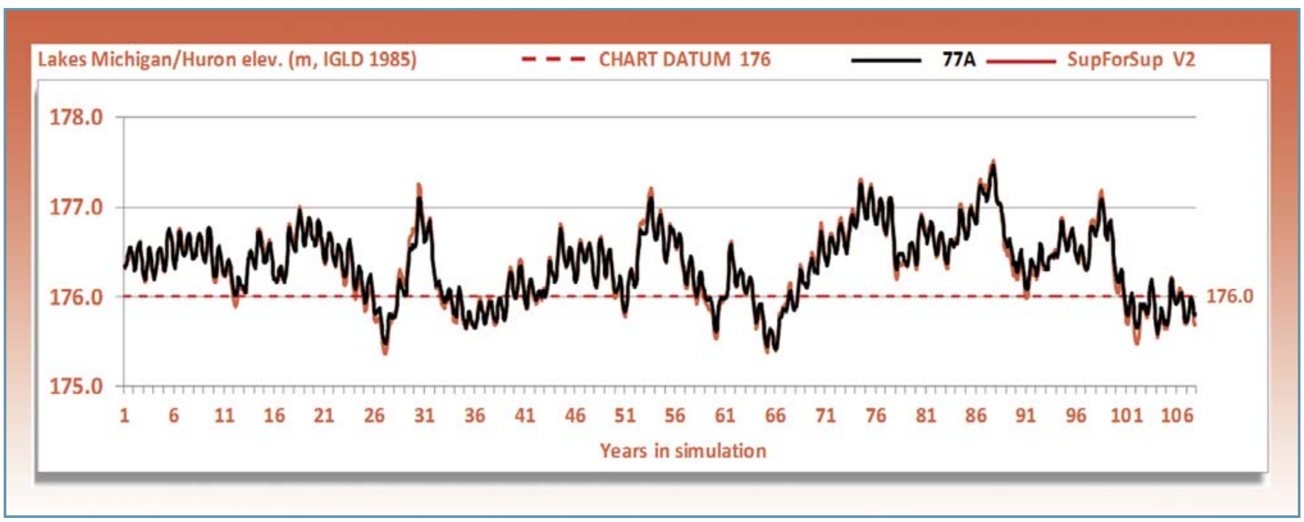


Figure 6-2 ***Comparison of Lake Michigan-Huron Levels under Fencepost Plan 1***
*Historical NBS with **1977A** (black) and the Fencepost Plan (brown)*

6.2.2 Fencepost Plan 2: "Lake Superior for Lake Michigan-Huron"

The second fencepost plan uses Lake Superior as a reservoir, with water retained or released so as to allow Lake Michigan-Huron levels to remain within a range preferred for shipping and coastal interests (figures 6-3 and 6-4). This plan does reduce extremes on Lake Michigan-Huron with historical NBS. But to compress the Lake Michigan-Huron level range by 28 cm (11 in), the "Lake Superior for Lake Michigan-Huron" plan increased the Lake Superior range by 1.33 m (more than 4 ft), raising the maximum level by half a metre (1.6 ft) and lowering the minimum level by more than a metre (3.3 ft).

These results illustrate an important fact about regulating the lakes: it takes a very large change in Lake Superior levels to affect a smaller change in Lake Michigan-Huron levels. This relationship is due primarily to the hydrological differences in basin-to-lake-area ratios and to the local runoff and overlake precipitation to Lake Michigan-Huron that Lake Superior regulation cannot control effectively.

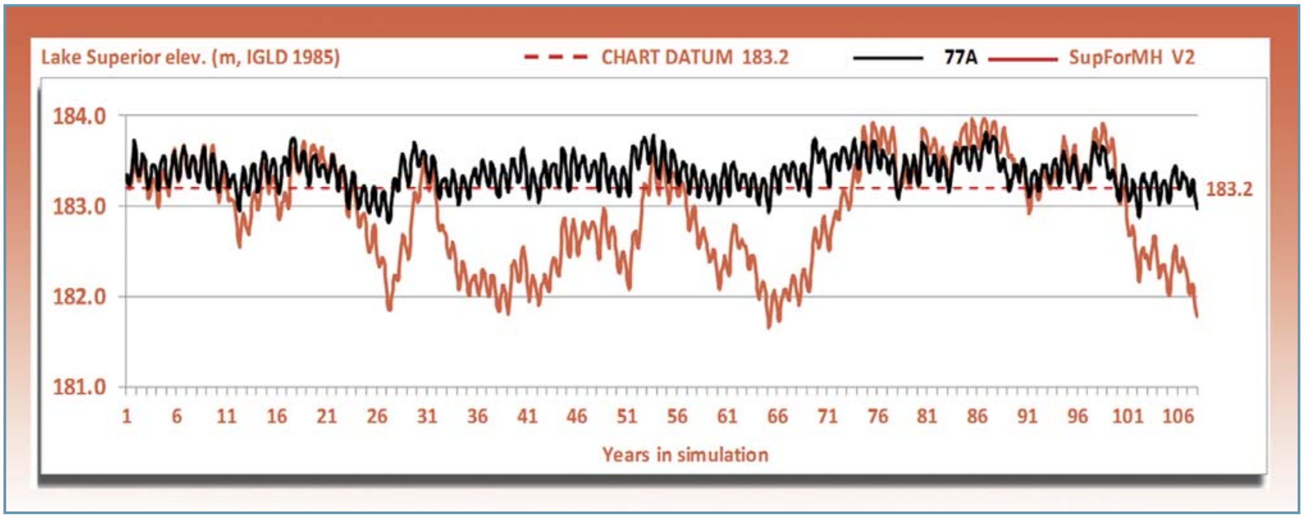


Figure 6-3 ***Comparison of Lake Superior Levels under Fencepost Plan 2***
*Historical NBS with **1977A** (black) and the Fencepost Plan (brown)*

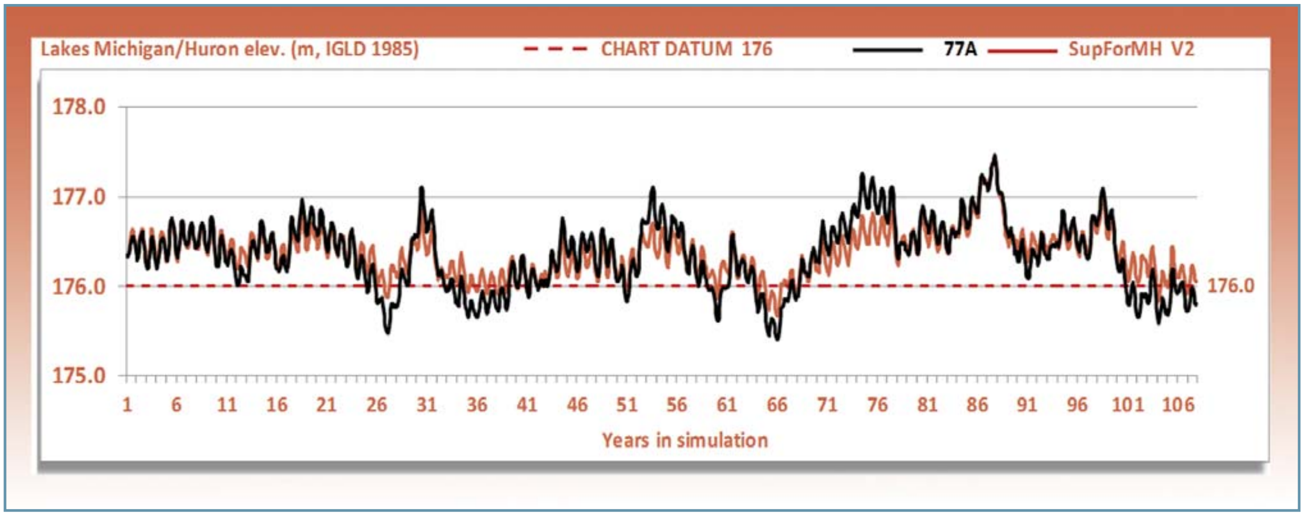


Figure 6-4 ***Comparison of Lake Michigan-Huron Levels under Fencepost Plan 2***
*Historical NBS with **1977A** (black) and the Fencepost Plan (brown)*

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6.2.3 Fencepost Plan 3: "Hydroelectric Generation Interests"

The third fencepost plan was designed to promote hydroelectric generation interests by avoiding the release of "excess" water that would not flow through the turbines. The results are shown in figures 6-5 and 6-6. Most releases were between 2,060 and 2,130 m^3/s (72,749 and 75,221 ft^3/s), with some flows as high 4,000 m^3/s (141,260 ft^3/s) when necessary to avoid Lake Superior levels over 184.0 m (603.7 ft). As indicated in Figure 6-5, this caused Lake Superior to rise 18 cm (7.1 in) higher and drop 78 cm (2.6 ft) lower than levels under **1977A**. The estimated hydroelectric generation benefit using this fencepost plan was $3.6 US million per year, an increase of nearly 6 percent over **1977A** that was nearly offset by adverse impacts to commercial navigation interests of $3 US million per year. Although shoreline protection costs were not calculated for this plan, the very high levels on Lake Superior would result in increased costs. For more information on how benefits were calculated as part of the evaluation of regulation plans, see Chapter 5. section 5.4.

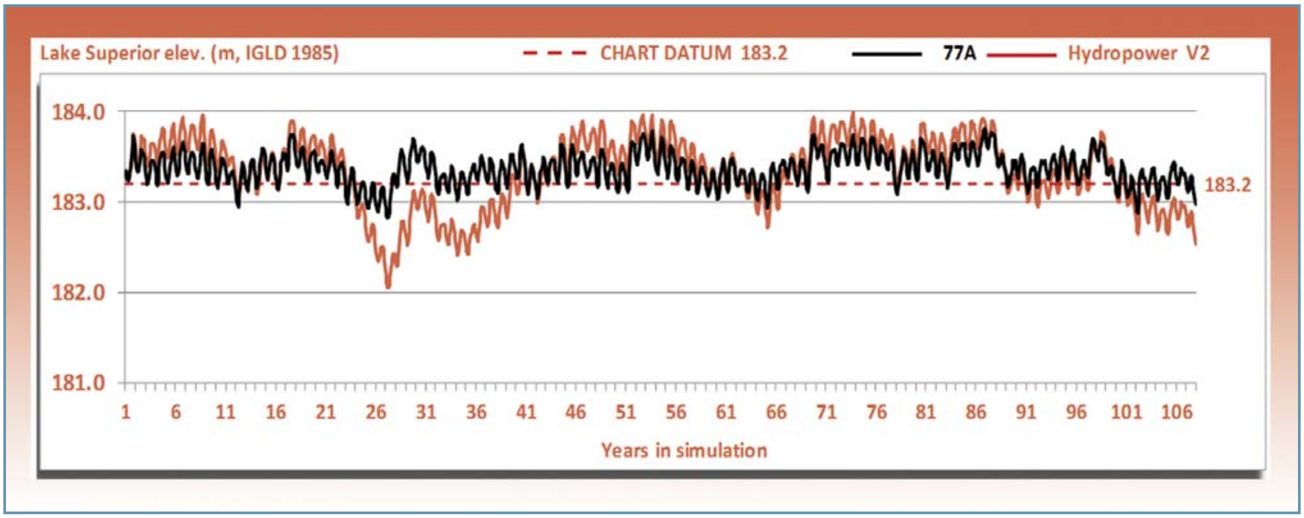


Figure 6-5 **Comparison of Lake Superior Levels under Fencepost Plan 3**

*Historical NBS with **1977A** (black) and the Fencepost Plan (brown)*

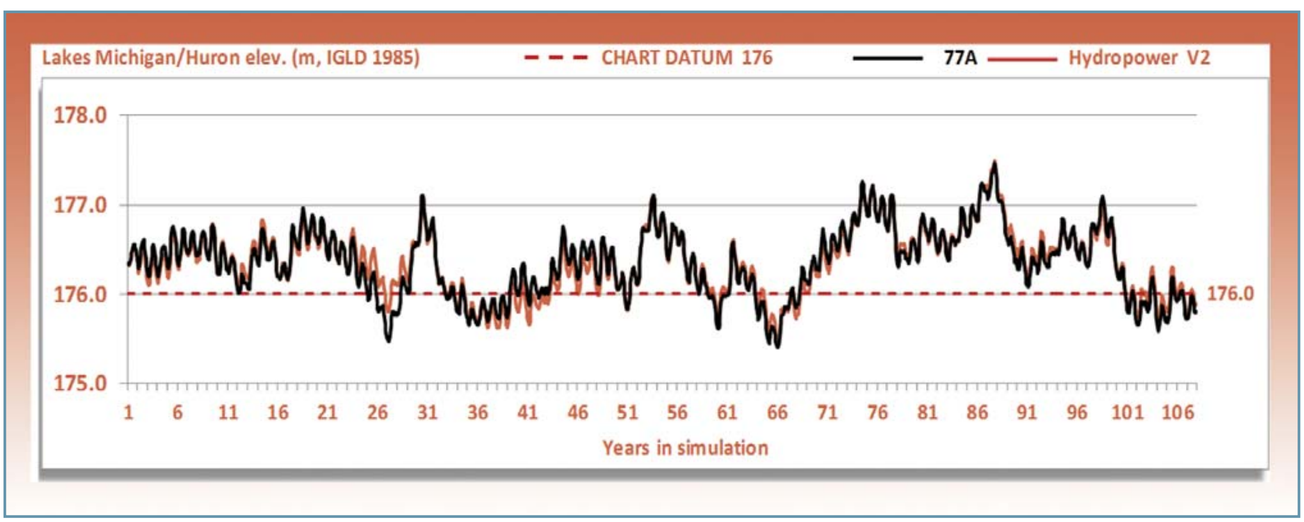


Figure 6-6 **Comparison of Lake Michigan-Huron Levels under Fencepost Plan 3**

*Historical NBS with **1977A** (black) and the Fencepost Plan (brown)*

6.3 Formulation of Regulation Plans

As part of a comprehensive search for new regulation plans, the Study teams pursued two particular approaches for plan development:

- *rule curves*, where plans are based on hydrological relationships, in which each month's release from Lake Superior was based primarily on current lake levels and levels downstream; and,
- *optimization*, where plans are based on the impacts (benefits) they would create for each of the main interests – both upstream and downstream.

6.3.1 Rule Curve Plans

1. Preproject

The simplest rule curve plan is based on a "preproject" or "no regulation of Lake Superior" condition, in which the release of water from Lake Superior is naturally a function of the level of that lake and, in winter, the resistance to flow caused by ice in the St. Marys River. The set of rules governed by this equation was called the "preproject plan" (see section 5.1.2, **Chapter 5**). The preproject release formula is intended to capture the physical configuration that governed the release of water from Lake Superior before it was changed by construction. The outflow from Lake Superior was naturally controlled by an underwater rock sill at the head of the St. Marys River rapids. The construction of locks, dams, bypass canals and bridge piers starting in 1798 eventually led to the regulation of the outflow. Outflows are considered to have been essentially unaffected by human activities until the construction of the International Railway Bridge and first power plant in 1887. Although actual regulation of outflows did not start until 1916, the preproject release models the 1887 conditions and thus represents the most recent understanding of what the "natural system" outflows might have been.

Figure 6-7 compares the rule curve relationship of the preproject plan (PP) to those of four other plans. The vertical scale shows the release flows for the St. Mary's River and the horizontal scale the Lake Superior water levels for that corresponding release. This relationship is based on 1,308 points, one for each simulated release in a 109-year (1900 to 2008) monthly simulation using historical NBS.

As indicated in Figure 6-7, graphing the relationship between Lake Superior levels and the flow of water out of Lake Superior reveals differences between plans even when they produce very similar lake levels. The narrowness of the Nat64d plot and, especially, the preproject plot shows that Lake Superior levels are the primary driver defining the release. That is, if the level of Lake Superior is known, then the release from the lake will vary within a small range. In contrast, the greater width shown for the **1977A** plot shows that the levels-release rules are based on more complex conditions. The nearly vertical right side of its plot means that at higher Lake Superior levels, the releases could vary a great deal, from about 2,400 m³/s (84,756 ft³/s) to almost 4,000 m³/s (141,260 ft³/s). Plan 129 has an even wider plot. The most natural release (preproject) produces the simplest plot.

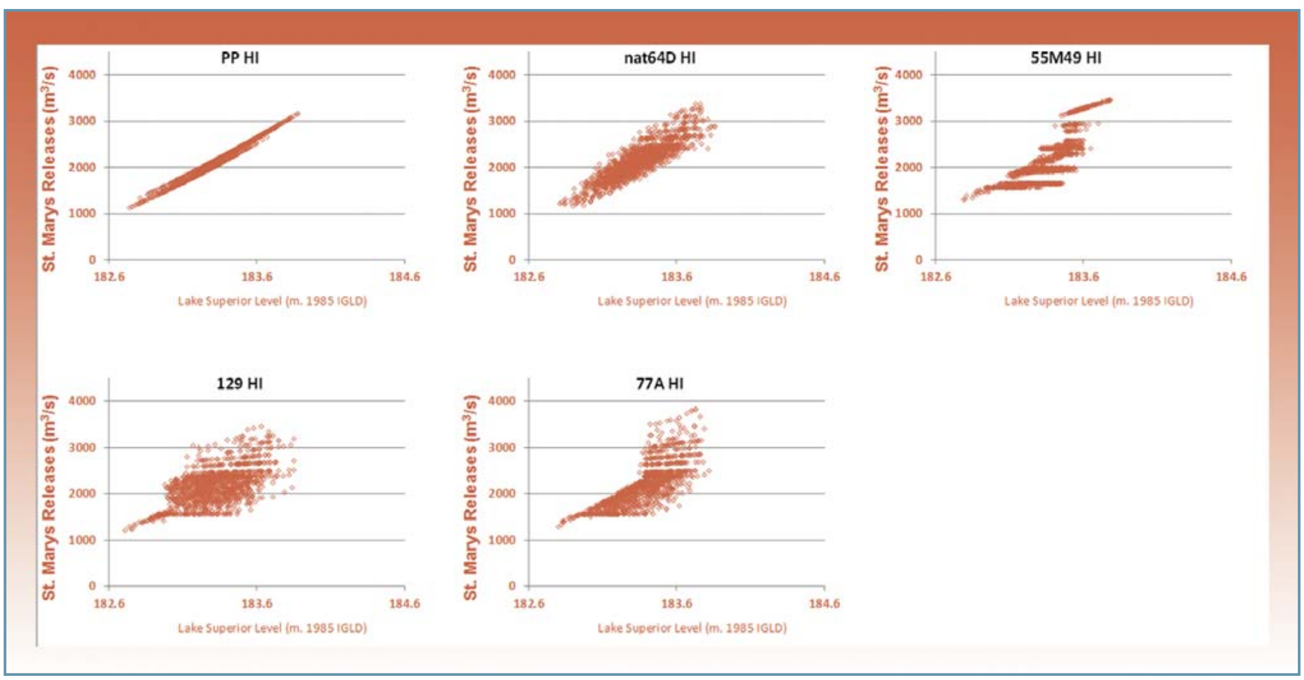


Figure 6-7 ***Comparison of St. Marys River-Lake Superior Level-Release Relationships for Rule Curve Plan Formulations***
PP: Preproject; HI: historical NBS series

2. Natural

The natural plan formulation began with the preproject release equation, with additional factors added to shape the preproject relationship based on the magnitude of the difference of lakes Superior and Michigan-Huron from their average levels for each calendar month calculated over 109 years of monthly level data. As with all plans, the practical requirements presently in place were imposed on the simulation, such as wintertime minimum flows that keep hydropower plant equipment from freezing. Plans developed this way were labeled **NatX**[3], where X was a number or combination of letters and numbers to signify how many "Nat" plans had been developed, evaluated and replaced with an improved version. The last of this series was labeled Nat64D, implying numerous iterations of the plan rules (including some that were never named). Each iteration varied the plan rules slightly to produce an enhanced mix of benefits and hydrological statistics, and to accommodate new NBS developed by the Study's Hydroclimatic TWG. Nat64D was subsequently improved by optimizing the parameters in its formulae.

3. Single-lake Rule

The 1955 Modified Rule of 1949 Plan was used prior to **1977A**. This previous plan, referred to as 55M49, was used to simulate what would happen if no attempt is made to balance Lake Superior levels with Lake Michigan-Huron levels. Single-lake rule curves are indifferent to conditions on the downstream lakes. For example, the 55M49 would call for high releases from Lake Superior even if levels on Lake Michigan-Huron are even higher than Lake Superior relative to their respective long-term average levels.

4. Modified Plan 1977A

The Levels Reference Study Board (1993) had proposed a plan called Plan 1.21 that made several changes to the existing rules of **1977A**. Plan 1.21, sometimes provides higher discharges at lower Lake Superior levels than **1977A**. Plan 1.21 produced hydropower benefits when simulated using the historical NBS. But early in the Study simulations, Plan 1.21 was tested using warm and dry climate change NBS, and the Study Board discovered that this plan would draw Lake Superior down to the point where there would be no release into the St. Marys River (*i.e.*, the level of the lake would be below the sill at the outlet of the St. Marys River, and the lake would no longer be connected to the river and would be land-locked).

Variations of **1977A** and Plan 1.21 that avoided the "no release" failure by imposing **criterion c** of the current Orders (release no more than would have been released by preproject flows) at different Lake Superior elevations were developed. Plans in this series were labeled from 121 to 130, plus a variation called 122C. With rare exceptions, the only difference among the plans was the Lake Superior elevation at which **criterion c** was applied. Figure 6-7 shows the level-release relationship for Plan 129, to the left of Plan **1977A**, to illustrate the differences between the derived and original plan.

Additional variations of **1977A** included 1977B, which limited the maximum month-to-month change in the flow in the St. Marys Rapids, and 1977C, which updated a number of the parameters including the lake level averages and standard deviations used in the balancing method.

Plan F was developed, using forecasted NBS to proactively balance lakes Superior and Michigan-Huron. Plan F uses the maximum side channel capacity and a half-gate setting at the Compensating Works. These plans were labeled **FNX**, where X is the number signifying how many plans that had preceded it. Several versions of the FN plan were developed.

5. Water Banking

An additional rule curve plan was formulated that established an annual volume of water based on Lake Superior levels which could be released during the year linked to hydropower prices. Although the concept was promising, no version of this plan was competitive across all nine Study Board decision criteria. Several iterations of this plan were evaluated but showed no real advantage and therefore were not pursued further.

6.3.2 Optimization Plans

Optimization can take many forms but always selects releases that will – at least according to algorithms developed by the plan designer – directly produce the best outcomes for a specified set of objectives and constraints, such as monetized benefits, or minimized ecological damages, with the outcomes being lake levels. This is in contrast to rule curve plans that produce releases based on lake levels, which are then translated to benefits and costs for each water-using sector.

3 The Study had no formal convention for naming the many plans being developed and evaluated. Some plan formulation teams adopted informal names for their suite of plans, based on the name of the team leader.

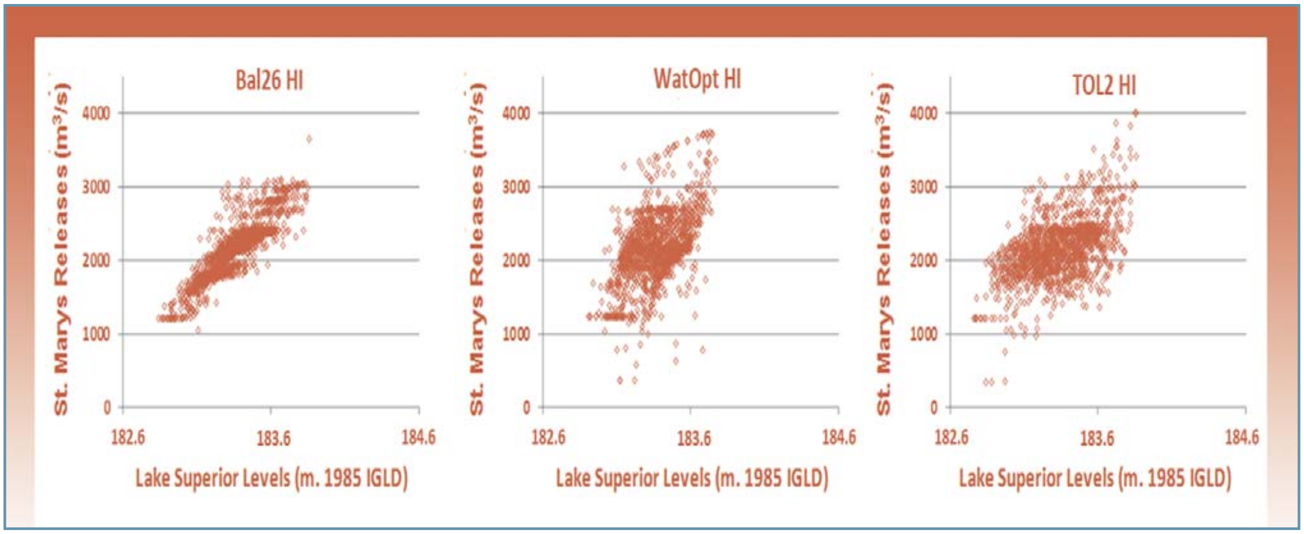


Figure 6-8 **Level-release Diagrams for Three Optimization Approaches to Plan Formulation**

The Study used three different approaches to developing optimization plans:

- **Balance** plans were developed which use curves representing the preferences of different interests and which iteratively test releases each month to achieve the best overall interest score. Plans in this sequence were labeled **BALX**.
- Plans were developed based on interest satisfaction curves which emulated the response of the economic benefit functions. Plans in this sequence were labeled **WATX**.
- A hybrid approach was also formulated which used the actual benefit algorithms to develop rule curve based releases optimized for a particular water supply sequence. Plans in this sequence were labeled **TOLX**.

Figure 6-8 shows the levels-release relationships for the optimization plans. As discussed above, with respect to Figure 6-7, the narrower the plot of the levels-release graph, the more natural the release conditions (*i.e.*, indicating that Lake Superior levels are the primary driver of the release of water from the lake.) Comparing the three graphs in Figure 6-8, the Bal26 plan clearly results in the simplest plot and the most natural release conditions.

6.3.3 Summary of Regulation Plans

Using the two plan formulation approaches described above, plan formulators generated more than a 100 different regulation plans for possible consideration by the Study Board (Table 6-1).

6.4 Regulation Plan Evaluation and Ranking

This section summarizes the Study Board's decisions in evaluating and ranking the regulation plans. It describes:

- the Study Board's process of narrowing down the many plans to identify first a preferred plan (6.4.1);
- the detailed evaluation of four plans to illustrate the application of the Study Board's evaluation process and decision criteria (6.4.2);
- the key factors in the Study Board's selection of a preferred plan (6.4.3); and,
- how the Study Board then evaluated several variations of this preferred plan to identify a recommended plan (6.4.4).

6.4.1 Study Board Evaluation Decisions

As described in **Chapter 5**, the Study Board used a series of practice decisions to evaluate possible regulation plans. Table 6-2 summarizes the step-by-step evolution of the Study Board's evaluation decisions. The plan formulation process began with the suite of plans generated by the two approaches and reduced the list of viable plans. The process evolved over time as more results for sectoral impact models became available, as a wider range of test NBS sequences could be applied and as the Study Board's knowledge of the nature and extent of tradeoffs increased with the series of practice decisions. The existing plan, **1977A**, was included throughout the evaluation and ranking process as the baseline comparison plan, because the fundamental objective was to see if, through the application of the SVM, a new regulation plan would produce improved results in comparison with **1977A** under a range of future NBS conditions.

Table 6-1: Summary of Regulation Plans Generated by the Study

Plans	Versions	Description
Preproject	One plan - preproject	Produces flows that would occur without regulation or channel improvements
Natural	Numerous iterations Called either NatX[1] or NatOptX[1]	Based on preproject with dampening rules that balance the lakes and avoid extremes
Single-lake	One plan -1955 Modified Rule of 1949 (55M49)	This plan was used from 1955 to 1979; releases do not consider Lake Michigan-Huron levels
Modified Plan **1977A**	Two plans -1977B and 1977C Several variations of Plan 121 recommended by the LRSB (1993)	These plans modified **1977A** rules or parameters The plans labeled from122-130 and 122C were variations on Plan 1.21 with different **criterion c** triggers
Water Banking	One plan	Allowed an annual volume of water to be allocated in supplemental monthly releases to specifically benefit hydropower
Optimization – Benefit Functions	WatX[1]	Optimized using benefit function surrogates, sometimes with perfect foreknowledge[2]
Optimization – Interest Satisfaction Curves	BalX[1]	Optimized monthly releases based on interest satisfaction curves
Optimization – SVM Benefit Functions	UWX[1]	Optimized using the SVM benefit functions

1 X is the number of the iteration.

2 A term used in modelling and simulations in which the computer makes decisions from the first month in the simulation based on all the NBS. That is, the computer is prescient. Although this is not realistic, it does help address the question of how much better the regulation plan could be with better forecasting.

The Study Board reduced the large suite of regulation plans down to seven potential plans (September 2011). In evaluating these seven plans against the decision criteria under a range of NBS sequences, the Study Board found that three of the plans had significant failings and eliminated them from further consideration. The eliminated plans were:

- Plan 1977B, which performed very closely to but no better than **1977A**, and which also failed in the most severe dry climate change scenario (showing Lake Superior levels falling to where the lake essentially stops releasing water into the St. Marys River);
- Plan WatOpt, which had lower overall economic benefits compared to **1977A** in all NBS sequences for which there were complete simulations (except for NBS sequence 4, where it provided over $6 US million average annual shore protection benefits, offset by $2.6 US million average annual navigation negative benefits [costs or losses] however with levels that failed the balance test); and,
- Plan 55M49, which did not balance levels on lakes Superior and Michigan-Huron, as it performed well on Lake Superior but not on Lake Michigan-Huron or for interests such as commercial navigation that benefitted from more balanced levels.

The remaining four plans were:

- Plan 129, a modification of **1977A**
- Plan PFN3, another modification of **1977A**
- Plan Nat64D, a Natural Rule Curve plan closer than the other plans to no regulation; and,
- Plan Bal26, an Optimization plan.

Table 6-2: Timeline of Selection Process of Regulation Plans

Study Board Practice Decision Session	Plans Considered (note: in addition to 1977A)	Evaluation Context	Outcome
September 2009	Alternatives considered included the reference and modified fencepost plans as well as Plan 1.21, all evaluated using initial historical supply sequences	The plans were ranked based on water level statistical performance No ecological or economic benefits were available at this time	This practice decision showed the limits of what could be done with only Lake Superior regulation No plans were eliminated
December 2009	Alternatives considered included the reference and modified fencepost plans as well as Plan 1.21, all evaluated using initial historical supply sequences	The plans were ranked based on water level statistical performance No ecological or economic benefits were available at this time	This practice decision showed the limits of what could be done with only Lake Superior regulation No plans were eliminated
September 2010	The comparison was among four specific plans based on a plan from LRSB (1993): 122C, 128, 129 and 130	First use of non-historical water supply sequences to test plan robustness	No plans eliminated, but the Study Board decided that maximizing net benefits was not as important as minimizing the maximum sectoral loss
February 2011	Improved versions of the September 2010 plans plus two Balance plans and the first version of the Wat series of optimization plans	This was the first practice decision in which all the plans were compared using six of the seven Study Board decision criteria then in place (no scores were available for environmental performance)	No plans eliminated The Study Board asked for more information on several evaluation categories A trial simulation showed that Lake Superior regulation could not reduce high water impacts on a restored Lake Michigan-Huron without unacceptable impacts to Lake Superior
June 2011	16 plans: PP, 1977B, 122, 122C, 123, 124, 125, 126, 127, 128, 129, 130, 55M49, Nat60, PFN3, and Bal25	Plans were evaluated with 13 NBS sequences Several plans had to stop releasing water from Superior under the new, very severe NBS The evaluation included new plan rules developed to enhance lake sturgeon spawning habitat in the St. Marys River	The Study Board selected five plans for further comparison Plan formulators revised three other plans and resubmitted them for the next session
September 2011	7 plans: 1977B, 55M49, 129, Nat64D, Bal26, PFN3, and WatOpt	A complete evaluation with a full set of PIs and NBS sequences, using eight Study Board criteria See section 6.5 for details	The Study Board made a tentative plan selection (Nat64D), based on the plan's high ranking regardless of the climate scenario it was tested under
October 2011	4 plans: Nat64D, NatOpt, NatOpt2 and NatOpt3	Ninth criterion added (**criterion c** replacement) See Section 6.5 for details	NatOpt2 was selected, primarily based on greater economic benefits (see Table 6-15)
November 2011	4 plans: Nat64D, NatOpt, NatOpt2 and NatOpt3	Ninth criterion (**criterion c** replacement) added See Section 6.6.1 for details	NatOpt3 was selected over NatOpt2 because it met the **criterion c** replacement criterion

Note: Table 6-2 summarizes the evolution of the Study Board's decision evaluations leading to the selection of a preferred regulation plan. Plan evaluations became increasingly complex, as additional decision criteria were incorporated and key concepts such as balance and disproportionate loss were clearly defined.

6

Section 6.4.2 presents the detailed evaluation of these four remaining plans. Table 6-3 summarizes the climate change scenarios and the NBS sequences used in the evaluations. Only 10 of the 13 NBS sequences are included in this assessment, as three of the sequences (Low range [LR], Dry [DS], and a second regional climate model sequence [AT]) produced comparable results to other sequences and did not provide any unique insight into the plan rankings. All of the evaluation tables are included in the TWG's final report (IUGLS, 2012).

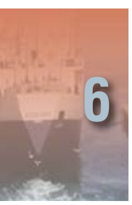
Based on the results of the evaluation of the four plans, the Study Board selected a preferred plan (section 6.4.3). Further refinements and testing of variations of that preferred plan enabled the Study Board to identify a recommended plan (6.4.4).

Table 6-3: Summary of Climate Change Scenarios and NBS Sequences used in Evaluation Tables

Climate Change Scenario	NBS Sequence	Comment
1. Stationary Climate	1. HI (Historical)	Over the next 30 years, NBS will be similar to the historical NBS
	2. LR[1] (Low range)	Representative of current climate, but the range of NBS varies little over the period
	3. DS[1] (Dry)	Representative of current climate, but the driest stochastic[2] sequence for Lake Superior
2. Uncertain Changes in Climate	4. HM (High Michigan)	Based on current climate, but creates the highest Michigan-Huron levels from the stochastic datasets, with a large range between wettest and driest years
	5. WS (Wet NBS)	Reflects a higher mean NBS, even though it is based on current climate conditions
	6. LM (Low Michigan)	Based on current climate, but creates the lowest Michigan-Huron levels from the stochastic datasets while still producing a maximum level greater than historical Includes 14 consecutive years of below average NBS
	7. AT[1]	One of the sequences produced by the Canadian RCM that produces higher highs and lower lows Plan rankings were similar to AV (Sequence 9)
3. Change to Drier Climate	8. LS (Low Superior)	Based on current climate, but produces the lowest Lake Superior level in entire stochastic simulation
	9. AV (Low Superior)	**1977A** produces lower levels with this sequence than with any in the stochastic sequences
	10. 174	One of the climate change sequences in which the climate change effect becomes more pronounced over time **1977A** Superior levels drop below 182.0 m (597.1 ft) using this sequence
	11. 370	Another sequence that got drier over the course of the 109 years, but even more severe than sequence 174
	12. TR (Extended trend)	This sequence was not derived from climate models, but from trend extrapolations of historical NBS, assuming the mean would continue to change as it has in the last two decades (Lake Superior NBS trend was down, the Lake Michigan-Huron trend was neutral, and the Lake Erie trend was up moderately) This was the most severe dry test for Superior regulation
4. Change to Wetter Climate	13. HS (High Superior)	Current climate with average NBS close to historical NBS, but with the highest Lake Superior level in the stochastic set The wettest portion of this supply sequence comes early in the simulation, as would be expected if recent dry NBS forecast a reversal to wet conditions

1 Note: these NBS sequences were included in the evaluation, but the corresponding evaluation tables are not included in this section because it was concluded that they produced very similar results to other sequences and did not provide any unique insight into the plan rankings. All the evaluation tables are included in the Plan Formulation and Evaluation TWG's final report (IUGLS, 2012).

2 Stochastic – Statistics involving or showing random behaviour. In a stochastic simulation, a model is used to create a new 'synthetic' series of plausible flows and lake levels, based on historical data. The synthetic series will, on average, preserve important properties of the historical record, such as the mean and standard deviation, while generating new combinations of high and low flow conditions that could represent more severe conditions than those seen in the past.



6.4.2 Testing Plan Performance

Tables 6-4 to 6-13 summarize the testing of the four final plans for robustness and benefits against the nine decision criteria under the various NBS sequences.

Each of the evaluation tables highlights the Study Board's assessment of the plans. In some cases, the observations draw attention to values that were more important in plan selection; in other cases, additional information is provided in the note to explain why some values were considered of lesser importance or discounted. Ecological performance includes a comparison between each alternative and Plan **1977A** based on the number of years Coping Zone Cs were induced by the alternative.

Note that there is an apparent inconsistency in some of the tables in that small improvements in average energy produced may not translate to increased energy benefits, and vice-versa. For example, in Table 6-7, the Bal26 plan produces slightly more energy than **1977A**, but less energy value (measured in terms of revenue), while Nat64D increases both energy and energy value. These differences arise because of the different value of energy at different times of the year (*e.g.*, energy is in greater demand when heating and cooling loads are the greatest).

In the Low Michigan NBS evaluation shown in Table 6-7, Nat64D improves **1977A** energy production in six months, from August through January, produces less energy than **1977A** in April and May, and produces about the same in other months. However, April and May have the lowest energy prices because there is generally less need for heating and cooling, so the energy production shift from months with lower demand to months with higher demand means the plan has greater value to those who use electricity. Bal26 produces more energy than **1977A** in seven of twelve months, from May to November, less in January through March, and about the same in other months. Prices are high in January, February and March. Even though Bal26 produces a little more energy on average than **1977A**, it shifts the production from months of high demand to months of low demand, and so is less valuable to consumers.

These results tend to occur when the changes in energy and energy value are close to zero. Although Bal26 has a less favourable result than Nat64D for the Low Michigan NBS, both plans are within a percentage point of **1977A** performance on the hydropower value criterion.

Decision Criteria for Evaluating Performance of Regulation Plans

1. How well does the plan perform in keeping Lake Superior water levels between 182.76 and 183.86 m (599.6 to 603.2 ft)?
2. Does the plan maintain the historical balance of Lake Superior levels with Lake Michigan-Huron levels?
3. How much does the plan lower the highest Lake Michigan-Huron levels and raise the lowest?
4. Does the plan create fewer Lake Superior levels below chart datum for the historical NBS than preproject?
5. Does the plan enhance ecological attributes and reduce negative environmental impacts?
6. Does the plan minimize disproportionate loss to any particular water interest?
7. How much does the plan reduce net shoreline protection costs?
8. How much does the plan increase benefits[1] for consumers affected by shipping costs?
9. How much does the plan increase benefits[1] for those who use hydropower generated on the St. Marys River?

1 *Benefits are used here in terms of benefits to the general public or consumers and not based on corporate revenue and profits. See* ***Chapter 5*** *for details on these criteria, including how the economic benefits were calculated.*

Table 6-4: NBS Sequence 1 (HI)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	Pass	Pass	Pass	182.71	Pass
2. Balance water levels	Pass	Pass	Pass	Fail	Pass
3. Balance Lake Michigan-Huron water levels	Pass	Pass	Mixed	Pass	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Pass	Pass	Pass	Fail	Pass
5. Minimize environmental impacts	Pass	Pass	Pass	Pass	Pass
Number of fewer Zone C PI-Years	1	2	2	2	0
Number of greater Zone C PI-Years	0	1	0	0	0
SUP-01	0.39	0.41	0.31	0.36	0.36
SUP-02	0.40	0.46	0.30	0.37	0.34
6. Minimize disproportionate loss					
Coastal (Δ SP Costs)	Pass	Pass	Pass	Pass	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	$0.12	-$0.03	-$0.10	$0.56	$0.00
8. Increase navigation benefits	$0.05	$0.02	$0.10	-$0.05	$0.00
9. Increase hydropower benefits	$0.33	$0.16	-$0.23	$0.08	$0.00
Increase average energy (kWh)	506	527	-465	90	0

Observations:

- *This test offers significant evidence that Nat64D would be a good Lake Superior regulation plan. It is the only plan to outperform **1977A** in every category.*
- *Bal26 does almost as well, and the differences among the best plans are so small that it is hard to argue they are significant, with the exception of the ecosystem impacts.*
- *Past NBS are the traditional standard for testing water management plans, even though they do not include rare but plausible wetter and drier conditions. Only Plan 129 fails this test, as it allows Lake Superior to fall below 182.76 m (599.60 ft), violating the first criterion and a condition of the Orders.*
- *PFN3 does well in many categories by compressing Lake Superior levels, but that also gives it lower SUP-01 and SUP-02 scores than **1977A**.*
- *Nat64D, Bal26 and PFN3 HI all reduce the Zone C incidence of SMQ-01 (lake sturgeon spawning habitat).*
- *All but Nat64D eliminate the one occurrence of LMH-07 under **1977A**. A LMH-07 Zone C is triggered when the average level of Lake Michigan-Huron is less than 176.0 m (577.4 ft) for four or more consecutive years during the growing season, April through October.*

Table 6-5: NBS Sequence 4 (HM)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	Fails Both	184.17	184.15	Fails Both	Fail
2. Balance water levels	Pass	Pass	Pass	Pass	Pass
3. Balance Lake Michigan-Huron water levels	Fail	Mixed	Mixed	Mixed	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Pass	Pass	Pass	Pass	Pass
5. Minimize environmental impacts	Fail	Fail	Pass	Pass	Pass
Number of fewer Zone C PI-Years	0	0	0	0	0
Number of greater Zone C PI-Years	2	1	0	0	0
SUP-01	0.46	0.49	0.41	0.47	0.44
SUP-02	0.45	0.54	0.35	0.42	0.42
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Pass	Fail	Fail	Fail	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	-$0.32	-$2.65	-$1.63	-$1.35	$0.00
8. Increase Navigation Benefits	-$0.09	-$0.37	$0.23	-$0.09	0
9. Increase Hydropower Benefits	$0.20	-$0.06	-$0.33	$0.28	0
Increase average energy (kWh)	272	174	-585	367	0

Observations:

- ***1977A** performs well in this test, which simulates the plans using a NBS sequence with the highest Lake Michigan-Huron levels in the entire 55,400-year sequence of stochastic NBS, an extreme test.*
- *Nat64D also does quite well after a more detailed analysis shows that the two ecological Zone Cs predicted by the SVM would not materialize.*
- *Based on the counts of Zone Cs, it was predicted by the SVM that both Nat64D and Bal26 would fail to minimize environmental impacts, but neither actually did.*
- *Nat64D has two SMQ-02 Zone Cs that **1977A** does not have. Zone Cs occur when there have not been sufficient flushing flows to maintain the substrate in the Lake George channel. The zone is triggered if the average flow rate during May-June is below 2,000 m^3/s (70,630 ft^3/s) for seven or more consecutive years. However, after these evaluations, biologists agreed that the PI does not take into account peaking and ponding; the peaking flows for Nat64D are well above 2,000 m^3/s (70,630 ft^3/s) rate and would provide the necessary flushing.*
- *Otherwise, Nat64D has slightly better SUP-01 and SUP-02 numbers, but overall, Nat64D criteria scores are slightly worse than **1977A**.*
- *Bal26 does cause a SUP-04 Zone C because it causes Lake Superior summertime peaks to rise above 184.0 m (603.7 ft) three years in a row, impacting conditions for wild rice growth at Kakagon Slough.*

Table 6-6: NBS Sequence 5 (WS)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	183.99	184.08	183.97	184.01	183.92
2. Balance water levels	Pass	Pass	Pass	Pass	Pass
3. Balance Lake Michigan-Huron water levels	Pass	Pass	Mixed	Pass	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Pass	Pass	Pass	Pass	Pass
5. Minimize environmental impacts	Pass	Fail	Pass	Pass	Pass
Number of fewer Zone C PI-Years	0	0	0	1	0
Number of greater Zone C PI-Years	0	1	0	0	0
SUP-01	0.44	0.45	0.37	0.43	0.38
SUP-02	0.44	0.50	0.36	0.42	0.37
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Fail	Fail	Fail	Fail	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	-$0.15	-$0.14	-$1.10	-$0.10	$0.00
8. Increase navigation benefits	$0.17	-$0.17	$0.50	$0.32	0
9. Increase hydropower benefits	$0.79	$0.27	-$0.18	$0.44	0
Increase average energy (kWh)	817	554	-420	630	0

Observations:

- *While Nat64D performs the best or very well on many criteria, it does create a disproportionately high increase (more than 8 percent) in shoreline protection costs on three of the eight Lake Superior reaches and hence gets a "Fail" under the principle of minimizing disproportionate loss.*
- ***1977A** has the lowest maximum Lake Superior level of all the plans (183.92 m (603.4 ft), 7 cm (2.8 in) lower than Nat64D.*
- *All alternative plans fail the disproportionate loss test; Bal26 does the worst of these plans, allowing Lake Superior to rise to 184.08 m (603.9 ft) and it increases shoreline protection costs on every reach of Lake Superior, for an overall Lake Superior increase of 16 percent.*

Table 6-7: NBS Sequence 6 (LM)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	183.93	Fails Both	Fails Both	Fails Both	Fail
2. Balance water levels	Pass	Pass	Pass	Pass	Pass
3. Balance Lake Michigan-Huron water levels	Mixed	Pass	Mixed	Mixed	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Fail	Fail	Pass	Fail	Pass
5. Minimize environmental impacts	Fail	Fail	Pass	Pass	Pass
Number of fewer Zone C PI-Years	1	7	8	7	0
Number of greater Zone C PI-Years	2	9	0	0	0
SUP-01	0.41	0.45	0.34	0.39	0.40
SUP-02	0.53	0.59	0.42	0.55	0.52
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Pass	Fail	Fail	Fail	Pass
Boating slips	Pass	Fail	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	$0.26	$0.11	-$0.39	$0.18	$0.00
8. Increase navigation benefits	$0.11	$0.43	$0.13	$0.06	0
9. Increase hydropower benefits	$0.37	-$0.25	-$0.44	-$0.34	0
Increase average energy (kWh)	407	51	-464	-310	0

Observations:

- *This NBS sequence includes the lowest monthly level in the 55,400-year stochastic NBS sequence and is an extreme test of how well plans handle very dry conditions.*
- *Nat64D performs better than the other plans, with the lowest maximum level and the highest minimum level for Lake Superior and net benefits for all three sectors.*
- *The Nat64D mixed results on compression of Lake Michigan-Huron levels is by the smallest margin (misses by 2 mm [0.08 in]). The increase in ecological Zone Cs is for SMQ-02, which is overcome by peaking and ponding (see Table 6-5).*
- *Both Nat64D and Bal26 reduce the incidence of SMH-04, which relates to the quality of habitat where the St. Marys River flows into Lake Michigan-Huron.*
- *Bal26 causes a SUP-05 Zone C (that neither **1977A** nor Nat64D trigger), indicating a significant decline in northern pike abundance.*
- *In the second decade of this NBS series, Bal26 drops Lake Superior levels by more than 30 cm (more than 1 ft) below those under **1977A** or Nat64D. Although Bal26 also kept Lake Michigan-Huron levels 20 cm (7.9 in) higher than **1977A** or Nat64D, the Study Board concluded that its decline in Lake Superior levels violated the principle of balance.*

Table 6-8: NBS Sequence 8 (LS)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	Fails Both	Fails Both	Pass	Fails Both	182.57
2. Balance water levels	Pass	Pass	Pass	Fail	Pass
3. Balance Lake Michigan-Huron water levels	Mixed	Pass	Fail	Mixed	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Fail	Fail	Fail	Fail	Pass
5. Minimize environmental impacts	Pass	Pass	Pass	Pass	Pass
Number of fewer Zone C PI-Years	2	3	9	4	0
Number of greater Zone C PI-Years	0	0	0	0	0
SUP-01	0.43	0.42	0.36	0.42	0.39
SUP-02	0.52	0.53	0.39	0.48	0.45
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Pass	Pass	Pass	Pass	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	$0.00	-$0.19	-$0.03	$0.36	$0.00
8. Increase navigation benefits	$0.06	$0.53	-$0.54	-$0.36	0
9. Increase hydropower benefits	$0.51	$0.30	-$0.27	-$0.38	0
Increase average energy (kWh)	554	598	-299	-337	0

Observations:

- *Plan PFN3 performances relatively well on this extremely dry NBS sequence, which creates the lowest levels of Lake Superior. Its Lake Superior minimum level is 182.76 m (599.6 ft).*
- *But this result for Lake Superior comes at a cost: the PFN3 minimum level on Lake Michigan-Huron is 10 cm (3.9 in) lower than the **1977A** minimum. In addition, PFN3 creates negative benefits for each of the three economic sectors.*
- *Bal26 has the best overall net benefits, but Nat64D is a close second and benefits for each sector are positive.*
- *Nat64D and Bal26 each eliminate a SUP-05 Zone C created by **1977A**.*

Table 6-9: NBS Sequence 9 (AV)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	Fails Both	Fails Both	182.70	182.47	182.52
2. Balance water levels	Pass	Pass	Pass	Fail	Fail
3. Balance Lake Michigan-Huron water levels	Mixed	Mixed	Mixed	Mixed	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Fail	Pass	Pass	Fail	Pass
5. Minimize environmental impacts	Pass	Pass	Pass	Pass	Pass
Number of fewer Zone C PI-Years	0	0	1	1	0
Number of greater Zone C PI-Years	0	0	0	0	0
SUP-01	0.44	0.45	0.36	0.44	0.41
SUP-02	0.49	0.54	0.40	0.48	0.47
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Pass	Pass	Pass	Pass	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	-$0.10	-$0.14	-$0.23	$0.14	$0.00
8. Increase navigation benefits	$0.41	$0.15	$0.58	-$0.22	0
9. Increase hydropower benefits	$1.27	$0.88	-$2.84	$0.21	0
Increase average energy (kWh)	1,370	1,188	-2,791	236	0

Observations:

- *Nat64D performs best overall on this climate change NBS simulation, though it is not best in all nine criteria. It has the largest net benefits but is only slightly better than **1977A** ecologically (better SUP-01 and SUP-02 scores).*
- *Nat64D does raise the **1977A** maximum on Lake Superior from 183.81 to 183.88 m (603 to 603.3 ft). It lowers the **1977A** maximum Lake Michigan-Huron by 3 cm. but has a minimum of 175.30 m (575.1 ft), three cm (more than 1 in) lower than **1977A**.*
- *Bal26 also performs well, with similar advantages and disadvantages to Nat64D but with slightly lower economic benefits.*

Table 6-10: NBS Sequence 10 (174)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	182.14	181.94	182.23	181.86	181.86
2. Balance water levels	Fail	Fail	Pass	Fail	Fail
3. Balance Lake Michigan-Huron water levels	Mixed	Mixed	Mixed	Mixed	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Pass	Pass	Pass	Fail	Pass
5. Minimize environmental impacts	Pass	Pass	Pass	Fail	Pass
Number of fewer Zone C PI-Years	54	65	58	6	0
Number of greater Zone C PI-Years	20	7	5	7	0
SUP-01	0.57	0.61	0.47	0.62	0.65
SUP-02	0.49	0.49	0.37	0.50	0.52
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Pass	Pass	Pass	Pass	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	$0.02	$0.06	-$0.10	$0.07	$0.00
8. Increase navigation benefits	$0.74	$1.94	$1.44	-$0.36	$0.00
9. Increase hydropower benefits	$0.41	-$0.76	-$0.24	-$0.39	$0.00
Increase average energy (kWh)	557	-325	323	-372	0

Observations:

- *The transitional climate change sequences imply a gradually increasing impact on NBS from climate change.*
- *PFN3 may be the best plan in this sequence. Levels are balanced, its Lake Superior minimum level is higher than any of these other plans, and it creates overall net economic benefits.*
- *Nat64D and Bal26 conserve a little more water on Lake Superior, with higher minimum levels than **1977A**. In addition, both have positive net economic benefits for the sectors.*
- *With the transitional NBS series such as this, the count of Zone Cs overestimates the real differences between plans. For example, Nat64D, Bal26 and PFN3 eliminate 47 and 46 SMQ-01 Zone Cs, caused when June Lake Superior releases are below 1,700 m^3/s (60,035.5 ft^3/s) for five years in a row. It is important that these plans avoid the first Zone C. However, the high count of Cs in **1977A** does not properly reflect the environmental damage – lake sturgeon habitat would be damaged continuously through nearly 50 consecutive years and eventually each successive low water occurrence would have a diminished impact.*

Table 6-11: NBS Sequence 11 (370)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	182.00	181.72	182.05	181.81	181.81
2. Balance water levels	Fail	Fail	Fail	Fail	Fail
3. Balance Lake Michigan-Huron water levels	Mixed	Pass	Mixed	Mixed	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Pass	Pass	Pass	Pass	Pass
5. Minimize environmental impacts	Pass	Pass	Pass	Pass	Pass
Number of fewer Zone C PI-Years	50	60	45	10	0
Number of greater Zone C PI-Years	8	10	0	0	0
SUP-01	0.58	0.61	0.47	0.63	0.67
SUP-02	0.53	0.52	0.39	0.55	0.58
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Pass	Pass	Pass	Pass	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	$0.03	$0.07	-$0.14	$0.07	$0.00
8. Increase navigation benefits	$0.80	$2.01	$1.70	-$0.47	$0.00
9. Increase hydropower benefits	$0.36	-$0.79	-$0.22	-$0.47	$0.00
Increase average energy (kWh)	508	-379	306	-472	0

Observations:

- *Sequence 370 is slightly more severe than the dry sequence 174 shown in Table 6-10, driving the minimum **1977A** Lake Superior level from 181.86m (596.6 ft) to 181.81m (596.5 ft).*
- *Nat64D performs best for this sequence.*
- *As in Table 6-10, the ecological advantages of Nat64D and Bal26 are evident.*
- *But the large reduction in **1977A** Zone Cs is based on repeated years in which the resource may already have been destroyed.*
- *All the new plans avoid the SMQ-01 Zone C occurrences that affect lake sturgeon spawning habitat.*
- *Nat64D has net benefits in all three sectors.*
- *Bal26 is notably better than the other plans in maintaining Lake Michigan-Huron levels, while the minimum levels for Lake Michigan-Huron under the other plans are all within one or two cm (less than 1 in) of each other.*

Table 6-12: NBS Sequence 12 (TR)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	181.66	181.52	181.84	0.00	Violation
2. Balance water levels	Fail	Fail	Fail	Fail	-
3. Balance Lake Michigan-Huron water levels	Pass	Pass	Mixed	Pass	-
4. Fewer Lake Superior levels below chart datum than preproject	Pass	Pass	Pass	Violation	-
5. Minimize environmental impacts	Pass	Pass	Pass	Pass	-
Number of fewer Zone C PI-Years	0	0	0	0	-
Number of greater Zone C PI-Years	0	0	0	0	-
SUP-01	0.66	0.78	0.55	#N/A	-
SUP-02	0.45	0.50	0.30	#N/A	-
6. Minimize disproportionate loss	No results here because there was no baseline result from **1977A** against which to compare				
Coastal (Δ SP Costs)					
Boating slips					
7. Reduce net shoreline protection costs (avg. annual reduction)					
8. Increase navigation benefits					
9. Increase hydropower benefits					
Increase Average Energy (kWh)					

Observations:

- *Violation: simulations for **1977A** and 129 could not be completed, as those plans drove Lake Superior levels below the mathematical threshold of the lake, reducing releases to zero.*
- *This NBS sequence represents the hypothesis that future NBS will continue to change as in the last two decades. It is the most severely dry NBS sequence used in the Study.*
- *The sill of Lake Superior has not been mapped carefully enough to determine at what level water would no longer flow out of the lake, but the failure of these plans in simulation can be taken as an indication that they offer a greater risk of this happening in reality.*
- *Because the **1977A** simulation was not completed, there is no baseline on which to calculate net economic or environmental scores for the other plans.*

Table 6-13: NBS Sequence 13 (HS)

Decision Criteria	Nat64D	Bal26	PFN3	129	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	184.31	184.35	184.23	184.25	184.28
2. Balance water levels	Pass	Pass	Pass	Pass	Pass
3. Balance Lake Michigan-Huron water levels	Pass	Mixed	Mixed	Pass	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Fail	Fail	Pass	Fail	Pass
5. Minimize environmental impacts	Fail	Pass	Pass	Pass	Pass
Number of fewer Zone C PI-Years	2	3	2	1	0
Number of greater Zone C PI-Years	3	2	1	0	0
SUP-01	0.57	0.42	0.50	0.58	0.52
SUP-02	0.67	0.53	0.54	0.65	0.61
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Pass	Pass	Pass	Pass	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	$0.22	-$0.17	$0.06	$0.76	$0.00
8. Increase navigation benefits	-$0.01	$0.09	-$0.40	-$0.24	0
9. Increase hydropower benefits	$0.30	$0.14	-$0.66	-$0.26	0
Increase average energy (kWh)	453	492	-819	-231	0

Observations:

- *The HS NBS sequence is an extreme test that includes the highest single month's elevation in the 55,400 years of stochastic NBS, an extraordinarily rapid and uncharacteristic increase in NBS.*
- *Nat64D performs well in this sequence. It creates more net Zone C occurrences than **1977A**, but the actual effects can be discounted because the Zone Cs are for SMQ-02 (see Table 6-5) and an occurrence of LMH-08 that is triggered by water levels less than 2.5 cm (1 in) lower than **1977A**.*
- *This NBS sequence has the highest Lake Superior levels of all; it rises to at least 184.23 m (604.4 ft) (Plan PFN3).*
- *Bal26 has the highest Lake Superior level (184.35 m or 604.8 ft).*
- *Nat64D has the highest net benefits for the sectors.*
- *None of the plans has disproportionate losses.*

6.4.3 Selection of the Preferred Plan

The Study Board concluded that the four plans reviewed in the previous section had different strengths and limitations (Table 6-14). In general, their performance was comparable to **1977A**, with some added benefits. The Study Board selection of a preferred plan was based on the following rationale:

- Plan 129 was eliminated particularly because of its poor performance in the severely dry NBS sequence (Table 6-12), in which simulations for **1977A** and 129 could not be completed, as those plans drove Lake Superior levels below the natural sill level.
- Plan PFN3 performed well under the severely dry NBS sequence, but was eliminated because of its limited ability to balance levels on lakes Superior and Michigan-Huron, compared with Nat64D and Bal26.
- Plans Nat64D and Bal26 performed about as well as the other regulation plans, regardless of the NBS sequence or the decision criterion applied. Thus, both satisfied the key objective of robustness.
- There were minor differences between the plans Nat64D and Bal26:
  - Bal26 causes significantly higher and lower Lake Superior levels and somewhat compressed Lake Michigan-Huron levels in the most extreme wet and dry NBS; and,
  - Bal26 generally performed worse on economic criteria than Nat64D for all the NBS sequences, though it performed marginally better for ecological criteria.

Based on this rationale, the Study Board tentatively selected Nat64D as the best regulation plan to replace **1977A**. The Study Board then requested that Nat64D be possibly further refined through optimization techniques to improve the coefficients used in the plan that were related to the balanced rule, and lake level releases under high and low water conditions. Plan formulators developed three variations of Nat64D, using different optimization strategies.

6.4.4 Refinement of the Preferred Plan

Plan formulators developed three variations of plan Nat64D as part of a final optimization analysis: NatOpt1; NatOpt2; and NatOpt3.

Figures 6-9 and 6-10 compare the monthly levels of lakes Superior and Michigan-Huron, respectively, of plan Nat64D and two of the three optimized variations under the historical NBS sequence. Table 6-15 summarizes the results of the evaluation of the performance of these optimized plans under the historical NBS sequence.

Table 6-14: Summary Evaluations of Robustness of Plans

Plan	Strengths	Limitations	Study Board Decision
129	Provides small net economic benefits under historical NBS	Like **1977A**, allows Lake Superior levels to drop too low in severe dry NBS sequences.	**Eliminated** because of poor performance in severely dry NBS sequences
PFN3	Compressed the range of Lake Superior levels Maintained Lake Superior levels in TR "severely dry" NBS sequence	Compression often caused slightly worse economic and ecological scores	**Eliminated** because of mixed performance and because it compressed Lake Superior levels at the expense of levels on Michigan-Huron
Bal26	Scores on all nine criteria were very close to Nat64D	Not clearly better than Nat64D and not balanced in extremely dry sequences	**Eliminated** because of limitations under dry NBS sequences
Nat64D	Better than **1977A** for most of the criteria and historical NBS Among the best plans for all NBS	Does not outperform **1977A** for all criteria and every NBS	**Preferred** because of the gained benefits and robustness

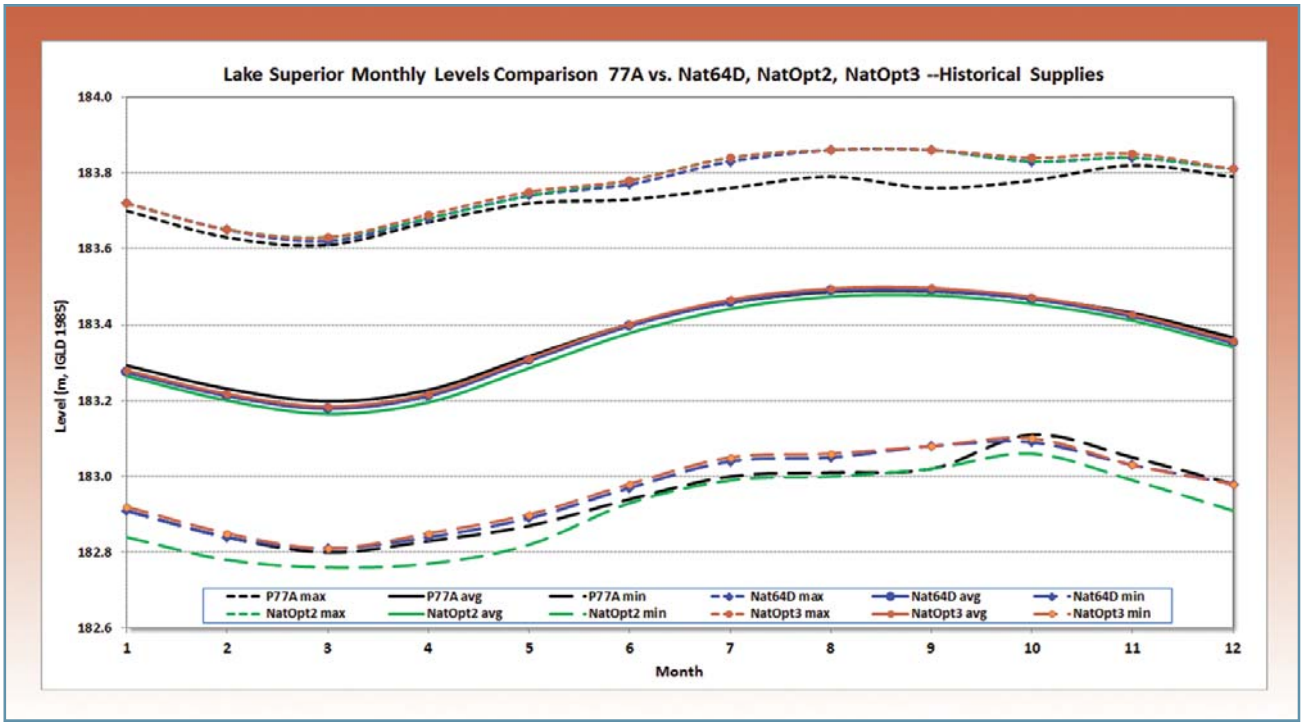


Figure 6-9 ***Comparison of Lake Superior Monthly Levels under Two Variations of Plan Nat64D***
(NBS Sequence 1, Historical NBS)

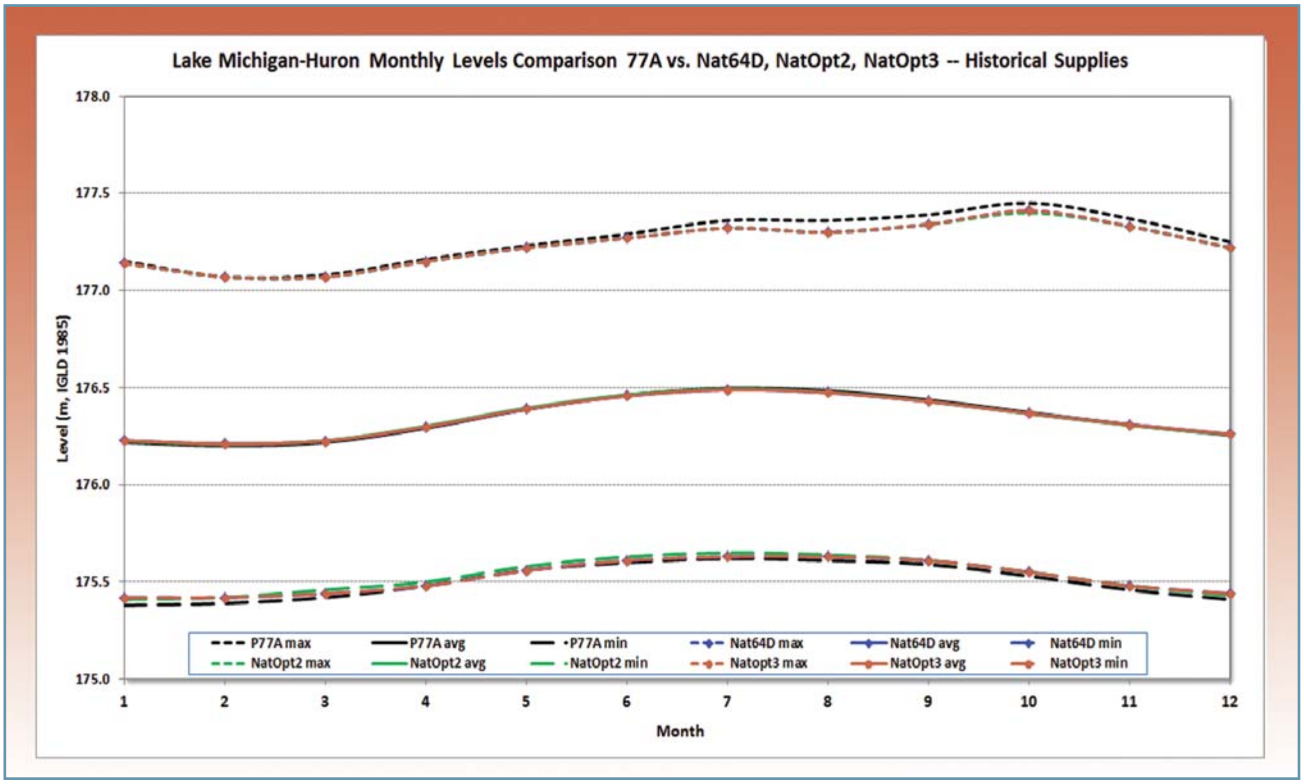


Figure 6-10 ***Comparison of Lake Michigan-Huron Monthly Levels under Two Variations of Plan Nat64D***
(NBS Sequence 1, Historical NBS)

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Table 6-15: Comparison of Performance of Variations of Plan Nat64D
(NBS Sequence 1, Historical NBS)

Decision Criteria	Nat64D	NatOpt1	NatOpt2	NatOpt3	1977A
1. Maintain Lake Superior between 182.76 and 183.86 m	Pass	Pass	Pass	Pass	Pass
2. Balance water levels	Pass	Pass	Pass	Pass	Pass
3. Balance Lake Michigan-Huron water levels	Pass	Pass	Pass	Pass	Pass
4. Fewer Lake Superior levels below chart datum than preproject	Pass	Pass	Pass	Pass	Pass
5. Minimize environmental impacts	Pass	Pass	Pass	Pass	Pass
Number of fewer Zone C PI-Years	1	1	1	1	0
Number of greater Zone C PI-Years	0	0	0	0	0
SUP-01	0.39	0.40	0.40	0.39	0.36
SUP-02	0.40	0.40	0.41	0.39	0.34
6. Minimize disproportionate loss					0
Coastal (Δ SP Costs)	Pass	Pass	Pass	Pass	Pass
Boating slips	Pass	Pass	Pass	Pass	Pass
7. Reduce net shoreline protection costs (avg. annual reduction)	$0.15	$0.13	$0.25	$0.06	$0.00
8. Increase navigation benefits	$0.05	$0.22	$0.10	$0.16	$0.00
9. Increase hydropower benefits	$0.48	$0.76	$0.89	$0.54	$0.00
Increase average energy (kWh)	506	734	825	572	0

Observations:

- *NatOpt3 performs slightly better than the other plans when the Natural plan variations are tested with the historical NBS.*
- *Although NatOpt1 and NatOpt2 have slightly higher economic benefits, those plans allow Lake Superior to drop below chart datum more often than preproject conditions.*
- *Those two plans have a minimum Lake Superior level 5 cm (1.97 in) lower than NatOpt3 as well, and a minimum Lake Michigan-Huron level about 1 cm (0.39 in) lower than NatOpt3.*

Key findings of this analysis were:

- Each of these plans produced slightly different lake levels and flows as well as performance for the nine criteria given the historical NBS case.
- When historical NBS are used, all three optimized plans performed better than Nat64D for economic benefits and had similar ecosystem metrics.
- The plans all compressed Lake Michigan-Huron levels compared to **1977A**, were considered to have balanced lake levels and did not produce any disproportionate loss.
- NatOpt3 had slightly lower economic benefits than NatOpt1 and NatOpt2 but unlike those two plans, it kept Lake Superior levels above chart datum more often than preproject (Lake Superior was below chart datum for 21.8 percent of all months in the historical preproject simulation).
- Under NatOpt1 and NatOpt2, minimum levels on Lake Superior and Lake Michigan-Huron were 5 and 1 cm (2 and 0.4 in) lower than NatOpt3, respectively.
- NatOpt3 had the highest minimum levels of Lake Superior in every other NBS sequences, as well, while its Lake Michigan-Huron minimum levels were often the same as the other natural plan variations, and at worst, only 3 cm (1.2 in) lower.

Based on economic benefits, NatOpt2 had a slight edge over NatOpt3. However, the Study Board was considering a replacement for **criterion c** in the existing orders (see section 6.6.1). The intent of the current and replacement language in the IJC's Orders of Approval was to ensure that low Lake Superior levels would not occur more frequently than under preproject conditions. NatOpt3 clearly did better for that objective than NatOpt2. The Study Board decided that the ability of NatOpt3 to maintain Lake Superior levels slightly higher when NBS were very low, outweighed the small advantage that NatOpt2 had in economic benefits. Ultimately, the Study Board selected NatOpt3 as the recommended new regulation plan.

6.5 *Lake Superior Regulation Plan 2012*

6.5.1 Assessment of the Plan

The selected plan, NatOpt3, was renamed **Lake Superior Regulation Plan 2012** to reflect the IJC's naming convention for regulation plans. The selected plan had gone through numerous iterations and refinements, as well as detailed comparisons and sequential deliberations by the Study Board. Each iteration responded to a new set of questions by Study Board members. No single plan was uniquely superior to all the other plans – there were tradeoffs that were made by the Study Board between economic performance, reliability under extreme lake levels and ecological performance. In all instances, the differences in economic performance among the final set of plans was very small – well within the range of measurement error. As a result, the Study Board focused on the relatively small difference among plans regarding ecological metrics and performance under extreme conditions – conditions that might materialize under a variety of future climate-driven sequences. The ultimate driver for decisions became "which plan is the most robust", and will perform the best under a range of extreme conditions.

Under most NBS conditions, there will be little difference between **Lake Superior Regulation Plan 2012** and **1977A**. About two-thirds of the time, Lake Superior levels under the new plan will be within 2.5 cm (1 in) of the levels they would be under **1977A** and 94 percent of the time, the levels of the two plans will be within about 5 cm (2 in) of each other. Where the new plan produces slightly better average economic benefits than **1977A** (*e.g.*, Table 6-4) over the 1,308 months of the simulation, the monthly benefits from **1977A** are still slightly better than the new plan nearly one-half of those 1,308 months.

Occasionally, however, there can be a more noticeable difference in plan performance under extreme NBS circumstances. When NBS is very high, the differences are not consistent. For example, in the simulation of the high water levels of 1986, **Lake Superior Regulation Plan 2012** creates a Lake Superior level of 183.86 m (603.2 ft) in September, while **1977A** results in a level 10 cm **lower** (almost 4 in). On the other hand, the corresponding levels on Lake Michigan-Huron, where the high water levels in the mid-1980s and 1990s created concerns among coastal zone interests and others, under the new plan would have been about 6 cm (2.4 in) lower than those experienced under **1977A**. Thus, **Lake Superior Regulation Plan 2012** adheres to the existing Orders of Approval by not exceeding the upper limit of 183.86 m (603.2 ft), but is able to reduce the high levels in Lake Michigan-Huron by a significant amount.

For a future NBS sequence that has even wetter conditions, however, the outcomes are reversed. In the High Michigan NBS sequence, the maximum level of Lake Superior under the new plan is 184.09 m (604 ft), while **1977A** allows Lake Superior to rise to 184.15 m (604.2 ft) – both exceeding the limit in the Orders of Approval, but less so for **Lake Superior Regulation Plan 2012**. The Lake Michigan-Huron highs for **1977A** and the new plan under the High Michigan NBS are 177.94 m and 178.02 m (583.8 and 584 ft) respectively, again reversing the comparison with historical NBS.

If NBS to Lake Superior are much less than any in the historical record, then the new plan clearly favours retaining slightly more water on Lake Superior. In the driest sequences used to test plans, the new plan produces noticeably higher levels on Lake Superior with just slightly lower Lake Michigan-Huron levels. These results indicate that there are possible future climate sequences that will exceed the capacity of the current regulation system to meet the criteria of the current Orders of Approval, as the Orders were established under less severe climate conditions than those tested by this Study. Nevertheless, it has been demonstrated that **Lake Superior Regulation Plan 2012** performs better than **1977A** for most of the NBS sequences and never performs significantly worse.

6.5.2 Benefits of the Plan

The Study Board evaluated all the comparisons of different plans under a variety of circumstances. No plan outperformed every other plan for all nine decision criteria and NBS sequences. Most importantly, though, the selected plan meets all the Study Board's decision criteria and is considered to be more robust. In addition, the proposed plan provides six distinct and noteworthy improvements over **1977A**:

1. Avoids extremely low levels of Lake Superior that would occur if NBS were much lower than any in recorded history, a plausible future scenario;
2. Benefits lake sturgeon, by protecting important spawning habitat;
3. Provides additional economic benefits for commercial navigation and hydroelectric generation;

4. Provides smaller, more predictable month-to-month release changes;
5. Provides more natural flows in the St. Marys River; and,
6. Uses simpler rules and coding.

These six benefits are described in more detail below. Overall, though, **Lake Superior Regulation Plan 2012** has the distinction of being a more 'natural' regulation plan, with lake level changes and release characteristics that are very close to the preproject natural hydrological conditions. It is this attribute that makes it important from ecosystem sustainability perspective.

Lake Superior Levels

Although the new plan will not change water levels much when NBS are similar to the historical NBS, it will preserve levels on Lake Superior if an NBS sequence becomes significantly drier, as is possible under climate change. Figure 6-11 shows the simulated levels of **1977A** under the historical NBS (grey), superimposed with the levels produced by **1977A** and **Lake Superior Regulation Plan 2012** for the extended dry trend NBS sequence (blue and red, respectively). Under these severe conditions (a 25-year drought), the simulated outflows of **1977A** fails in the 91st year of the simulation with Lake Superior at 181.74 m (596.25 ft), a metre (3.28 ft) below the historical minimum, and below the natural sill level. That is, discharges from Lake Superior cease. At the same time, **Lake Superior Regulation Plan 2012** produces a level of 182.00 m (597.1 ft), and continues outflows from Lake Superior – a significant improvement.

Lake Sturgeon Habitat

The new plan will avoid infrequent but serious impacts to the St. Marys River spawning habitat of lake sturgeon, an endangered species. This would have occurred only once in the historical **1977A** simulation, but would be a more frequent problem if NBS were drier. In the simulations, **Lake Superior Regulation Plan 2012** never created these very low water conditions in the river, even in the driest supply series. Avoiding these conditions is considered to be essential for protecting this important species.

Economic Benefits

The new plan will provide additional economic benefits to commercial navigation, hydroelectric generation and coastal zone interests, on the order of a million dollars per year depending on NBS. In the driest NBS sequence, shown in Figure 6-11, navigation through the Sault Ste. Marie locks and hydroelectric production at the Sault Ste. Marie plants would be threatened with closure under **1977A**, but not under **Lake Superior Regulation Plan 2012**.

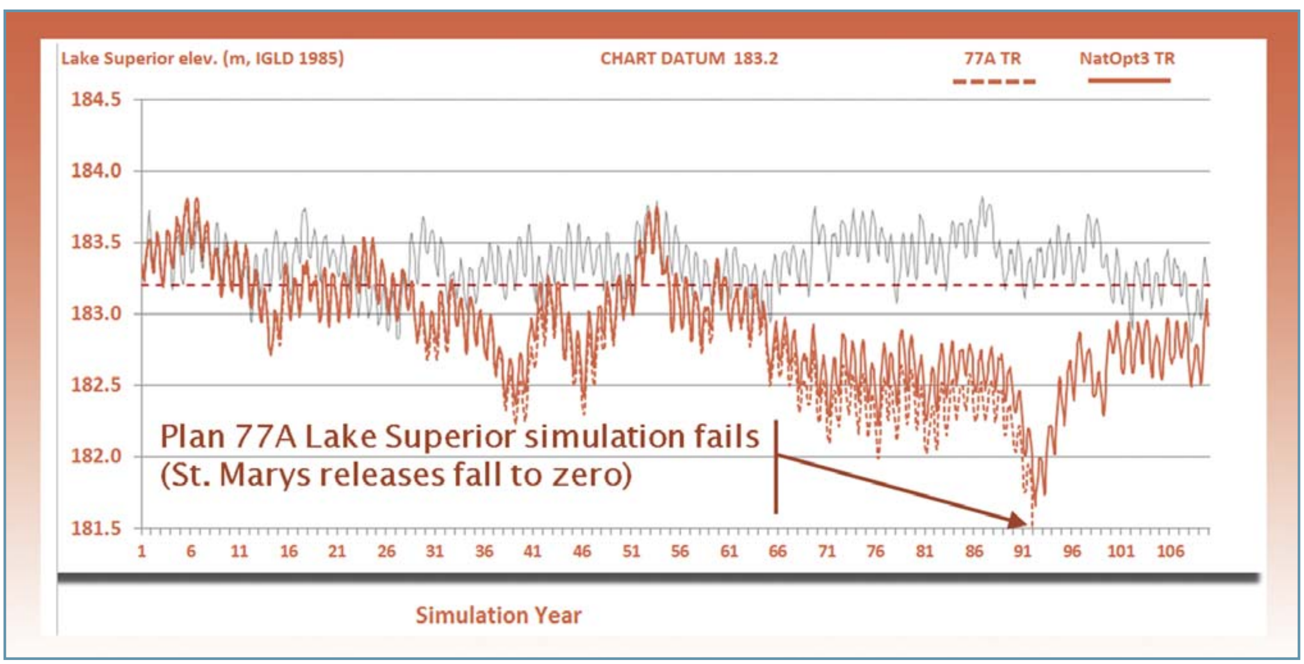

***Figure 6-11* *Comparison of Lake Superior Levels under* Plan 1977A *and* Lake Superior Regulation Plan 2012**

Note:

*Grey line: simulated levels with **1977A** under the historical NBS*

*Dashed line: simulated levels with **1977A** under the extended dry trend NBS sequence*

*Brown line: simulated levels with **Lake Superior Regulation Plan 2012** under the extended dry trend NBS sequence*

More Predictable Changes in Releases

Under the new plan, month-to-month flow changes will generally be smaller than they were with **1977A**. Although not featured in the Study Board's main decision criteria, this is a secondary performance indicator for hydropower producers. More than 90 percent of the monthly flow changes under **Lake Superior Regulation Plan 2012** will be less than 320 m^3/s (11,300 ft^3/s) as opposed to 500 m^3/s (17,656 ft^3/s) for **1977A**. Annual flow range is reduced with the recommended plan as well: only 21 percent of historical simulation years would experience a range more than 1,000 m^3/s (35,315 ft^3/s), compared to 41 percent for **1977A**. Lower flow changes result in fewer gate openings and closings, thus saving labour costs.

More Natural Flows

Under **Lake Superior Regulation Plan 2012**, St. Marys River flows will have a more natural relationship to Lake Superior levels under the new plan (Figure 6-12). Based on the Integrated Ecological Response Model (IERM), no metrics that were used could make the case that a natural regime would provide greater systemic ecological benefits to the lakeshore ecosystems. However, ecologists believe that restoring natural river flow frequencies is fundamental to sustaining aquatic ecosystems. The more natural flow relationship is also related to the smaller month-to-month changes described above, which is also considered important from an ecosystem perspective.

Simpler Rules and Coding

The plan rules for **Lake Superior Regulation Plan 2012** are considerably less complex than the rules for the **1977A** plan. The recommended plan applies rules in three layers, starting with the natural, linear release, then adjusting that if Lake Superior is farther or closer to its average levels than Lake Michigan-Huron, and finally, imposing limits on the flows in some months, primarily to avoid problems with ice. This makes the plan easier to manage with this simpler approach and therefore simplified coding.

6.6 Changes to the Orders of Approval

The IJC's Orders of Approval govern how outflows are regulated and must be consistent with the principles set out in the *Boundary Waters Treaty of 1909*. The applicable principle of the treaty in this case is that *"…regulation will provide suitable and adequate provision for the protection and indemnity of interests that may be affected by regulation of the outflow of Lake Superior…"* (IJC 1979 Supplementary Order). This principle guided the Study Board in setting the goals, objectives and decision criteria used to select a proposed plan. This was also a prime consideration in the Study Board's review of the IJC's original and supplementary Orders of Approval now in force.

6

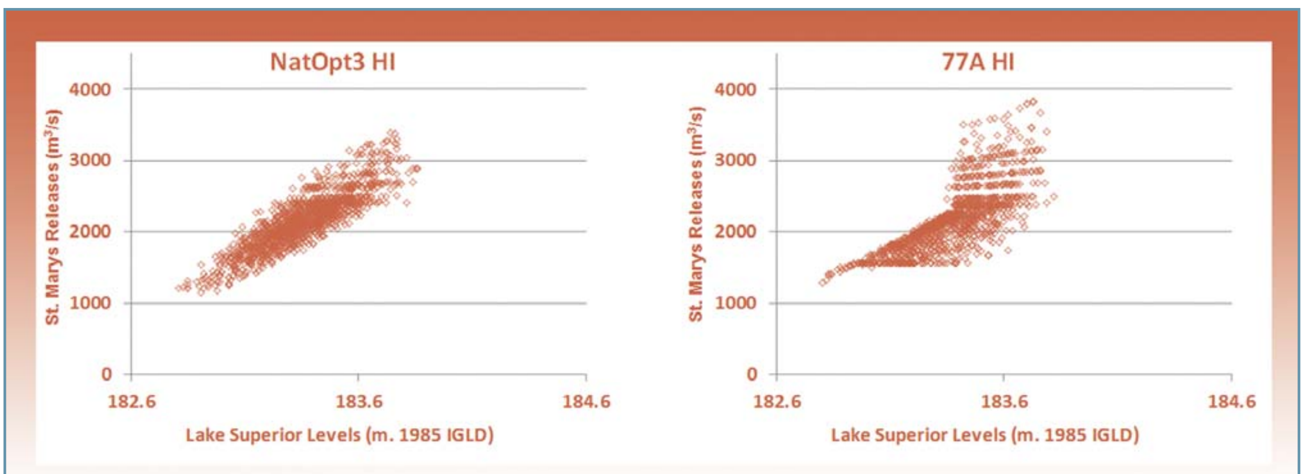

Figure 6-12 ***Comparison of Natural Flow Levels***

*The natural release pattern is essentially linear; the higher Lake Superior, the greater its release into the St. Marys River. The graphs show that neither plan is completely natural and linear, but under **Lake Superior Regulation Plan 2012**, the range of flows that will occur when Lake Superior is at a given elevation are much smaller. For example, when Lake Superior is at 183.6 m (602.4 ft), **1977A** flows range from about 1,500 to 3,700 m^3/s (about 52,970 to130,665 ft^3/s) , while the flows under **Lake Superior Regulation Plan 2012** vary from about 2,100 to 3,200 m^3/s (about 74,160 to 113,000 ft^3/s). That is, the flows are more stable.*

In conducting its review of the Orders of Approval, the Study Board found it confusing to have the conditions that are still in force spread between the original 1914 Orders and several much more recent Supplementary Orders, amid many superseded conditions. It concluded that the implementation of a new regulation plan provides the IJC with an opportunity to establish new integrated Orders to bring greater clarity and efficiency to the conditions. New integrated Orders can consolidate all of the applicable conditions of the Orders still in force, as well as the additional considerations required to implement the recommended new plan, **Lake Superior Regulation Plan 2012**.

6.6.1 New and Amended Conditions

The Study Board has identified the following new and amended conditions for the new integrated Orders of Approval.

1. Adding a requirement to limit the rate of gate opening changes

In its review and assessment of the sensitivities of the aquatic ecosystem of the St. Marys River to flow regulation, the Study found that if the flow through the Compensating Works gates changes too quickly, then the resulting abrupt rise or fall of water levels and flows in the St. Marys River rapids can impact fish habitat in the rapids (Bain *et al.*, 2010). It was recommended that the rate of change in the gate openings be such as to limit the change in water level to no more than 10 cm (3.9 in) per hour in order "to reduce loss of young fishes considerably and improve resident fish populations in the rapids." The Study Board concluded that the new Orders of Approval recognize this important concern and require that the maximum rate that gates in the compensating works are opened or closed shall be such as to protect fish in St. Marys River rapids.

2. Recognizing peaking and ponding in the Orders

In the past decade, the IJC, through its International Lake Superior Board of Control (ILSBC), investigated the effects of flow variations during the day and week through the hydropower plants on the St. Marys River (ILSBC, 2002; Bain, 2007). This led to the IJC's guidelines that set limits on these flow variations, known as "peaking" and "ponding", carried out by hydroelectric generation companies. The Study Board concluded that the new Orders of Approval should formally recognize that peaking and ponding operations may be conducted by the hydropower entities subject to guidelines approved by Commission.

3. Updating "supplies of the past as adjusted" provision

Condition 6 of the 1979 Supplementary Order sets out most of the criteria that **1977A** had to satisfy to be approved for use. The criteria in the 1979 Orders apply only when tested with "supplies of the past as adjusted", which is defined in the Order as the 1900-1976 historical NBS to the lakes as adjusted for typical flows of the diversions into and out of the lakes. However, it was recognized in the 1979 Order that future NBS could be more extreme than NBS of the past. The Order states that in that event, the IJC "will indicate the appropriate outflows from Lake Superior to suitably and adequately protect all interests upstream and downstream of the works."

The Study's plan formulation and evaluation were not limited to an updated 1900-2008 historical case, but also thoroughly considered a wide range of plausible future climate scenarios. NBS sequences in many of these climate scenarios were more extreme than those experienced from 1900 to 2008. Although the IJC retains its authority to direct outflows when necessary, the Study Board believes that the proposed plan will provide suitable and adequate protection for all interests under the climate scenarios considered relative to the preproject flows.

The Study Board found that the range of Lake Superior levels specified in **condition 6** of the 1979 Order is still appropriate but that the period defining NBS of the past as adjusted should be updated to 1900-2008. This extended period expands the range of NBS within which a regulation plan must satisfy the condition. The flows defining the adjustments to NBS to account for diversions should be updated in the new Orders to 91 m^3/s (3,213.7 ft^3/s) from Lake Michigan at Chicago and the combined diversions into Lake Superior from the Albany River basin should reflect their average monthly amounts.

4. Amending the Sault Ste. Marie flooding specification

Criterion b of the 1979 Order protects interests affected by flood levels of Sault Ste. Marie Harbour from increased damages and should be maintained in an updated order. However, the equation listed in the **criterion b** of the 1979 Order that describes the 1887 preproject outflow relationship is outdated and does not take into account the effects of glacial isostatic adjustment (Southam and Larsen, 1990). This equation should be replaced by that listed in section 5.1.2. of this report. **Criterion b** should continue to apply while NBS are within the historical record as adjusted. When regulation plans were tested with extremely high NBS scenarios, beyond those contained in the historical NBS sequence, it was found that levels could overtop the gates of the compensating works if this criterion was strictly followed. Such high levels could threaten the integrity of the compensating works and adjacent dikes. Therefore, the Study Board concluded that if future NBS are greater than past NBS, as adjusted, then the IJC should take this risk of structural failure from overtopping into consideration.

5. Broadening the directive on flows that may cause ice jam flooding

High outflows in winter may break up the ice cover in Sault Ste. Marie Harbour and downstream and lead to ice jams in the lower St. Marys River that could in turn cause flooding of shoreline property and the hydroelectric generation plant (Knack *et al.*, 2011) as well as hindering navigation. All of the regulation plans developed in this Study, as well as **1977A**, include maximum outflow constraints that apply in the winter to limit the risk of causing such ice jams. The Study Board concluded that the Orders of Approval should be revised to include a requirement that regulated maximum winter flows explicitly take ice management into consideration.

6. Modifying criterion c

The Study found that **criterion c**, as formulated in the 1979 Order, limited the system-wide benefits that could be achieved through Lake Superior regulation. **Criterion c** requires that when Lake Superior levels are at 183.40 m (601.7 ft) IGLD 1985 or lower, the plan release cannot be greater than what would have occurred with 1887 outlet conditions (*i.e.*, the preproject release). The intent of criterion c is to protect interests affected by very low levels on Lake Superior from increased damages relative to the preproject state. However, as shown in the evaluation of regulation plans in this chapter, a similar degree of protection from extremely low levels can be provided to Lake Superior interests through other mechanisms in a regulation plan, while providing greater overall system benefits. Therefore, the Study Board concluded that **criterion c** of 1979 Order should be revised to require that any regulation plan must not result in a greater frequency of Lake Superior levels being below 183.20 m (601 ft) (the Chart Datum[4]) than would occur with the preproject St. Marys River condition.

6.6.2 Existing Conditions

The Study Board identified the opportunity to include the following existing conditions in a new integrated Orders of Approval.

1. Reaffirming the balancing requirement

The Study Board recommends that the Orders continue to require that the flows be regulated to balance levels of Lake Superior and Lake Michigan-Huron to the extent consistent with meeting the other criteria of the Orders. This requirement was found to improve overall system benefits, though the levels of Lake Michigan-Huron are driven primarily by local NBS and constraints needed to protect Lake Superior interests limit the effect of Lake Superior regulation.

2. Continuing the requirement for IJC approval for deviations from the plan, recognizing the need for discretion in emergencies

In its review of the regulation plan and flow control operations, the Study Board considered whether it would be advantageous for the ILSBC to have discretionary authority to specify outflows that deviate from those specified by the approved regulation plan. The Study Board concluded that there was no need to grant the control board such discretionary authority. It found that the existing ILSBC authority to deviate from the plan only in emergencies (as recognized in an IJC letter to the ILSBC in 2002) should be included in the Orders of Approval.

3. Retaining the existing required flow allocations

The Study Board reviewed the required flow allocations for the various uses at Sault Ste. Marie as stipulated in the 1978 and 1985 Orders. The Study Board concluded that no change in these allocation requirements was necessary at this time.

6.7 Key Points

With respect to the Study's formulation and evaluation of plans for Lake Superior regulation and selection of a recommended plan, the following points can be made:

- The central challenge to the Study was to identify a regulation plan that performed better than the existing plan, **1977A**, under both the historical NBS conditions and a wide range of uncertain NBS conditions resulting from climate variability and change.
- In the earlier stages of plan formulation and evaluation, the Study developed three "fencepost" plans to identify the boundaries of what could be done for specific lakes or interests. The "fencepost" plans showed that Lake Superior regulation could have only a small effect on Lake Michigan-Huron levels even if the regulation were artificially allowed to maximize benefits to interests downstream from Lake Superior.
- Study plan formulators generated more than 100 alternative regulation plans, using a variety of scientific approaches, such as rule curves and optimization approaches, so as to ensure a comprehensive search for new regulation plans.
- The Study Board used a series of practice decisions to narrow down the list of plans for detailed evaluation using the SVM. The iterative approach allowed the Study Board to review the tradeoffs among criteria and refine the decision criteria to produce plans with a better mix of outcomes.
- The final four plans, reviewed in this chapter's evaluation tables, all performed well, with the only significant differences evident in lake levels and associated impacts experienced in a few very extreme NBS conditions.
- One of the final four plans, Nat64D, performed better than or as well as any other regulation plan considered, regardless of the NBS sequence or the decision criterion applied. This performance satisfied the objective of *robustness* in a new plan, and Nat64D was identified as a preferred plan.

4 Also known as Low Water Datum in the United States.

- As a final step in the selection process, plan formulators developed three variations of plan Nat64D as part of an optimization analysis. One of the variations, NatOpt 3 was identified as the most robust among the variations, and was selected as the recommended plan.
- The recommended regulation plan, named **Lake Superior Regulation Plan 2012**, will perform similarly to **1977A**, but has several important advantages:
  - it will preserve levels on Lake Superior if NBS become significantly drier, as is possible under climate change;
  - it will avoid rare but serious impacts to lake sturgeon spawning habitat in the St. Marys River;
  - it will provide additional economic benefits to commercial navigation, hydroelectric generation and coastal zone interests under a wide variety of wet and dry NBS conditions;
  - it will require smaller month-to-month changes in St. Marys flows, providing benefits for hydropower generation stations at Sault Ste. Marie;
  - it will result in a more natural pattern to St. Marys River flows, which could help sustain riverine ecosystem health; and,
  - its plan rules are much less complex, making it easier to manage.
- In reviewing the IJC's Orders of Approval governing how Lake Superior outflows are regulated, the Study Board concluded that there was no need for major revisions to the Orders. However, the Study Board concluded that there is a risk of confusion in having the numerous conditions that are still in force spread between the original 1914 Orders and several much more recent Supplementary Orders, amid many superseded conditions. Implementing a new regulation plan would provide an opportunity for the IJC to integrate various existing Orders and Supplementary Orders and recognize some existing policies or practices within new Orders of Approval.

6.8 Recommendations

In developing, evaluating and ranking a set of new Lake Superior regulation plans, the Study Board identified one regulation plan that would be more robust than the existing plan, **1977A**. The new plan would perform similarly under historical NBS conditions, but much better if future climatic conditions are either drier or wetter than in the period of historical record (1900-2008). The new plan would also provide additional benefits.

The Study Board also concluded that the implementation of a new regulation plan provides the IJC with an opportunity to establish new integrated Orders of Approval to bring greater clarity and efficiency to the regulation process.

On the basis of the Study's analysis and findings, and in accordance with its mandate under the IJC Directive, the Study Board makes the following recommendations to the IJC:

1. *The IJC should approve **Lake Superior Regulation Plan 2012** as the new plan for regulating Lake Superior outflow and advise governments that the **1977A** plan will be replaced with the new plan.*

2. *The IJC prepare and issue new integrated Orders of Approval that consolidate all of the applicable conditions and requirements of the original and Supplementary Orders, as well as the additional considerations required to implement the recommended new plan, **Lake Superior Regulation Plan 2012**.*

   The integrated Orders of Approval should include provisions to:

   - *add a requirement to limit the rate of gate opening changes so as to protect fish and fish habitat in the St. Marys River rapids;*
   - *formalize within new Orders the current guidelines governing peaking and ponding operations conducted by the hydropower entities;*
   - *update the period defining "supplies of the past as adjusted" to 1900-2008 (from 1990-1976), so as to expand the range of NBS within which the regulation plan must satisfy the condition;*
   - *amend the Sault Ste. Marie flooding specification so as to take into account the effects of glacial isostatic adjustment;*
   - *include a requirement that regulated maximum winter flows take into consideration ice management;*
   - *modify **criterion c** of the 1979 Supplementary Order to require that any regulation plan must not result in a greater frequency of Lake Superior levels being below 183.20 m (the Chart Datum/Low Water Datum level) than would occur with the preproject St. Marys River condition;*
   - *reaffirm the requirement that the flows be regulated to balance levels of Lake Superior and Lake Michigan-Huron to the extent consistent with meeting the other criteria of the Orders;*
   - *continue to require IJC approval for deviations from the plan but maintain the existing emergency discretion of the International Lake Superior Board of Control; and,*
   - *retain the existing required flow allocations for the various uses at Sault Ste. Marie as stipulated in the 1978 and 1985 Supplementary Orders.*

Chapter 7

Feasibility and Implications of Restoring Upper Great Lakes Water Levels

Chapter 7 analyzes the feasibility and implications of raising water levels of Lake Michigan-Huron to compensate for past natural and human-induced changes by means of restoration structures in the St. Clair River.

7.1 Introduction[1]

7.1.1 Scope of the Restoration Analysis

In the context of the International Upper Great Lakes Study (the Study), the term *restoration* refers to providing a permanent increase in Lake Michigan-Huron water levels, relative to what they would otherwise be, by constructing structures in the St. Clair River so as to reduce the river's conveyance capacity (*i.e.*, ability to discharge water). Restoration structures would compensate for past lowering resulting from natural and human-induced changes in the St. Clair River that increased the channel's conveyance capacity.

Restoration structures typically are non-adjustable, and have a permanent impact on water levels upstream. They also would have a temporary effect on water levels downstream, immediately after the structures are built. Regulation structures, by contrast, are adjustable, and can be raised or lowered to adjust water levels and flows both upstream and downstream (within certain limits), as desired.

The Study conducted an exploratory analysis of restoration focused primarily on the feasibility and impacts of non-adjustable restoration structures that would permanently raise Lake Michigan-Huron water levels. This included an analysis of structures proposed in previous studies, such as submerged weirs and dikes used to partially obstruct the channel. The analysis also considered two adjustable structures – inflatable flap gates and inflatable rubber weirs – that were reviewed for their potential to achieve some level of restoration, though they would also provide a limited ability to regulate the water levels of Lake Michigan-Huron. Finally, an emerging technology, hydrokinetic turbines, was considered for its potential to raise water levels, while also providing the benefit of renewable energy. The impacts of hydrokinetic turbines on water levels would be partially adjustable, given that turbine operation could be stopped and water level impacts thereby reduced.

The restoration analysis examined the effects of all these structures on water levels and flows throughout the upper Great Lakes and the associated impacts of the different scenarios on the key interests served by the waters of the lakes and connecting channels. These effects included both the shorter term construction-related impacts, as well as the longer term system-wide impacts. The environmental impacts and institutional issues related to building restoration structures in the St. Clair River were also reviewed.

7.1.2 IJC Direction on Restoration Analysis

The Study's focus on restoration grew out of the findings of its first report to the International Joint Commission (IJC) on the physical processes and possible ongoing changes in the St. Clair River and their impacts on water levels of Lake Michigan-Huron (IUGLS, 2009). In that report, the Study Board concluded that erosion of the St. Clair River had occurred subsequent to the last navigation dredging project, resulting in an increase in the conveyance capacity of the St. Clair River and a lowering of Lake Michigan-Huron water levels by approximately 7 to 14 cm (2.8 to 5.5 in). In addition, the Study Board found that conveyance changes in the river do not appear to be ongoing.

1 This chapter is based on peer-reviewed research on restoration structures that was commissioned by the Study (IUGLS, 2011).

In accordance with the Study's mandate, the Study Board recommended that:

- "… *remedial measures [in the St. Clair River] not be undertaken at this time*"; and,
- "…*the need for mitigative measures in the St. Clair River be examined as part of the comprehensive assessment of the future effects of climate change on water supplies in the Upper Great Lakes basin in Report 2 of the Study, on Lake Superior regulation*" (IUGLS, 2009).

In August 2010, the IJC provided further guidance to the Study Board by asking it to investigate methods and impacts of restoring Lake Michigan-Huron water levels as potential compensation for past lowering caused by natural and anthropogenic changes in the St. Clair River. The restoration analysis would include a description of possible structures that would be capable of restoring Lake Michigan-Huron water levels by various amounts, as well as the implications on interests throughout the Great Lakes-St. Lawrence River system.

The IJC did not request that the Study Board make any recommendation as to implementing a particular restoration option. Rather, it directed that the restoration analysis:

> "… *provide Governments and the public with extremely valuable information and insight to help form the basis for rational and scientifically-based decision making*".

The IJC directed the Study Board to investigate several restoration scenarios for Lake Michigan-Huron to approximate the desired levels of compensation. Table 7-1 summarizes these restoration scenarios.

7

7.2 The Study's Approach to Restoration Analysis

7.2.1 Restoration Analysis Strategy

The Study Board developed a strategy to guide its restoration analysis. The strategy focused on using currently available information and models to conduct the exploratory assessment. The main components of the strategy were to:

- undertake system modelling by adjusting St. Clair River hydraulics to simulate the physical effects of water level restoration options on Lake Michigan-Huron and the effects downstream through Lake Erie;
- identify candidate physical structures from past studies and evaluate these in the context of the restoration analysis, including estimating their costs;
- carry out upstream and downstream water level/flow impact analysis on the key interests served by the waters of the upper Great Lakes (see **Chapter 3**), to the extent possible using the shared vision model (SVM) (see **Chapters 5** and **6**);
- conduct an exploratory environmental review of proposed restoration options, focusing on the St. Clair River; and,
- prepare an analysis of the institutional considerations related to constructing and operating restoration structures in the Great Lakes.

The findings of the restoration analysis should be viewed within the context of the limitations and caveats that are associated with the various analyses upon which it is based. In addition, broader issues such as glacial isostatic adjustment (GIA) and climate change were addressed only in a limited way in this analysis.

Table 7-1: Lake Michigan-Huron Water Level Restoration Scenarios

Restoration Scenario	Description
Zero	Represents status quo (*i.e.*, taking no restorative action)
10 cm (3.9 in)	Compensation for increases in conveyance since 1963, with the magnitude as established in the Study's St. Clair River Report (IUGLS, 2009)
25 cm (9.8 in)	Combining the 10 cm (3.9 in) scenario with the estimated impact of the 1960-1962 8.2 m (27-ft) navigation channel dredging project on conveyance of the St. Clair River
40 cm (15.7 in)	Scenario would approximately equal the physical effects of regime change in the St. Clair River from 1906 through today, including the 1933 to 1937 excavation of the 7.6 m (25-ft) navigation channel, the 1960 to 1962 excavation of the 8.2 m (27-ft) navigation channel, and the changes since 1963
50 cm (19.7 in)	Extends the previous analysis to cover the period of 1855 to 1906, which reflects the impacts on the St. Clair and Detroit Rivers from the deepening associated with the 6.1 m (20-ft) navigation channel

7.2.2 Modelling of Impacts on Water Levels and Flows

The first step of the restoration analysis was to evaluate the impacts on water levels and flows throughout the Great Lakes system resulting from restoration of Lake Michigan-Huron water levels. One way to restore water levels on Lake Michigan-Huron is to reduce the conveyance capacity of the St. Clair River. Based on the directives provided by the IJC, this was the focus of the Study Board's analysis. Additional measures to raise levels of Lake Michigan-Huron – such as reducing or eliminating the Lake Michigan diversion at Chicago or adding or increasing the amount of water diverted into the lake from external watersheds – would be limited in their effectiveness and could have unintended consequences, and therefore were not considered in this analysis.

It was assumed for the system modelling analysis that structures of some undefined form in the St. Clair River could be used to raise levels of Lake Michigan-Huron by any of the 10, 25, 40 and 50 cm (3.9, 9.8, 15.7 and 19.7 in, respectively) scenarios outlined by the IJC. The system modelling was used to predict the physical impacts of these hypothetical structures on water levels of Lake Michigan-Huron over time, as well as the hydrological impacts on the system downstream of Lake Michigan-Huron, through lakes St. Clair, Erie and Ontario, all the way to Montreal Harbour on the St. Lawrence River, including both the transient impacts that occur immediately after construction, as well as longer term impacts. All results were compared to the base case, which represents the current conditions or the "zero" restoration scenario.

The Great Lakes-St. Lawrence River system was simulated, using recorded data for the historical period (1900-2008), through a combination of regulation plan logic (using current plans **1977A** and **1958DD** for lakes Superior and Ontario, respectively), hydrological routing, and various empirical equations that were updated as part of the Study. A key assumption in the analysis was that under any restoration scenario, the most probable scenario for future Lake Superior releases would involve controlling outflows from Lake Superior such that any Lake Michigan-Huron restoration option would have no discernible impact on Lake Superior levels or outflows. As such, when simulating the system hydrology, lake levels and interconnecting channel flows, the flows in the St. Marys River were in most cases fixed to the flows that would be simulated by the **1977A** plan without any restoration. The system was simulated using inputs of time series of net basin supplies[2] (NBS), diversions, ice and weed retardation factors, as well as initial outflows and lake levels.

2 Net basin supply (NBS) is the net amount of water entering each Great Lake resulting from precipitation falling directly on the lake surface, runoff to the lake from the surrounding drainage basin, and evaporation from the lake. It does not include the inflow from the upstream Great Lake or any diversions.

The Coordinated Great Lakes Regulation and Routing Model (CGLRRM) was used to simulate the dynamic hydrology and lake levels of the mid-lakes (Michigan-Huron, St. Clair and Erie). A separate program simulated Lake Ontario levels and outflows, and empirical equations were used to estimate hydrological impacts of restoration at Montreal.

1. Simulation Assumptions

For the purposes of the analysis, the level of restoration was defined as the rise in the long-term average surface elevation of Lake Michigan-Huron caused by a permanent structural change to the St. Clair River, as compared to the base case (*i.e.*, the "zero" restoration scenario). All restoration scenarios were simulated using water supplies for each lake as actually recorded in the historical period from 1900 to 2008. The different restoration scenarios were simulated by adjusting the parameters in the stage-fall-discharge equations used in the CGLRRM to describe the existing conveyance regime of the St. Clair River. The base case values of the parameters represent the conveyance regime determined by a statistical regression equation from the revised coordinated St. Clair River monthly outflows for the period 1987-2006. These parameters were adjusted until the desired restoration level was achieved.

Two different simulation timing conditions were used for each of the different restoration scenarios:

- that construction could be completed instantaneously, and that water levels and flows would begin to react at the very start of the simulation period; and,
- that restoration would take place in five stages, with one-fifth of the full restoration provided instantaneously every five years.

The first (and clearly unrealistic) "instantaneous" assumption illustrates the shortest period that water levels upstream would take to adjust. However, the impacts to downstream water levels and flows would also be greater under this assumption. The second "staged" assumption would see construction undertaken over a total of 25 years and therefore would require a longer period to achieve the full effect of restoration upstream, though with greatly reduced magnitude of undesirable downstream impacts, particularly in the St. Clair River-Lake St. Clair corridor. In reality, construction of restoration structures would take a number of years to complete regardless of the scenario chosen, but the instantaneous and staged simulations that were reviewed provided estimates of the range of hydrological impacts that could be anticipated.

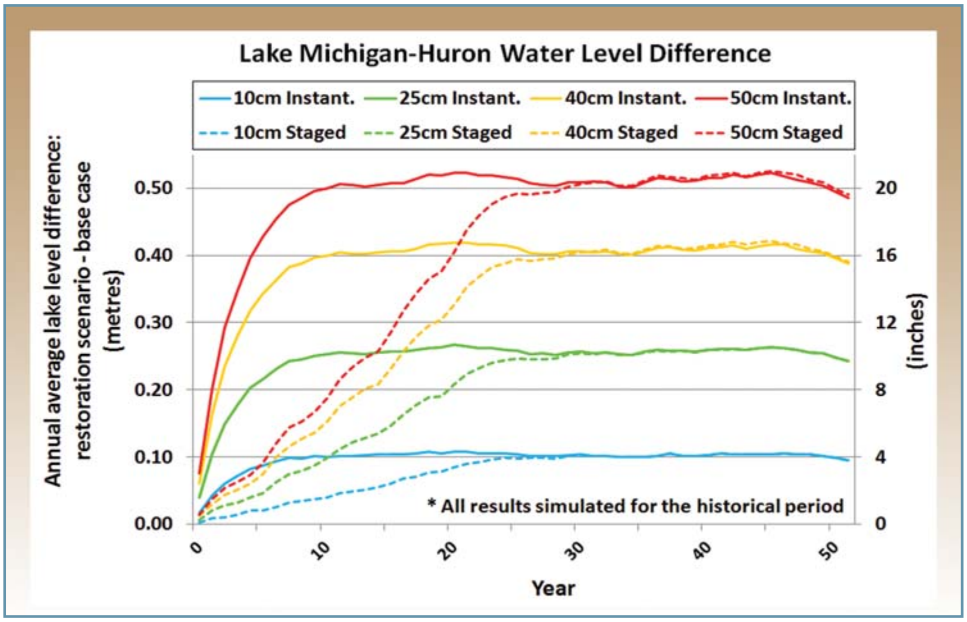

Figure 7-1 **Simulated Restoration Impacts on Lake Michigan-Huron Water Levels**

2. Lake Michigan-Huron Water Levels

Figure 7-1 illustrates the first 50 years of simulated restoration impacts on the annual average surface elevation of Lake Michigan-Huron compared to the base case for instantaneous and staged restoration scenarios. The results showed that water levels on Lake Michigan-Huron would start to rise as soon as the St. Clair River conveyance was reduced, with the full level of restoration achieved about 10 years later for the instantaneous assumption, or about 30 years later in the case of staged construction.

Restoration would reduce the occurrences of extreme low water levels on Lake Michigan-Huron, but also increase the number of occurrences of extreme high lake levels. For example, under the 10 cm (3.9 in) instantaneous restoration scenario, the maximum monthly surface levels simulated in the base case were found to be exceeded 1 to 3 percent of the time, depending on the month; similarly, for the 50 cm (19.7 in) instantaneous restoration scenario, maximum monthly surface levels simulated in the base case were found to be exceeded about 15 percent of the time.

3. Downstream Impacts on Water Levels and Flows

Restoring water levels would also have short-term downstream impacts, as flows in the St. Clair system are temporarily decreased while water is gradually stored on Lake Michigan-Huron. Figure 7-2 illustrates the simulated restoration

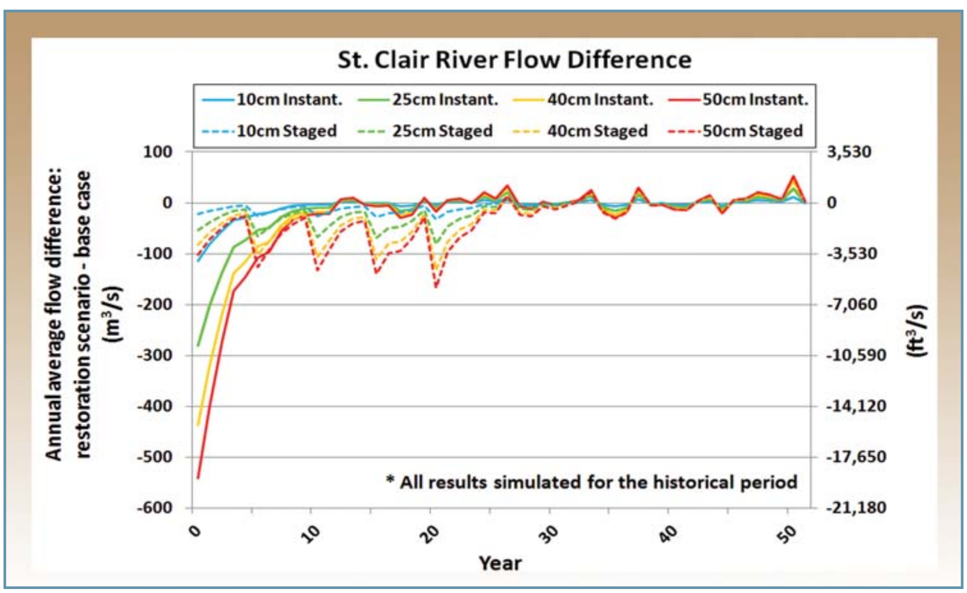

Figure 7-2 **Simulated Restoration Impacts on St. Clair River Flows**

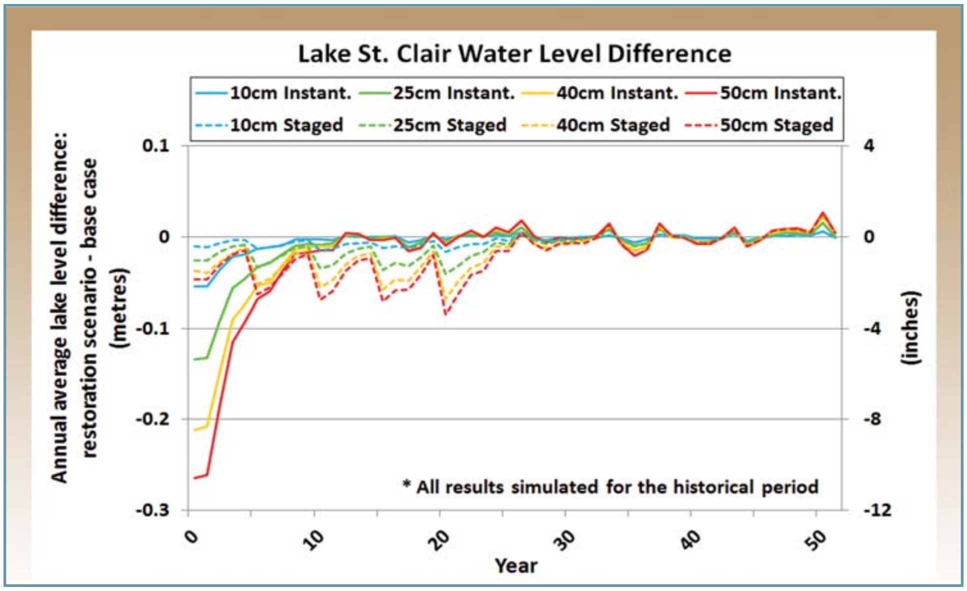

Figure 7-3 **Simulated Restoration Impacts on Lake St. Clair Water Levels**

impacts on the annual average flow on the St. Clair River compared to the base case for instantaneous and staged restoration scenarios. The reduction in conveyance capacity would initially lower the flow through the St. Clair River. However, as levels on Lake Michigan-Huron rise, flows through the St. Clair River would again gradually increase (because of increasing head differential) until they were essentially the same as they would have been prior to restoration construction.

The initial reduction in flow would also temporarily lower the levels of the downstream lakes. Figure 7-3 shows the impacts of different restoration scenarios on Lake St. Clair water levels. Note that as the restoration level increases, its downstream impacts also increase. One way to mitigate downstream impacts is by employing a staged construction scenario, where construction of restoration structures would be scheduled over several years or even decades. For example, if it were decided to restore Lake Michigan-Huron levels by 25 cm (9.8 in), with the full restoration structure constructed all at once, then the maximum impact on the annual average water level of Lake St. Clair would be an estimated 13 cm (5 in). If instead the restoration structure construction were staged in five equal increments, each spaced five years apart, then the maximum downstream impact on Lake St. Clair would be only about a 4 cm (about 1.6 in) reduction in lake levels, though this would occur each time an additional stage of the new series of structures was installed.

The timing of restoration also plays a critical role in the magnitude of possible impacts. For example, if restoration were to occur during a low water period, then it would exacerbate downstream impacts on lakes St. Clair, Erie and Ontario. Results showed that a "worst-case", poorly-timed 10 cm (3.9 in) instantaneous restoration would drop "record" low Lake Erie water levels by an additional 7 cm (2.8 in). Similarly, a "worst-case" poorly-timed 25 cm (9.8 in) instantaneous restoration would drop "record" low Lake Erie water levels by an additional 12 cm (4.7 in).

7.3 Overview of Options for Restoration Structures

The second component of the restoration analysis involved the description and technical assessment of specific structural options that could be constructed in the St. Clair River to restore Lake Michigan-Huron water levels. Given the exploratory nature of the analysis, the work was limited to an examination of four structures previously reviewed in the literature (Bruxer, 2011), as well as two relatively new technologies. The structures reviewed from past studies were limited to restoring water levels by up to 25 cm (9.8 in). Structures to provide greater levels of restoration likely are possible, but have not been examined to date, and would therefore require further study.

The structures reviewed here do not comprise a comprehensive list of possible restoration options, but rather illustrate a range of technically feasible options that could be used to raise levels of Lake Michigan-Huron. Similarly, the construction costs presented in this section are intended to provide a general indication of the order of magnitude of the likely costs for various restoration structures, and are not intended to represent a formal estimate of future cost streams discounted to present values.

Table 7-2: Summary of Options for Restoration Structures

Restoration Structure	Restoration Level[1]	Impact Duration[2]		Estimated Minimum Construction Cost[3]
		Lake Huron	Downstream Lakes and Channels	
1. Submerged Sills	10 cm (3.9 in) to 25 cm (9.8 cm)	Permanent	Transient	10 cm (3.9 in): $30 million 25 cm (9.8 cm): $65 million
2. Fixed Dikes/Weirs (extending into Lake Huron at its outlet)	16 cm (6.3 in)	Permanent	Transient	$150 million
3. Fixed Dikes (across east channels at Stag and/or Fawn Islands; with training walls)	Stag Island only: 16 cm (6.3 in) Fawn Island only: 5 cm (2 in)	Permanent	Transient	Stag Island: $120 million Fawn Island: $80 million
4. Hydrokinetic Turbines	3 to 19 cm (3.5 to 7.5 in) (depending on size, number and location of turbines)	Partially adjustable[4]	Transient, but recurring	No estimate
5. Inflatable Flap Gates (across east channels at Stag and/or Fawn Islands; with training walls)	10 to 16 cm (3.9 to 6.3 in)	Adjustable	Transient, but recurring	$130-170 million
6. Inflatable Rubber Weirs	No estimate	Adjustable	Transient, but recurring	No estimate

1 Depth of water restored on Lake Michigan-Huron based on designs from previous studies and studies conducted specifically for this analysis
2 Fixed restoration structures cause permanent impacts on upstream water levels and transient impacts downstream; adjustable structures can be regulated to raise upstream water levels only when desired, but this also results in recurring transient impacts
3 Costs in 2010 $US
4 Water level impacts of turbines could be reduced, but not eliminated, if turbine operation ceased

7

Table 7-2 summarizes the restoration structures reviewed, including the restoration level on Lake Michigan-Huron that could be achieved by means of that particular technology (based on the designs presented in past studies) and an estimate of the corresponding minimum construction costs.

7.3.1 Series of Submerged Sills in the Upper St. Clair River

Submerged sills act as “speed bumps” at the bottom of the river, restricting channel conveyance and raising upstream water levels by reducing the channel cross-sectional area and increasing the river bed roughness (Figure 7-4). Submerged sills have been the most studied option to date, likely as a result of their effectiveness, relatively low capital

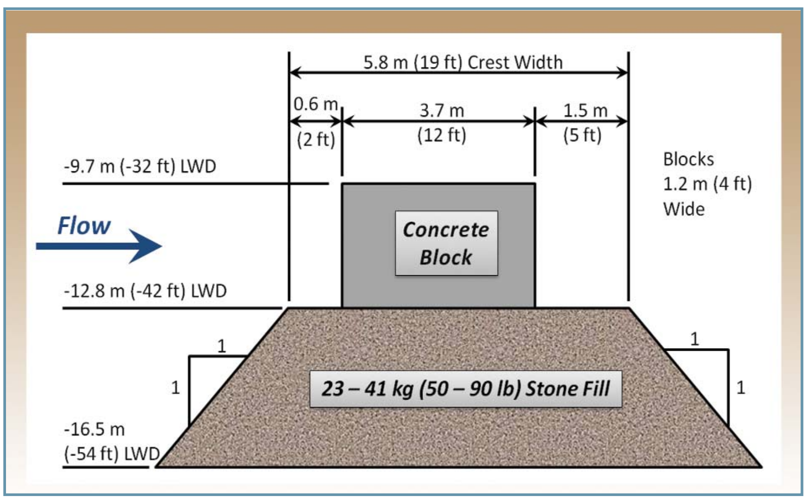

Figure 7-4 ***Cross-section of a Submerged Sill***
Source: Adapted from Baird (2005)
Note: LWD = Low water datum

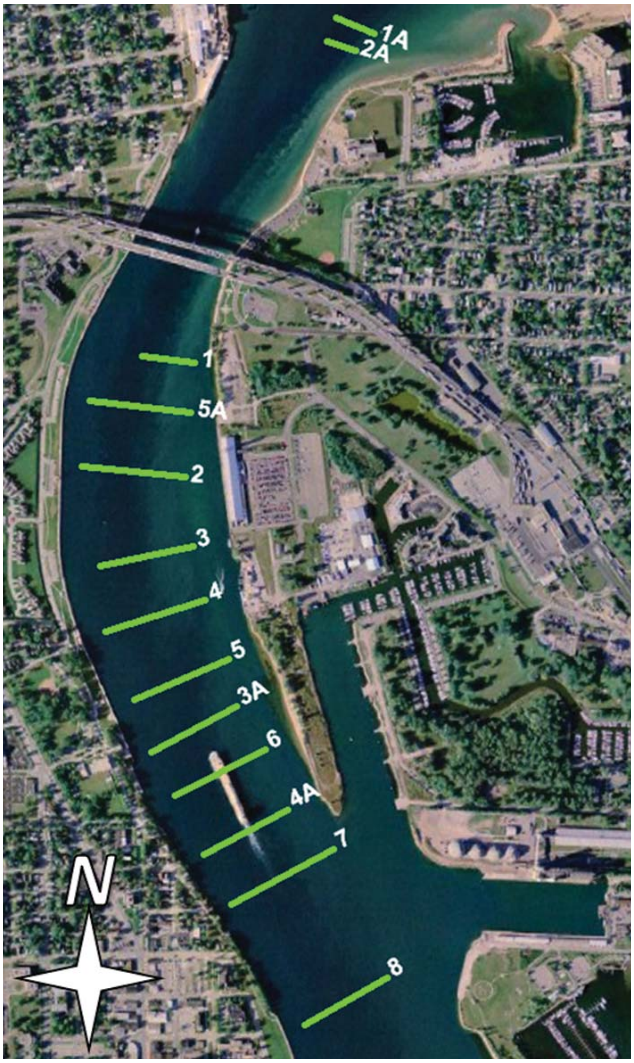

Figure 7-5 **Potential Submerged Sill Locations in the Upper St. Clair River**
Source: Adapted from Franco and Glover (1972)

costs, and negligible impact on navigation. Previous studies (*e.g.*, Moore, 1933; Franco and Glover, 1972) have suggested installing these structures in the upper reaches of the St. Clair River (Figure 7-5), given the close proximity to the outlet of Lake Huron, the narrowest and deepest area of the channel and the section with the highest velocity. Different combinations of sills could be used to provide different levels of restoration. In general, more and larger sills result in greater levels of restoration, though sill placement also affects their impacts.

Of all the different restoration structure options investigated in the restoration analysis, submerged sills were found to be the most economical alternative for nearly all levels of restoration (Frost and Merte, 2011). For example, restoration of 10 cm (3.9 in) would cost an estimated $30 million[3] using submerged sills.

3 Note: all dollars are in US$ unless otherwise noted.

7.3.2 Parallel Dikes and Fixed Weirs

A second previously proposed restoration structure option involved the use of parallel dikes and weirs extending into Lake Huron. These dikes and weirs would raise the water level of the lake by decreasing the cross-sectional area of the lake outlet (*i.e.*, the St. Clair River) and extending the narrowed cross-section into the lake (Figure 7-6). Such a structure, as designed in previous studies, could be used to raise the water level of Lake Michigan-Huron by approximately 16 cm (6.3 in). The total project cost, including both construction and indirect costs, was estimated to be about $150 million.

With such a structure, some of the negative environmental impacts on the St. Clair River discussed in section 7.5 might be avoided. For example, it would not restrict fish migration between the St. Clair River and Lake Huron. However, this structure might also interfere with sediment transport, as it could trap sediment that normally enters the St. Clair River from Lake Huron. This extensive structure would also be large and visually obtrusive.

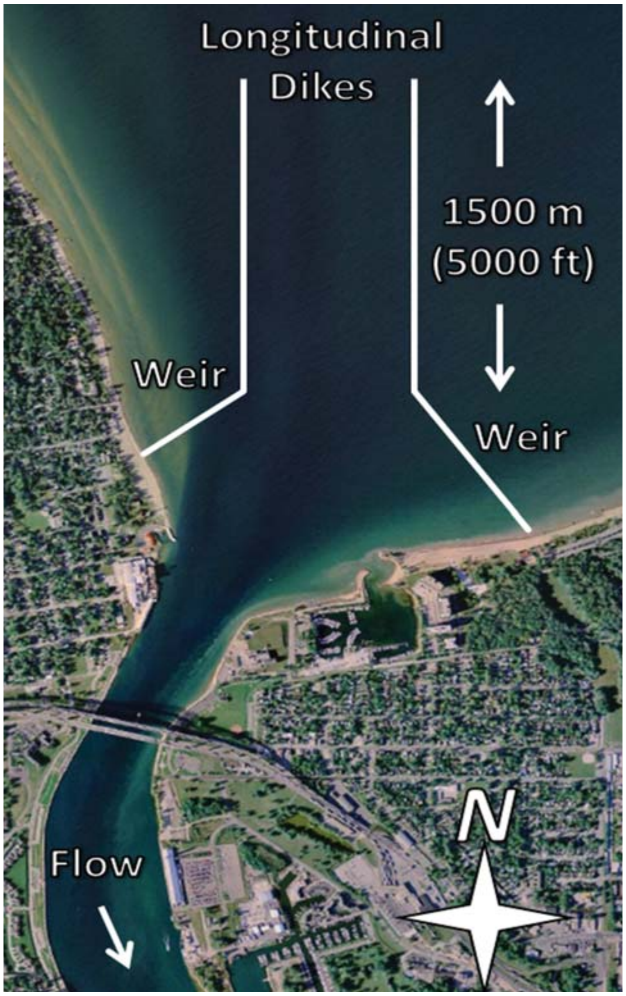

Figure 7-6 **Plan View of Parallel Dikes Extending into Lake Huron**
Source: Adapted from Moore (1933)

7.3.3 Rock-fill Dike Obstructions at Stag and Fawn Islands

Fixed rock-fill dikes acting as embankment dams across the east channel at Stag Island and Fawn Island could be used to raise water levels by restricting the total cross-sectional area of the St. Clair River and forcing all flow to pass through the west channel at each island (Figure 7-7). Training walls would be extended upstream and downstream from each island to increase the effectiveness of the structures and make the head drop more gradual so as not to interfere with navigation or cause other unintended negative consequences.

This option could be detrimental to both commercial navigation (due to increased velocities in the main navigation channel) and non-commercial boating (due to closure of the secondary eastern channels). However, effects on navigation during construction would likely be smaller than for construction of submerged weirs because vessels would be able to proceed through the unobstructed western channel.

***Figure 7-7** Plan View of Rock-fill Dike Obstruction at Stag Island*

Source: Adapted from Moore (1933)

Based on previous studies and hydrodynamic modelling, the Study found that without the training walls, the effect of the Stag Island obstruction would be about a 9 cm (3.5 in) increase in water levels on Lake Michigan-Huron. With the addition of the training walls, the resulting backwater effect would be about 16 cm (6.3 in). For the Fawn Island obstruction, the effect of the weir alone was estimated to be only a 1 cm (about 0.4 in) increase in Lake Michigan-Huron water levels. With the addition of training walls, the lake level restoration effect of the Fawn Island obstruction would be increased to 5 cm (2 in).

The combined effect of dike obstructions with training walls at both Stag Island and Fawn Island was estimated to be an increase in water levels of 21 cm (8.3 in). The total cost of the Stag Island obstruction was estimated to be about $120 million, while the total cost of the Fawn Island obstruction was estimated to be about $80 million.

7.3.4 Hydrokinetic Turbines

A fourth form of restoration structure considered in the analysis was hydrokinetic turbines. Similar to wind turbines, which harness the power of wind to produce energy, hydrokinetic turbines can be used to convert the kinetic energy of moving water into hydroelectricity (Figure 7-8). This emerging technology is already being considered for power generation in some of North America's largest rivers[4], including the Mackenzie River in Canada and the Mississippi River in the United States. The St. Clair River may also be a good candidate for such turbines, as are the other Great Lakes connecting channels, given their relatively swift currents in some areas, the relatively low variability of their flows and their large cross-sections. In fact, experimentation with this technology has taken place in recent years in the Great Lakes, with pilot demonstrations of turbines conducted in the St. Lawrence River near both Cornwall, ON, and Montreal, QC, and an alternative technology being tested with prototypes installed in the St. Clair River itself.

The installation of hydrokinetic turbines in a flowing stream would have several impacts on the hydrodynamics of the river. The physical presence of the turbines would modify flow patterns, and generation of power from the turbines will remove energy from the flowing water. Both of these impacts would result in an increase in water levels upstream. It follows that water level impacts of turbines could be reduced, but not eliminated, if turbine operation were

4 Information regarding recent prototype hydrokinetic technologies installed in North American can be found online for the Mackenzie River (www.newenergycorp.ca), Mississippi River (free-flow-power.com), St. Lawrence River near Cornwall, ON (verdantpower.com), St. Lawrence River near Montreal, QC (rehydro.com) and the St. Clair River (vortexhydroenergy.com).

***Figure 7-8* Example of In-stream Hydrokinetic Turbines**
Adapted from: verdantpower.com

ceased. Therefore, hydrokinetic turbines can be considered a partially adjustable option for restoring water levels of Lake Michigan-Huron. The turbines could be operated when levels were low to maximize water level impacts, and turned off when levels were high to minimize water level impacts. However, this might be undesirable from a hydropower production perspective, and operations would need to be managed with a regulation plan.

The impact of hydrokinetic turbines on water levels would be small and would depend on a number of factors. Results of a hydrodynamic modelling study of hydrokinetic turbines in the St. Clair River commissioned by the Study showed that the rise in Lake Michigan-Huron water levels varied depending on the number of turbines deployed, where they were located, and the flow in the river (National Research Council Canada, 2011). The most effective location for power production would be the upper St. Clair River near the Bluewater Bridge, where current velocities are highest and the channel is deepest, thereby allowing for the installation of the turbines without interfering with navigation.

Hydrodynamic modelling showed that if deployed in this area, 56 large turbines (Figure 7-9), each 6.5 m (about 21 ft) in diameter, would have an incidental impact on raising lake levels by 9 cm (about 3.5 in) under average flow conditions, while producing approximately 1.3 MW of power. Similarly, 151 turbines of the same size would raise levels by about 19 cm (about 7.5 in), while producing 2.5 MW of power.

However, as discussed in section 7.5, the upper St. Clair River is also a primary spawning area for an at-risk species, the lake sturgeon. If a similar number of turbines were instead installed further downstream, where currents are slower, then the resulting rise in Lake Michigan-Huron water levels would be reduced substantially, with the impact of 150 turbines being between 3 and 7 cm (about 1 to 2.8 in), and with power production ranging from 0.3 to 1.1 MW, depending on turbine configuration. In addition, since depths are shallower in the downstream reaches of the river, turbines in these areas would encroach on and increase velocities in the navigation channel and interfere with commercial navigation traffic.

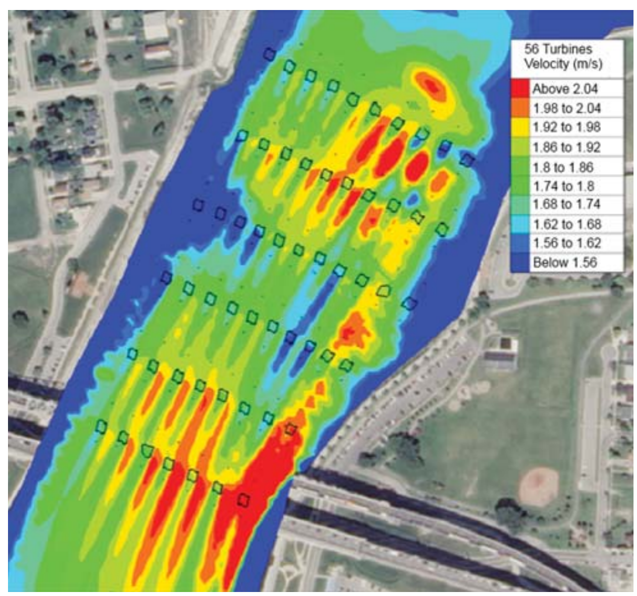

***Figure 7-9* Wake Simulated by 56 Turbines in the Upper St. Clair River**
Source: National Research Council Canada (2011)

7.3.5 Inflatable Flap Gates

Another structural option reviewed from previous studies was an adjustable structure, using inflatable flap gates at Stag Island and/or Fawn Island (International Great Lakes Levels Board [IGLLB], 1973; Levels Reference Study Board, 1993) (Figure 7-10). Strictly speaking, this structure would not be considered a restoration structure, given that it is adjustable and would provide a limited ability to regulate water levels of Lake Michigan-Huron.

Under this option, compressed air would be pumped into the metal flap gates to raise them and obstruct flow. The gates could be deflated to lower them out of operation. Based on the rock-fill dike results above, it is assumed that such a structure, if located at Stag Island and combined with training walls, would provide the ability to raise water levels by approximately 10 to 16 cm (3.9 to 6.3 in) when the structure is in a raised, operating position. However, in contrast to the fixed structures described above, the inflatable gates could also be lowered when levels are high, so as not to raise water levels further.

It is important to note that after raising the gates, a time-lag of several years would be required for the full effect to be realized. Similarly, upon lowering the gates, several years would be required for their impacts to be dissipated.

In addition, if the flap-gate structure were raised, then velocities in the western channel would increase such that, similar to the fixed obstruction option, mitigative measures may be required to slow the current and prevent erosion in this reach of the river.

The total cost of constructing the inflatable flap gate option at Stag Island (with training walls) was estimated to be in the range of $130 to $170 million. The analysis estimated that the cost of providing 150 low-submerged sills as mitigative measures would be about $50 million (in addition to the costs of the flap-gate structures themselves). Finally, any adjustable regulation structure would require a regulation plan and associated ongoing operation and maintenance costs.

7.3.6 Inflatable Rubber Weirs

Inflatable rubber weirs, one of the two relatively new technologies (along with the hydrokinetic turbines) explored in the restoration analysis, have been proposed in the past as an adjustable option for raising the water levels of Lake Michigan-Huron (Baird, 2009). Similar to the inflatable metal flap gates, inflatable rubber weirs would be considered a regulation option, as opposed to a fixed restoration option, given that they are adjustable.

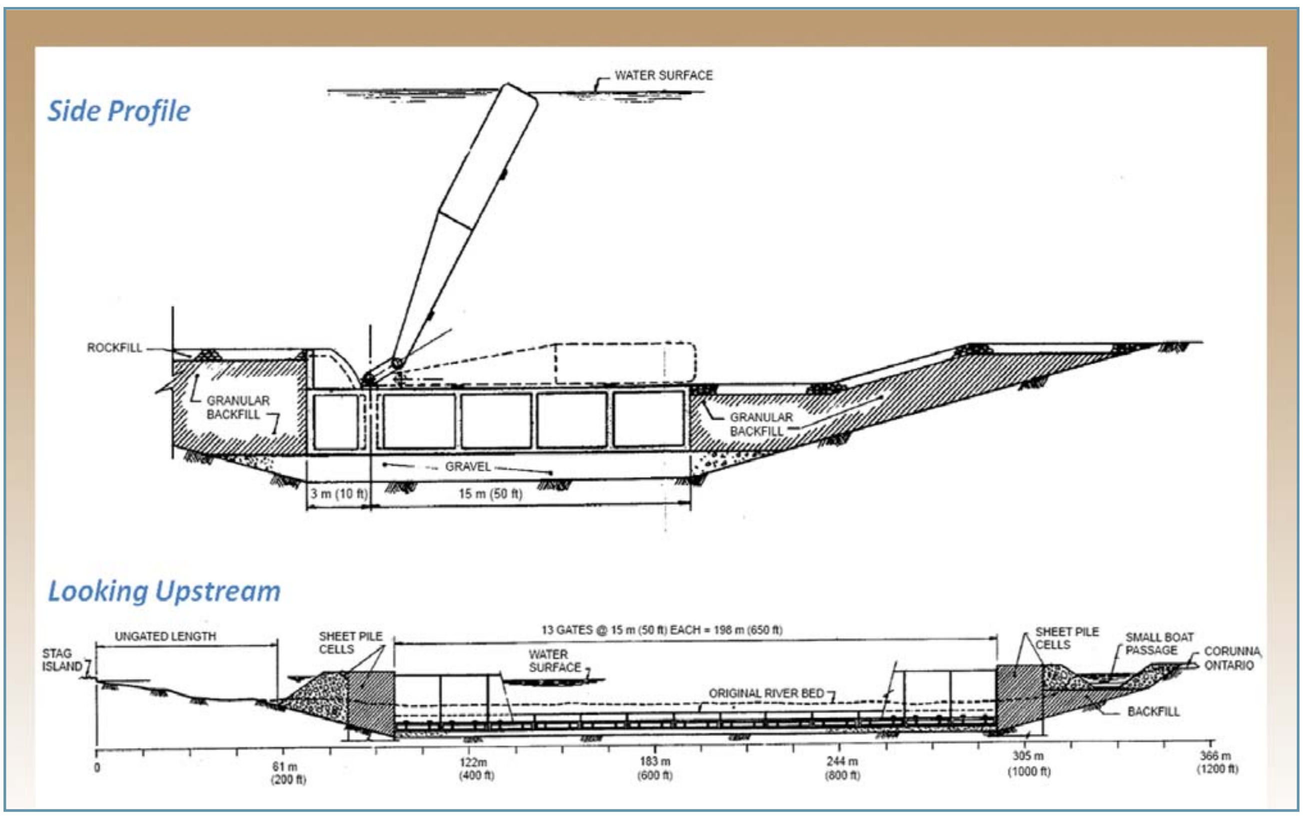

***Figure 7-10** Preliminary Design of an Inflatable Flap Gate at Stag Island*

Source: Adapted from International Great Lakes Levels Board (IGLLB) (1973)

These weirs are an alternative to more conventional gate options used in regulation structures. They have been primarily used in much smaller applications, such as raising the crest of an existing dam or spillway (American Society of Civil Engineers, 1994; International Commission on Large Dams [ICOLD], 1998). Currently, the largest inflatable rubber weir system in the world is the Ramspol Storm Surge Barrier in the Netherlands (Jongeling and Rövekamp, 1999) (Figure 7-11). It consists of three weirs, each 75 m long, 13 m wide and 8.35 m high (about 246 ft by 43 ft by 27 ft), which are used to prevent flooding caused by storms during periods of high water. The St. Clair River, in comparison, is much wider, between 400 and 800 m (about 1,312 to 2,624 ft) in the main channel, and much deeper, about 10 to 25 m (about 33 to 82 ft). The east channels at Stag and Fawn Islands are also relatively wide (400 and 250 m [1,312 and 820 ft], respectively) and deep (about 10 m or 33 ft). There is no known precedent for an inflatable rubber weir of this size.

Figure 7-11 ***Inflatable Rubber Weirs at the Ramspol Storm Surge Barrier***

Source: Delta Marine Consultants; see www.dmc.nl

Inflatable rubber weirs could also be used as submerged sills, but no examples of this application were found, and the literature reviewed indicated that these may deflate when the depth of water above the inflatable bladder is 30 to 40 percent of its height (ICOLD, 1998). Given these limitations, it appears unlikely that inflatable rubber weirs would be a viable option for the St. Clair River at this time.

7.4 Analysis of Impacts of Restoration on the Key Interests

The third component of the restoration analysis involved evaluating the impacts of various restoration scenarios on the key interests served by the upper Great Lakes system (see **Chapter 3** for more information on these key interests) using the SVM.

7.4.1 Restoration Scenarios

The Study examined 11 restoration scenarios. These included the eight original 10, 25, 40 and 50 cm (3.9, 9.8, 15.7 and 19.7 in, respectively) restoration scenarios using both the instantaneous and staged construction assumptions described in section 7.2.2. These were labelled by the depth of water, in cm, restored on Lake Michigan-Huron and whether the restoration was effected instantaneously (10 RI, 25 RI, 40 RI and 50 RI) or in stages (10 RS, 25 RS, 40 RS and 50 RS).

Two additional scenarios, denoted as 77R1 and 77R2, representing different Lake Superior regulation options for restoring lake levels, were also evaluated. Each of these would result in an instantaneous 10 cm (3.9 inch) restoration on Lake Michigan-Huron, but having different Lake Superior release assumptions:

- 77R1 employed the current plan **1977A** release rules for Lake Superior as opposed to the static Lake Superior assumption used for the eight RI and RS plans introduced above; and,
- 77R2 had rules to reduce the Lake Superior outflow to Lake Michigan-Huron when the latter lake is high, allowing water to be stored in Lake Superior.

The final scenario evaluated, denoted as StagIs LR, provided for the special case of limited regulation using a simple inflatable flap gate structure to obstruct flow through the east channel at Stag Island on the St. Clair River. Such a structure would require a set of operating rules, and for this initial investigation it was assumed that the gates would be raised and flow restricted whenever the level of Lake Michigan-Huron at the beginning of the month was below 176 m (577.4 ft), the chart datum elevation on this lake.

7.4.2 Summary of Restoration Impacts on the Key Interests

The Study Board criteria used to rank Lake Superior regulation plan options (see **Chapter 6**) were applied to evaluate the acceptability of the 11 different restoration scenarios. Figure 7-12 provides an overview of the impacts on the key interests and indigenous peoples.

Overall, the evaluations of the restoration scenarios revealed a mix of benefits and costs, and both positive and negative environmental impacts on the different interests. Note that the economic values assigned to benefits and impacts in this section are intended to provide an order of magnitude value by which to compare relative impacts of different restoration scenarios to the baseline (zero restoration) case. The values do not represent the results of a formal cost-benefit study in which a net stream of future benefits or costs is discounted to present values.

For example, commercial navigation interests would benefit from greater depths resulting from restoration, with the SVM estimating net benefits of about $4 million annually for the 10 cm (3.9 in) restoration scenarios, and up to $15 million annually for the 50 cm (19.7 in) scenarios. Recreational boating interests would also benefit from greater depths. By contrast, coastal zone interests would be adversely affected, with annual shore protection costs estimated to increase by $500,000 for the 10 cm (3.9 in) staged restoration scenario (10 RS) and up to approximately $3 million dollars for the 50 cm (19.7 in) instantaneous restoration scenario (50 RI). Hydroelectric generation interests would also experience negative impacts, with losses estimated at up to an average of $3 million annually for the 50 cm (19.7 in) restoration scenarios. Similarly, there is a tradeoff between the positive and adverse ecological effects. Positive ecological effects would be concentrated in the wetlands of the Georgian Bay region. For example, under the base case scenario, Georgian Bay wetlands experience up to six years of severe, long-lasting or permanent adverse impacts, but these were found to be entirely eliminated by restoration of 25 cm (9.8 in) or greater. By contrast, uniformly negative ecological effects would be experienced in the St. Clair River system (*i.e.*, the St. Clair River, Lake St. Clair and the Detroit River) as a result of any of the proposed restoration structures.

Also of note is that while the StagIs LR scenario would help prevent adverse shore protection impacts (because this adjustable structure would be lowered during periods of high water), the benefits to navigation and the ecosystem interests would be reduced (e.g., net benefits of only $1 million annually on average for commercial navigation; Georgian Bay wetlands would experience only three fewer years of the most adverse water level conditions). This is a result of the small increase in water levels this structure would establish (about 10 cm or 3.9 in) coupled with the long period of time it would take to achieve this (about 10 years) whenever the structure was put into operation.

Finally, there has been considerable development around the Great Lakes over the past 50 years. Much of this development has adapted to the historical range of levels through various land use regulations. Adding an increment of restored water levels to the Lake Michigan-Huron system would require a broad-scale regulatory adjustment, across numerous agencies and jurisdictions, to minimize future flood damages.

Restoration, GIA and Climate Change

In considering the impacts of restoration on the key interests, the effects of both GIA and climate change must be taken into account. For example, note that in the Georgian Bay area, GIA is causing the land in this area to rise, relative to the lake outlet, at a rate of approximately 17 to 27 cm (about 6.7 to 10.6 in) per century (Mainville and Craymer, 2005), depending on the location (see **Chapter 1**). As a result of GIA, Georgian Bay will continue to experience relatively lower water levels over time compared to other areas of Lake Michigan-Huron. Restoration would temporarily help to counteract the effects of GIA and lowered water levels in Georgian Bay. However, much of the densely populated southern portion of each of the Great Lakes, which includes large urban centers such as Chicago and Milwaukee, is experiencing an increase in water levels over time as a result of GIA. The land in this region is subsiding relative to each lake's outlet, with rates varying from about 8 to 25 cm (3.1 to 9.8 in) per century. Therefore, even a 10 cm (3.9 inch) restoration of Lake Michigan-Huron levels would compound the effects of GIA, with increased flood damage and erosion in this southern portion.

Domestic, Municipal and Industrial Water Uses

Restoration would have no adverse impact on municipal and industrial water users, based on historical water supplies. However, if future climate conditions are significantly drier, restoration would be expected to help offset the adverse impacts of extreme low water.

Commercial Navigation

Restoration would permanently raise Lake Michigan-Huron levels, allowing ships to carry heavier loads and reduce costs. There would be some negative impacts on lakes St. Clair and Erie during the initial period as water levels adjust to the new regime, but these negative impacts would be minimal when compared to the long-term benefits gained on the upstream lakes.

Hydroelectric Generation

At the St. Marys River, restoration of Lake Michigan-Huron levels would cause a decrease in the head difference between the upper and lower St. Marys River, resulting in a permanent decrease in power production. Downstream, restoration would cause a temporary decrease in hydropower production at Niagara River plants, as water held back to raise levels of Lake Michigan-Huron would be unavailable downstream.

Ecosystems

Restoration would provide some benefits to ecosystems, including improved fish spawning habitat in the St. Marys River and maintenance of fish access to eastern Georgian Bay wetlands. However, ecosystems in the St. Clair River system, including habitat that supports several species at risk, would be adversely affected.

Coastal Zone

Restoration would increase extreme high lake levels, leading to more flooding and erosion. Changes in water level management scenarios could alter the magnitude, frequency and duration of water levels outside the normal range, adversely affecting the functional lifespan of existing shore protection infrastructure and leading to increased failures. Restoration would generally cause the greatest damages around the more heavily-populated southern shores of Lake Michigan and the south-eastern shores of Lake Huron.

Recreational Boating and Tourism

Restoration of Lake Michigan-Huron water levels would be beneficial for recreational boaters, as there would be less chance that marina slips would have insufficient depth to be used during low water periods, and boat launches would not have to deal with low water conditions. Downstream, restoration would not benefit recreational boaters, but the negative impacts would be only minor, temporary increases in unusable marina slips during the period immediately after the restoration project is constructed.

Indigenous Peoples

Indigenous peoples make extensive use of the fish and biological resources of the St. Clair River system. They would be adversely affected by restoration structures that impact fish habitat and ecosystems in the St. Clair River and Lake St. Clair.

Figure 7-12 ***Summary of Restoration Impacts on the Key Interests and Indigenous Peoples***

In addition, the impacts of restoration that were analyzed by the Study were based on simulated results using recorded historical NBS. Future climate scenarios were not directly considered. However, as outlined in **Chapter 4**, the Study Board concluded that there is significant uncertainty regarding how climate change will affect Great Lakes water levels. The possibility cannot be ruled out that water levels both higher and lower than those observed in the past could be experienced in the future. As a result, the impacts of restoring Lake Michigan-Huron water levels – both positive and negative – would be magnified by the impacts of climate-driven changes in water supplies. For example, if water levels become generally lower in the future, the commercial navigation sector and Georgian Bay wetlands will be negatively impacted, and restoration could help mitigate these adverse effects. Conversely, if water levels become generally higher in the future, flood damages would increase, and restoration would exacerbate these negative impacts.

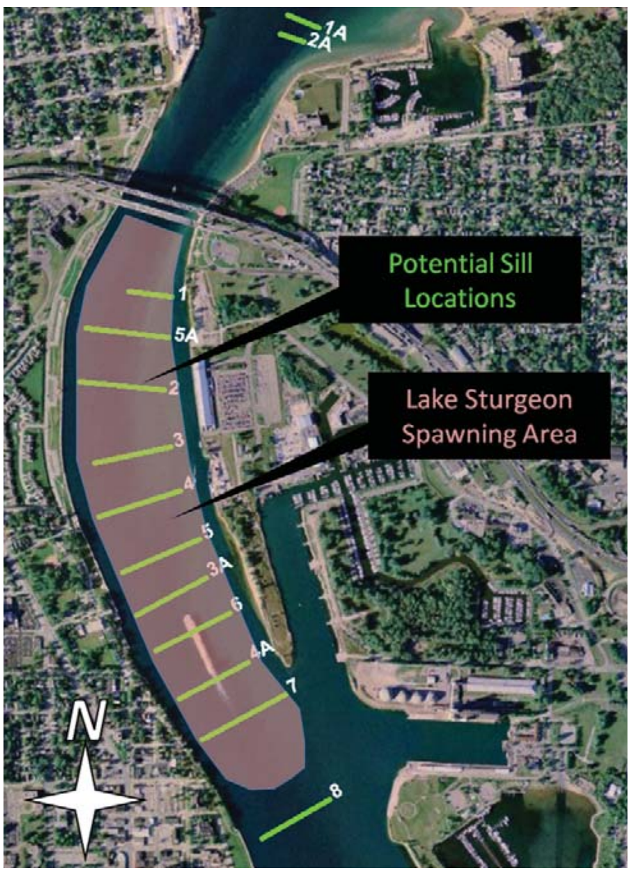

Figure 7-13 ***Overlapping Zone of Potential Sill Locations and Lake Sturgeon Spawning Habitat in the Upper St. Clair River***
Source: Adapted from Haas and Thomas (2011)

7.5 Environmental Considerations in the St. Clair River System

The Study concluded that restoration structures would have both positive and negative environmental effects. Higher Lake Michigan-Huron levels as a result of restoration would provide benefits in:

- the St. Marys River, with improved fish spawning habitat; and,
- Georgian Bay, where wetlands, which have suffered during low water levels in the past, support important fish habitat.

However, the Study determined that restoration structures would have significant adverse environmental impacts on the St. Clair River system, home to five listed species-at-risk (endangered or threatened), including the lake sturgeon. Environmental laws of both Canada and the United States require that this unique habitat be protected.

For example, a series of submerged sills or a network of hydrokinetic turbines in the upper St. Clair River would have serious adverse impacts on the lake sturgeon population, as this area of the river, with its fast currents and clean cobble substrate, represents the most significant lake sturgeon spawning habitat in the Great Lakes (Figure 7-13). Lake sturgeon also migrate through this area as they travel between the lower reaches of the river and Lake Huron during their life cycle. Potential lake sturgeon spawning habitat sites have also been identified near Stag and Fawn Islands. Moreover, the lake sturgeon has been extirpated[5] from every tributary in Lake Erie as well as the Michigan side of Lake Huron. The St. Clair-Detroit River corridor population now functions as the source population for this region, and is vital to recovery efforts taking place in this part of the Great Lakes in both the United States and Canada. Additional stresses on this population caused by structures of any form would unquestionably impede these efforts. The potential for significant adverse environmental effects on lake sturgeon and other fish species as a result of the establishment of restoration structures on the St. Clair River was confirmed to the Study by independent experts in both Canada and the United States.[6]

Significant reductions in water levels, such as those that would occur downstream of restoration structures during the time it takes for water levels to adjust after construction, could also have important adverse, though transient, impacts on the St. Clair-Detroit River ecosystem. As indicated in Figure 7-3, transient impacts of restoration on Lake St. Clair could last about 10 years after construction was completed.

5 A condition where a species ceases to exist in a particular geographic area, though it still exists elsewhere.

6 Personal communications to the Study, October 17, 2011 from: L. Mohr, Ontario Ministry of Natural Resources; and J. Boase, United States Fish and Wildlife Service.

This could adversely affect the Lake St. Clair fishery, as the lake supports a valuable recreational fishery for walleye, yellow perch, smallmouth bass and muskellunge, and provides habitat for several other recreationally and commercially important species. Furthermore, invasive plant species, such as *phragmites* and purple loosestrife, have replaced many native wetland plant species in the wetland areas around Lake St. Clair and the St. Clair River delta, creating monotypic stands of dense reeds that significantly reduce plant and habitat diversity and wetland function. The expansion of invasive plant species is facilitated by extreme changes in water levels, and is of special concern during periods of extended low water in the St. Clair system, since once established, these species are difficult to eradicate.

Restoration also could cause an increased risk for disturbance and re-suspension of the contaminated sediments that are located throughout the St. Clair River, particularly along the Canadian shoreline. The placement of structures at or near Stag Island may be of particular concern, given that this location is associated with high priority contaminated sites. Additionally, restoration structures can disrupt sediment transport. For example, the longitudinal dikes and weirs extending into Lake Huron could trap sediment that normally enters the St. Clair River from the lake, while structures constructed in the river can trap sediment that normally moves down the channel itself. This loss of sediment supply from Lake Michigan-Huron could affect bottom substrates further down the river, impacting critical fish habitat.

Finally, residents of the First Nations Reserve Walpole Island, located at the St. Clair River delta, make extensive use of fish and biological resources in this area. Any negative impacts to these resources would affect this interest directly and require formal consultations.

7.6 Institutional Considerations

The Study investigated the key institutional issues concerning restoration of Lake Michigan-Huron water levels, focusing on procedures and requirements for building new structures (Brown, 2011). These considerations included: an assessment of the need for a bi-national study and the scope and nature of that study; required authorizing legislation; the requirement for new IJC Orders of Approval; other required regulatory and environmental approvals; the specific role of the IJC compared to other jurisdictions and how the decision process could function; possible funding mechanisms; an assessment of whether the benefits justify the costs; and a review of past approvals for dredging in the St. Clair River system and related commitments to mitigate.

The construction of any new restoration structure would require the ongoing commitment and financing of the governments of Canada and the United States, a process that could take 20 years or more for the full range of planning, environmental reviews, regulatory approvals and design steps. If the IJC were to recommend structural measures in the St. Clair River and the governments of Canada and the United States agreed to pursue this recommendation, then it is likely that a new bi-national entity, comparable to the one established for the St. Lawrence Seaway project, would need to be considered. Furthermore, the IJC and its International Lake Superior Board of Control would have to adjust the Lake Superior regulation plan to accommodate the higher water level regime that would be established on Lake Michigan-Huron.

7.7 Key Points

With respect to the analysis of the feasibility and implications of raising water levels of Lake Michigan-Huron to compensate for past natural and human-induced changes by means of restoration structures in the St. Clair River, the following points can be made:

- Non-adjustable restoration structures have a permanent impact on water levels upstream, as well as a temporary effect on water levels downstream. Adjustable restoration structures affect water levels upstream and downstream with each deployment.
- The IJC directed the Study to conduct an exploratory analysis of methods and impacts of restoring Lake Michigan-Huron water levels. The IJC did not request the Study Board to make any recommendation as to implementing a particular restoration option. Rather, it directed that the restoration analysis "*… provide Governments and the public with extremely valuable information and insight to help form the basis for rational and scientifically – based decision making*".
- The Study conducted modelling of the Great Lakes-St. Lawrence River system by adjusting St. Clair River hydraulics to simulate the physical effects of water level restoration options on Lake Michigan-Huron and effects downstream through Lake Erie. The results showed that:
  - water levels on Lake Michigan-Huron would start to rise as soon as the St. Clair River conveyance was reduced, with the full level of restoration achieved about 30 years later in the case of staged construction;
  - restoration would reduce the occurrences of extreme low water levels on Lake Michigan-Huron, but also increase the number of occurrences of extreme high lake levels;

7

- the reduction in conveyance capacity would initially lower the flow through the St. Clair River; however, as levels on Lake Michigan-Huron rise, flows through the St. Clair River would again gradually increase until they were essentially the same as they would have been prior to restoration construction; and,
- the initial reduction in flow of the St. Clair River would temporarily lower the levels of the downstream lakes; the greater the restoration level, the greater the downstream impacts.

- The Study reviewed the feasibility of permanently raising Lake Michigan-Huron water levels by means of four previously studied and two new engineering technologies that could be installed in the St. Clair River system. The analysis concluded that several of the technologies were technically feasible. The four technologies reviewed from past studies were limited to providing up to 25 cm (9.8 in) of restoration. Updated construction cost estimates ranged from about $30 million to about $170 million, depending on the technology and level of restoration provided.
- The analysis examined the impacts of 11 restoration scenarios. The results showed a mix of benefits and costs for the key interests served by the upper Great Lakes system. Commercial navigation and recreational boating and tourism interests would benefit, while coastal zone and hydroelectric generation interests and indigenous peoples in the St. Clair River area would be adversely affected.
- The analysis found that restoration structures would have both positive and negative environmental effects. Positive effects would be concentrated in the wetlands of the Georgian Bay region, which have suffered significantly during low water levels in the past, but would benefit from higher Lake Michigan-Huron levels. Significant adverse environmental effects would be experienced in the St. Clair River system, a system that has also been stressed in the past, as restoration structures would impact important habitat of the lake sturgeon, an endangered species, and would have adverse effects on the Lake St. Clair fishery. Restoration also could lead to an increased risk for disturbance and re-suspension of the contaminated sediments that are located throughout the St. Clair River, particularly along the Canadian shoreline.
- Any future restoration effort in the upper Great Lakes basin must take into account GIA, which is causing different regions of the basin to rise or fall relative to each lake's outlet. Without restoration, as a result of GIA, Georgian Bay will continue to experience relatively lower water levels over time compared to other areas of Lake Michigan-Huron. Restoration would temporarily help to counteract the effects of GIA and lowered water levels in Georgian Bay. However, restoration of Lake Michigan-Huron levels would compound the effects of GIA in much of the densely populated southern portion of the upper Great Lakes.
- The impacts of restoring Lake Michigan-Huron water levels – both positive and negative – also would be magnified by the impacts of climate change. For example, if water levels become generally lower in the future, the commercial navigation sector and Georgian Bay wetlands would be adversely affected, and restoration could help mitigate these adverse effects. Conversely, if water levels become generally higher in the future, flood damages would increase, and restoration would exacerbate these adverse effects.
- Finally, in reviewing the institutional considerations of restoring Lake Michigan-Huron water levels, the analysis found that restoration structures would require the ongoing commitment and financing of the governments of Canada and the United States, a process that could take 20 years or more for the full range of planning, environmental reviews, regulatory approvals and design steps.

Chapter 8

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

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[1]

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[2], 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 give no further consideration" to any multi-lake regulation scenario considered at that time (Levels Reference Study Board [LRSB], 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.

1 This chapter is based on peer-reviewed research on multi-lake regulation commissioned by the Study (Tolson *et al.*, 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.

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[3] (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[4] 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.

3 Net basin supply (NBS) is the net amount of water entering each Great Lake resulting from precipitation falling directly on the lake surface, runoff to the lake from the surrounding drainage basin, and evaporation from the lake. It does not include the inflow from the upstream Great Lake or any diversions.

4 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."

8.2.2 Limitations of Analysis

The Study Board recognized that it was beyond the scope of the exploratory analysis to evaluate the impacts of the different multi-lake regulation plans on the key interests directly. 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 indicators into the objective function. Instead, given that most Great Lakes interests generally face adverse consequences when water levels exceed historical extremes, the impacts of multi-lake regulation were evaluated indirectly using extreme water levels (both high and low) to provide an acceptable metric for representing adverse water level conditions for these interests.

Two other 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 NBS 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.

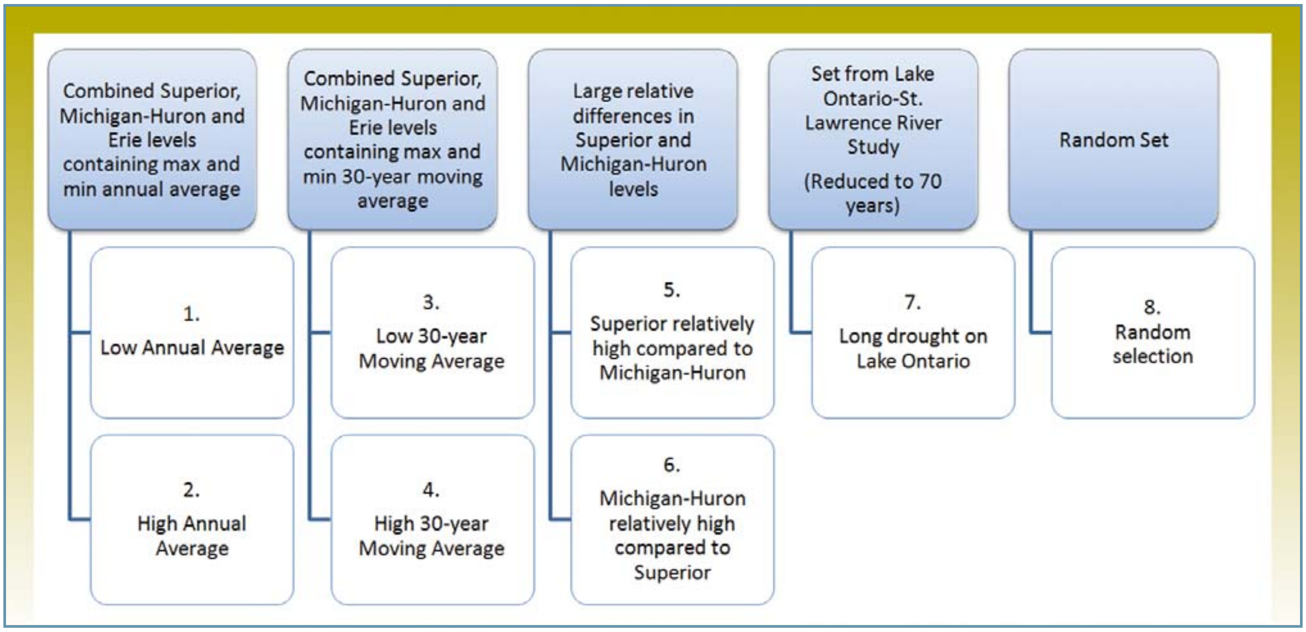

Figure 8-1 NBS Scenarios for Multi-lake Regulation Analysis

Scenarios chosen from the 50,000-year stochastic NBS dataset from the Lake Ontario-St. Lawrence River study (Fagherazzi et al.*, 2005). Scenarios were between 70 and 80 years in length.*

Eight different NBS scenarios were chosen from the 50,000-year stochastic[5] 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 NBS, 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;

5 *Stochastic* – Statistics involving or showing random behaviour. In a stochastic simulation, a model is used to create a new 'synthetic' series of plausible flows and lake levels, based on historical data. The synthetic series will, on average, preserve important properties of the historical record, such as the mean and standard deviation, while generating new combinations of high and low flow conditions that could represent more severe conditions than those seen in the past.

Table 8-1: Multi-lake Regulation Scenarios

Regulation Scenario	Location of Control Structure: St. Marys R. (L. Superior Outlet)	St. Clair R. (L. Michigan-Huron Outlet)	Detroit R. (L. St. Clair Outlet)	Niagara R. (Lake Erie Outlet)	Upper St. Lawrence R. (L. Ontario Outlet)	Lower St. Lawrence River
Two-Point	Existing Control	No control	No control	No control	Existing Control	No control
Four-Point	Existing Control	Hypothetical Control	No control	Hypothetical Control	Existing Control	No control
St. Clair Three-Point	Existing Control	Hypothetical Control	No control	No control	Existing Control	No control
Niagara Three-Point	Existing Control	No control	No control	Hypothetical Control	Existing Control	No control

- ***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.

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.[6] 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.

6 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.

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

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

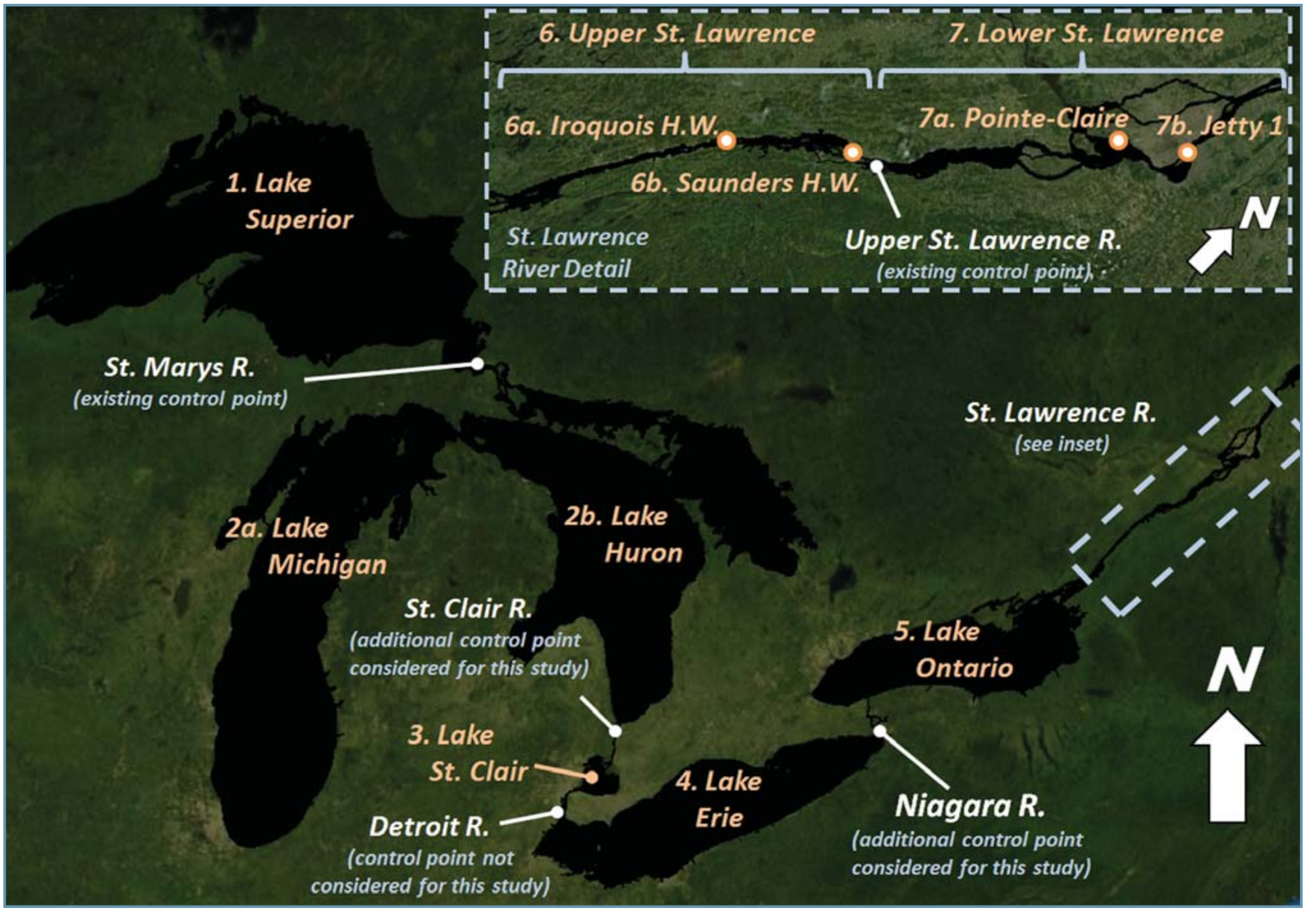

Figure 8-2 ***Great Lakes-St. Lawrence River System and Multi-lake Evaluation Points***

The seven multi-lake regulation plan evaluation points are: 1. Lake Superior, 2. Lake Michigan-Huron, 3. Lake St. Clair, 4. Lake Erie, 5. Lake Ontario, 6. the upper St. Lawrence River (represented by the combined results at Iroquois Headwater and Saunders Headwater); 7. the lower St. Lawrence River (represented by the combined results at Pointe-Claire and Jetty 1 near Montreal).

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).

8

Rule Curves

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.

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 **1977A** for Lake Superior and Plan **1958DD** 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).

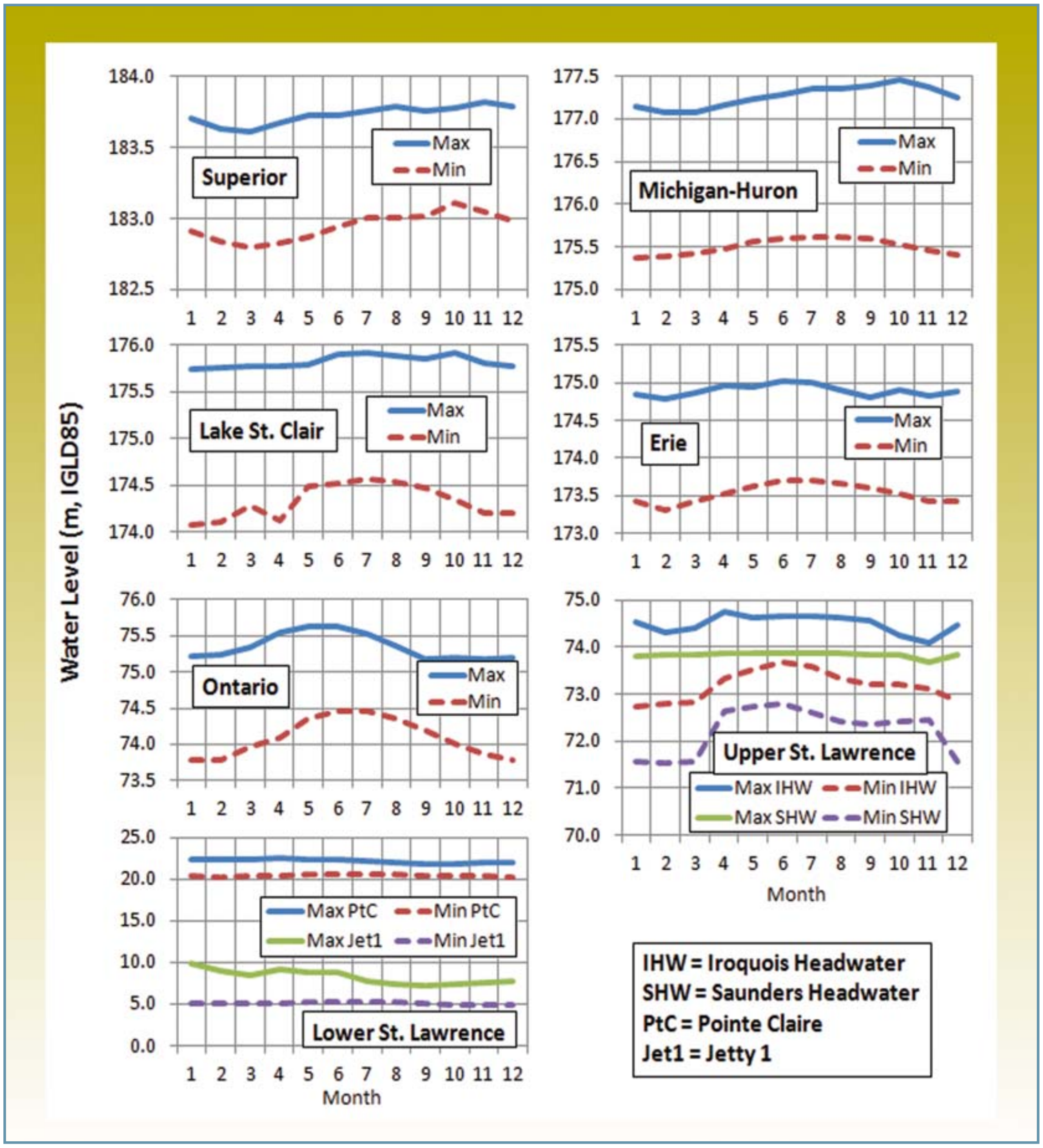

Figure 8-3 **Simulated Historical Extreme Water Levels at Each Evaluation Point**

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 (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[7]. These structural costs were assumed constant for all degrees of flow reduction relative to natural connecting channel flow and for any range of lake

7 All costs have been updated to 2010 U.S. dollars unless otherwise noted. See Bruxer and Carlson (2010).

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.

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.

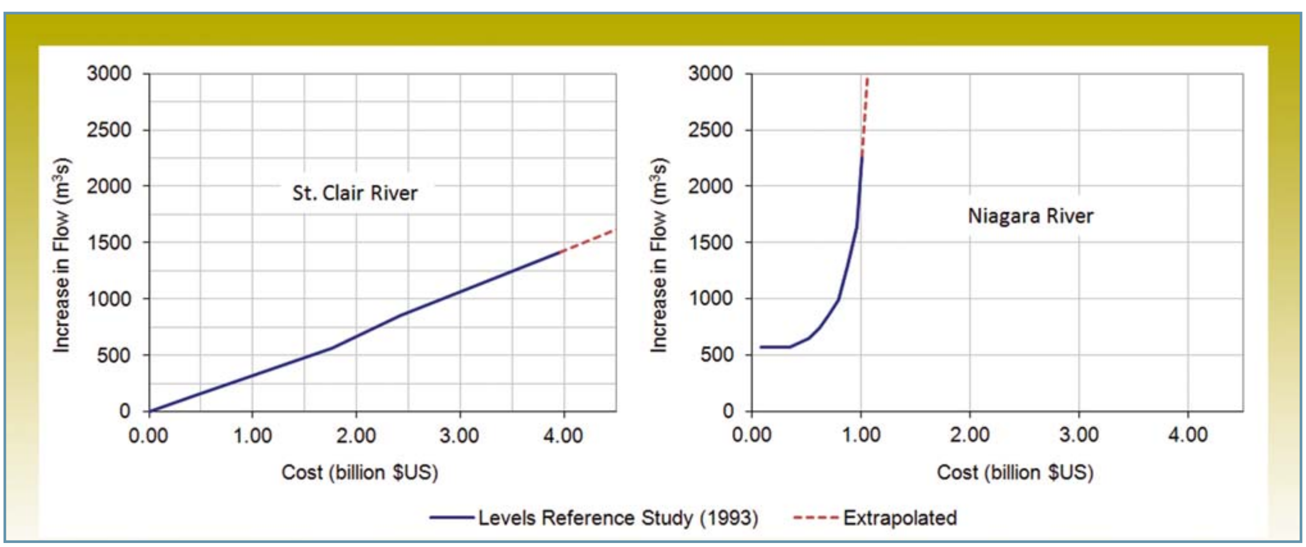

Figure 8-4 ***Flow Increase versus Cost Curves***

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 range of 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).

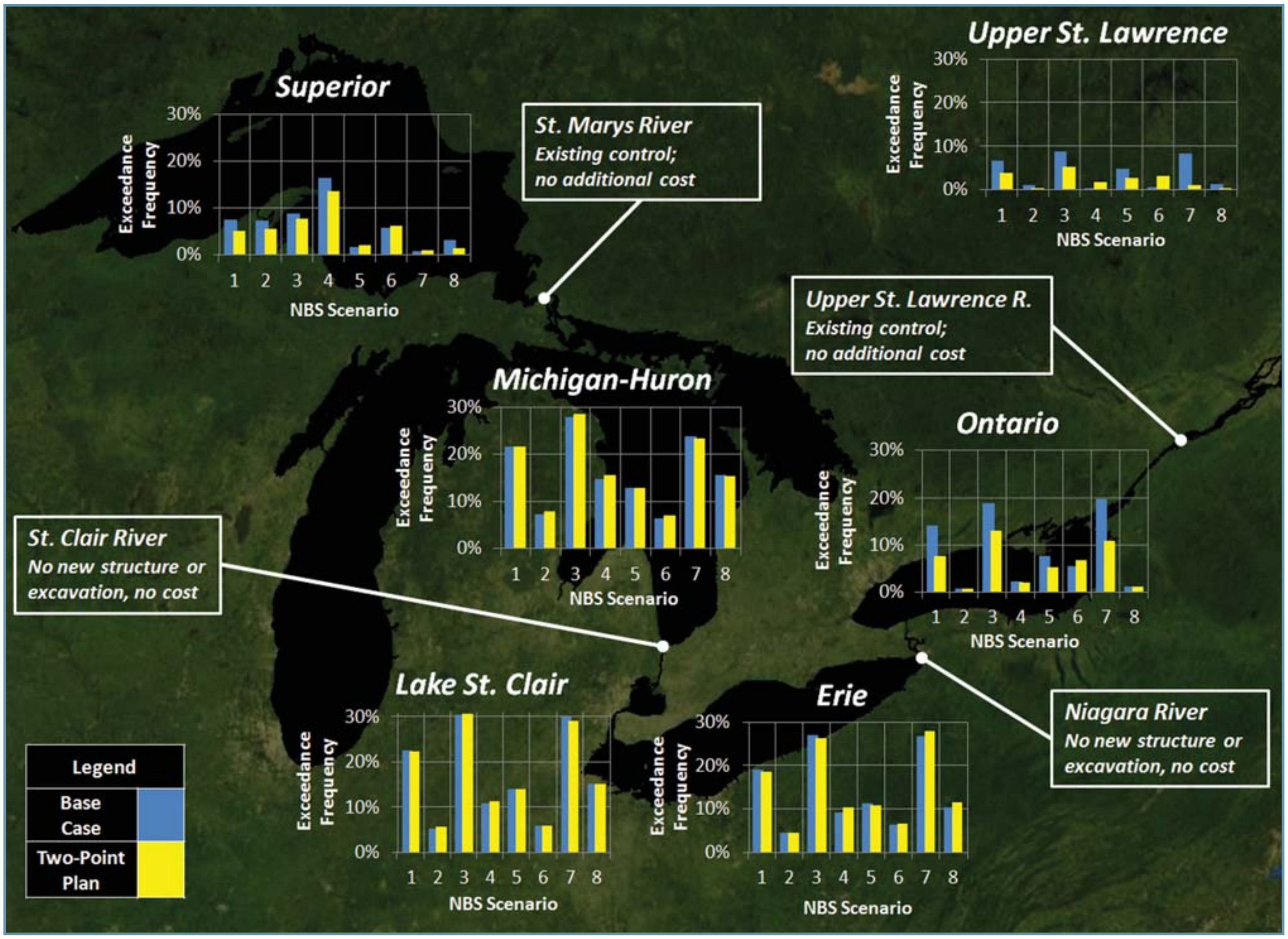

Figure 8-5 **Performance of Two-point Multi-lake Plan Based on the Frequency-based Objective**

Exceedance frequency is equal to the percentage of months simulated for each NBS scenario that exceed the simulated historical extreme water levels. For example, the two-point multi-lake regulation plan results presented here show that this plan was only able to reduce the frequency of exceeding simulated historical extremes on Lake Superior, Lake Ontario and the upper St. Lawrence River; a two-point plan can do little for the other evaluation points.

8

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.

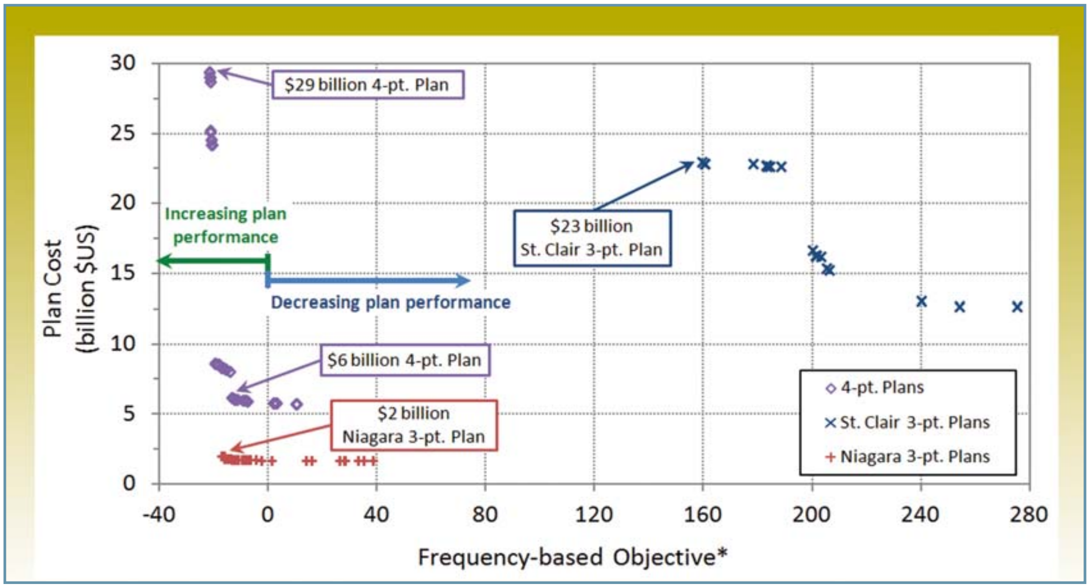

Figure 8-6 **Estimated Tradeoffs between Frequency-based and Regulation Cost Objective Functions**

Note: The frequency-based objective function does not have interpretable units; however, a negative value describes generally improved performance overall, as it implies that the frequency of violating extremes is improved or equal to what would occur under the current base case regulation scenario everywhere and for all eight NBS scenarios.

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.

Table 8-2: Best-performing Tradeoff Plans

Plan	Frequency-Based Objective Value[1]	Structure Costs (billion $US)		Excavation Costs (billion $US)	
		St. Clair	Niagara	St. Clair	Niagara
$29 billion Four-point	-22	$0.5	$0.5	$27.0	$1.3
$6 billion Four-point	-13	$0.5	$0.5	$3.9	$1.2
$23 billion St. Clair Three-pt.	159	$0.5	—	$22.4	—
$2 billion Niagara Three-pt.	-17	—	$0.5	—	$1.4

1 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.

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.

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.

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.

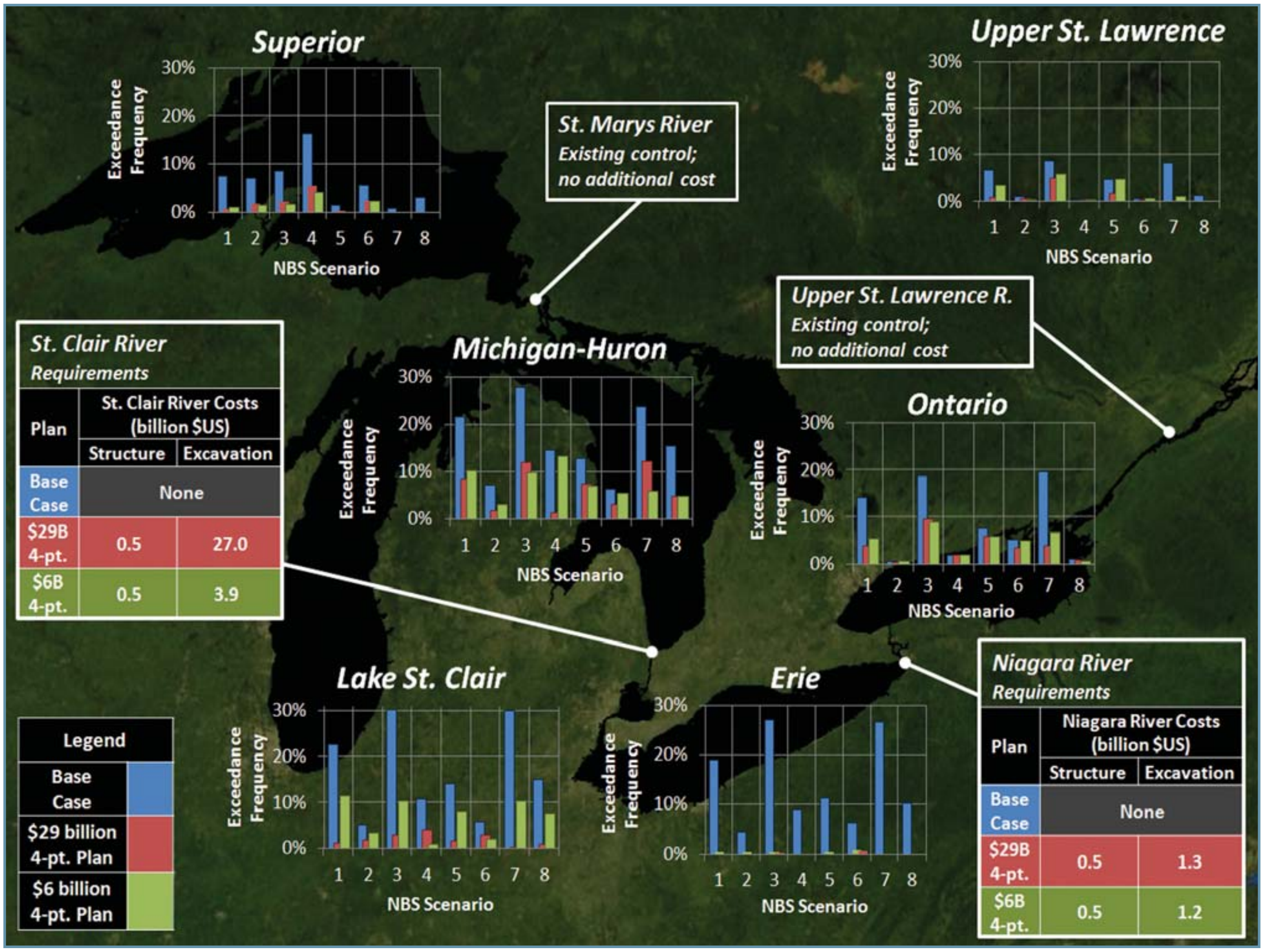

Figure 8-7 **Comparison of Performance of the $29 and $6 billion Four-point Plans**

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.

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.

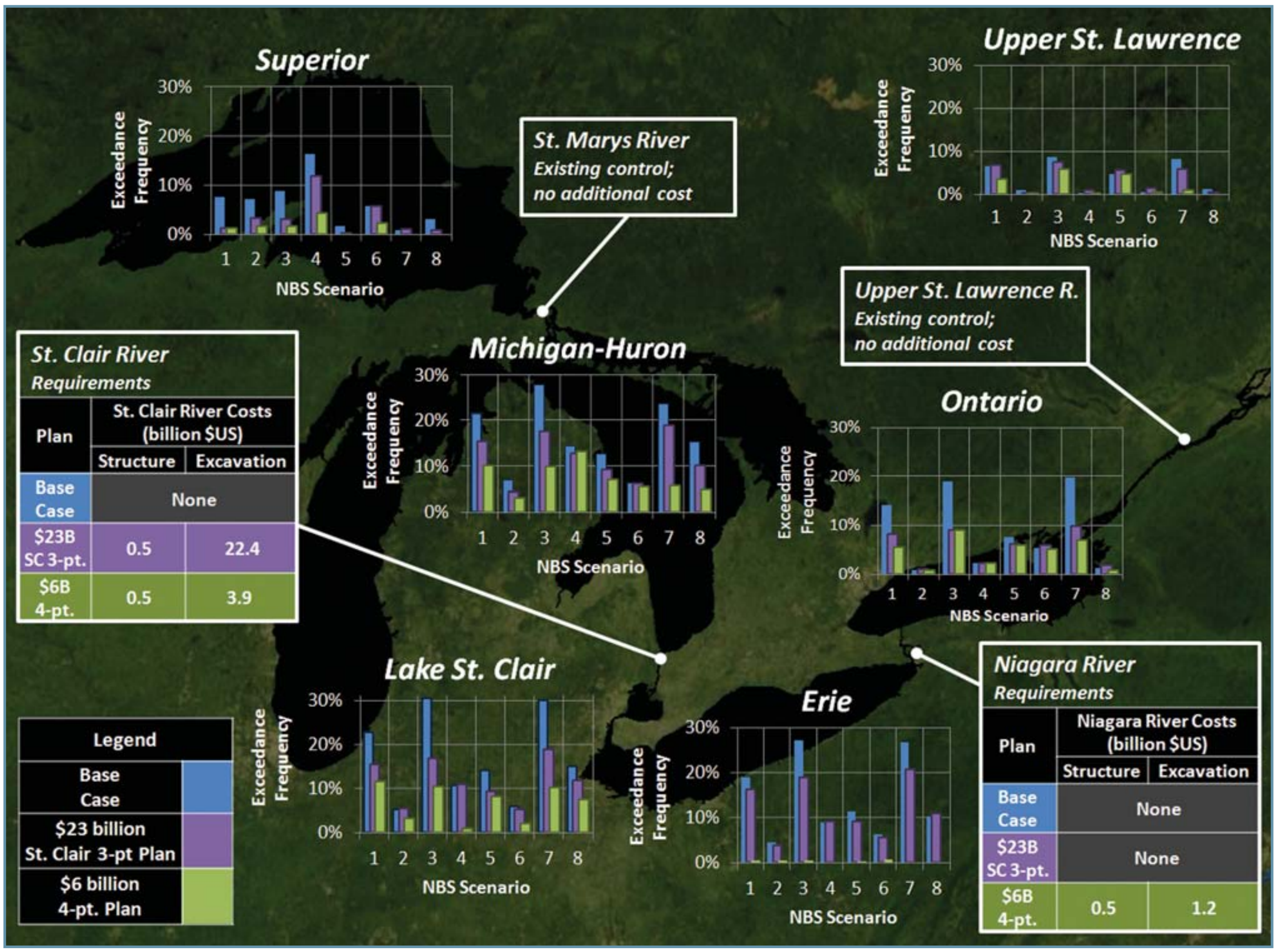

Figure 8-8 ***Comparison of Performance of the $23 billion St. Clair River Three-point Plan and the $6 billion Four-point Plan***

Exceedance frequency is equal to the percentage of months simulated for each NBS scenario that exceed the simulated historical extreme water levels. Despite the higher costs (due to greater amounts of excavation required in the St. Clair River), the $23 billion St. Clair River three-point plan performed worse than the $6 billion four-point plan at all six evaluation points and for nearly all NBS scenarios.

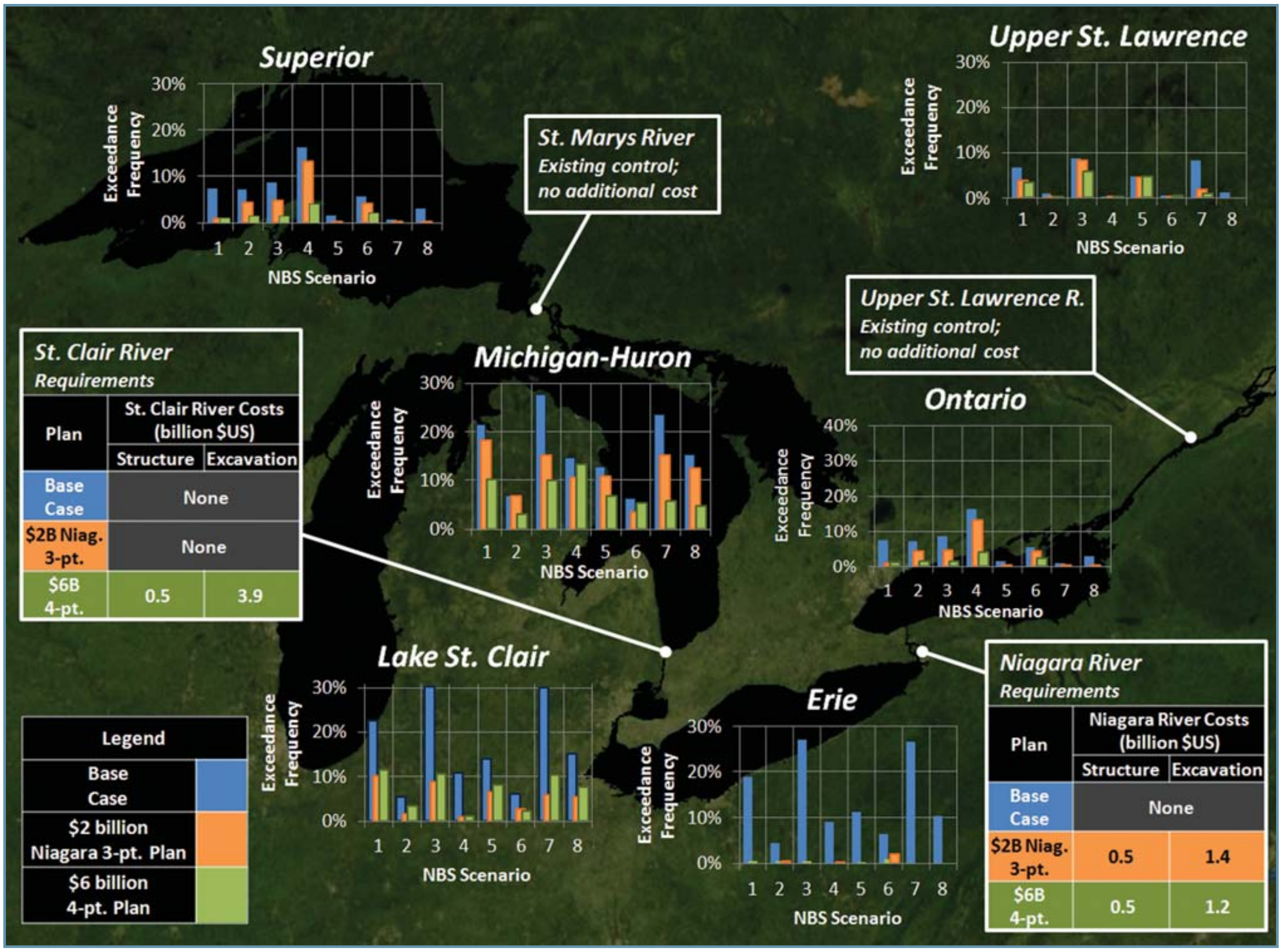

Figure 8-9 **Comparison of Performance of the $2 billion Niagara River Three-point Plan and the $6 billion Four-point Plan**

Exceedance frequency is equal to the percentage of months simulated for each NBS scenario that exceed the simulated historical extreme water levels. The $2 billion Niagara three-point plan performance is equal or better than the base case for all NBS scenarios and at all evaluation point, but somewhat degraded compared to the $6 billion four-point plan for lakes Superior and Michigan-Huron in particular.

8.4.6 Performance of the $2 billion Niagara Three-point Plan

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 Best-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

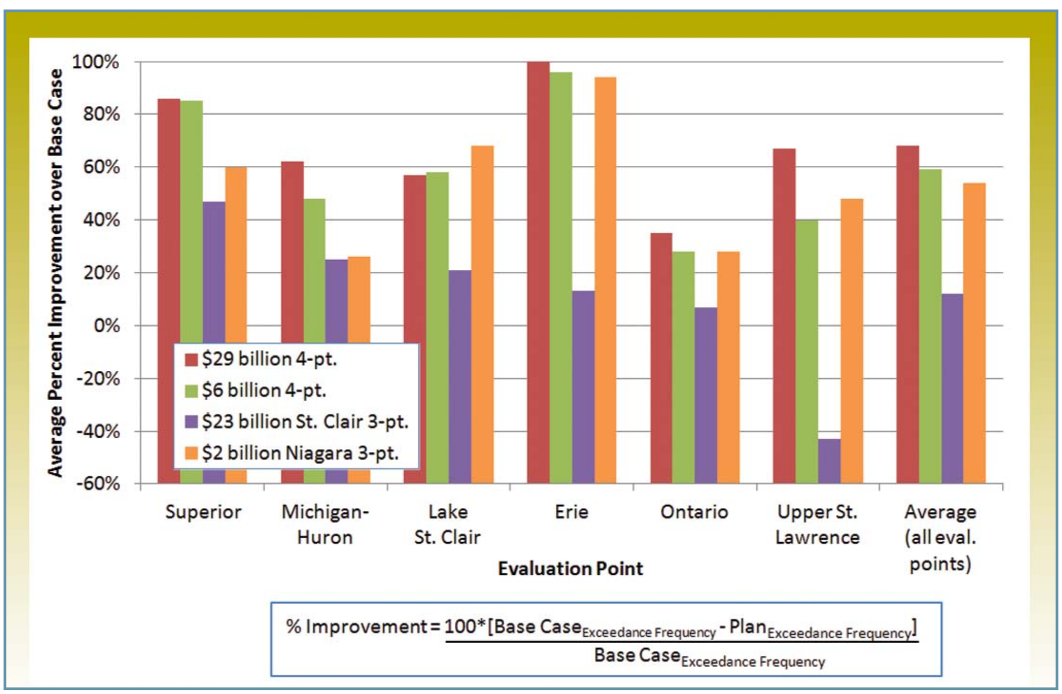

***Figure 8-10** Comparison of Average Improvement of Different Plans over Base Case*

Figure 8-11 ***Frequency of Exceeding High and Low Extreme Water Levels from Full 50,000-year Stochastic Simulation***

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.

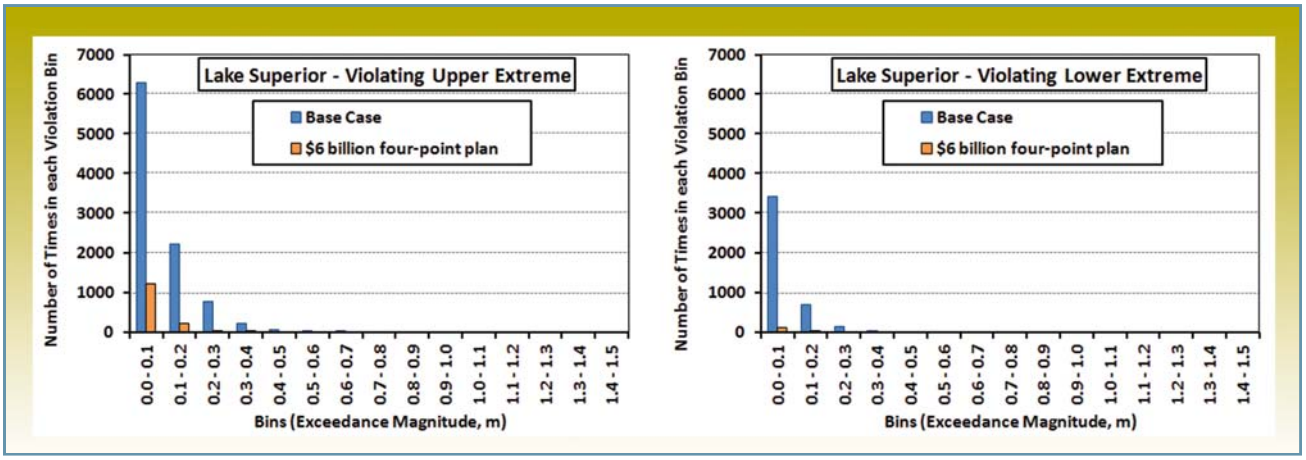

Figure 8-12 ***Example Histograms for Lake Superior of Monthly Average Extreme Violation Magnitudes***
($6 billion four-point plan)

Note: histograms developed from the 50,000-year simulation under the $6 billion four-point plan and the base case plan. Bins are separated by magnitude (in metres) by which simulated historical extreme water levels are exceeded. Total number of time intervals (months) is 600,000.

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.

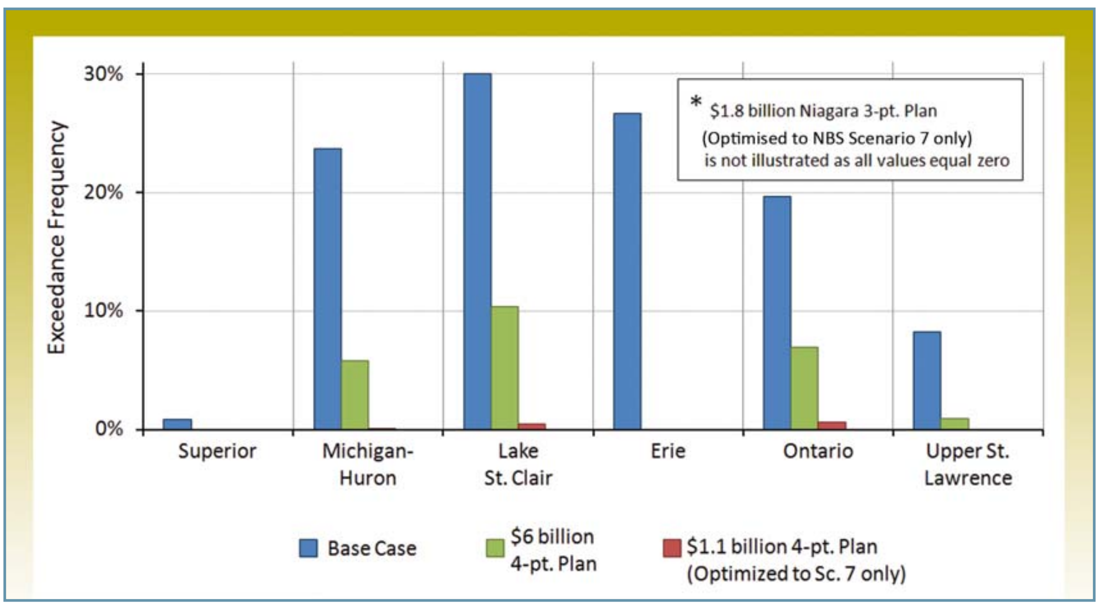

***Figure 8-13* Performance of Multi-lake Plans Optimized for Driest Scenario Only**

Exceedance frequency is equal to the percentage of months simulated for NBS scenario 7 that exceed the simulated historical extreme water levels.

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-

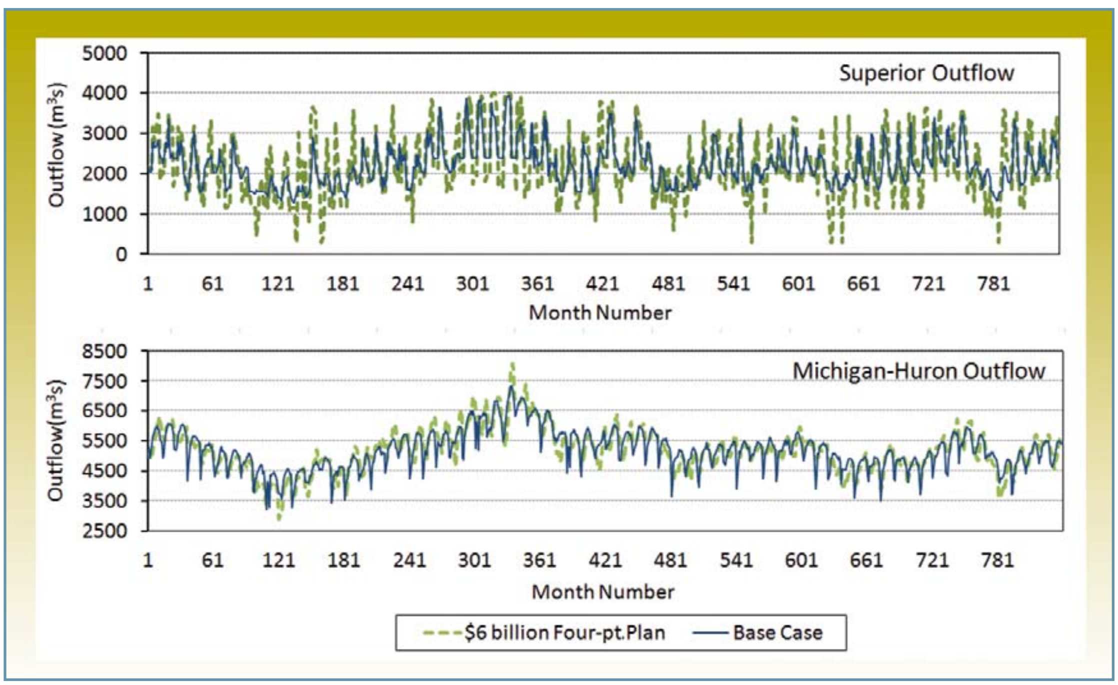

Figure 8-14 **Comparison of Simulated Lake Superior and Lake Michigan-Huron Outflows: $6 billion Four-point Plan versus Base Case**

8

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, 2010). This review included a comprehensive evaluation of mitigative requirements in the St. Lawrence River made during the Levels Reference Study (Hydrosult Inc., 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 m^3/s (40,000 ft^3/s) below what was identified as the minimum design flow of 5,210 m^3/s (184,000 ft^3/s), and plans that would increase flows by no more than 1,700 m^3/s (60,000 ft^3/s) above what was determined to be the maximum design flow of 14,500m^3/s (510,000 ft^3/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.

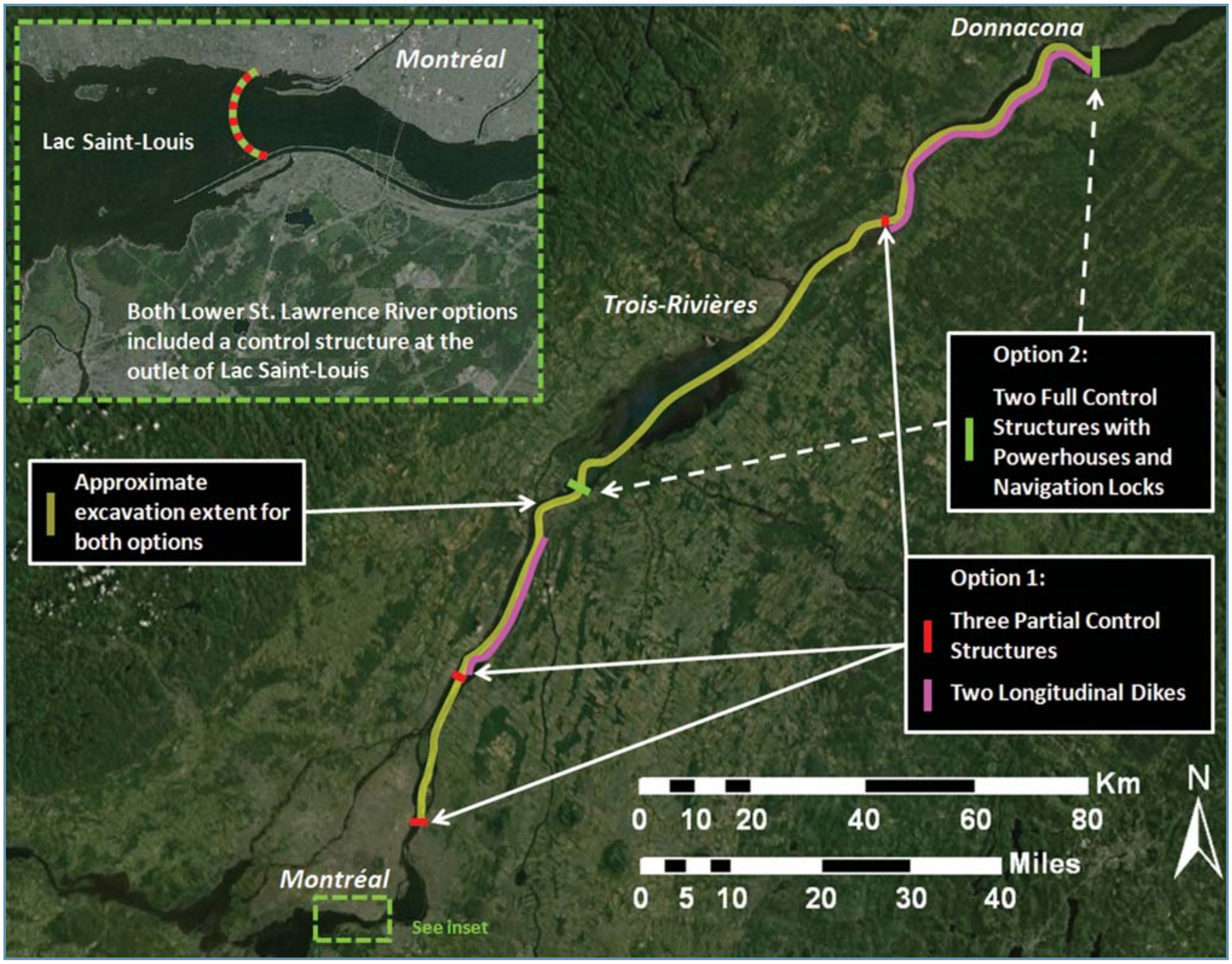

Figure 8-15 ***Potential Lower St. Lawrence River Mitigative Measures***

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.

Source: adapted from Hydrosult Inc. (1993)

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

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

	Upper Great Lakes Study Multi-lake Regulation Plans			Levels Reference Study Multi-lake Regulation Plans[1]			Difference		
Plan	**Max Lower St. Law. Flow**	**Min Lower St. Law. Flow**	**Costs of Lower St. Law. Mitigation**	**Max Lower St. Law. Flow**	**Min Lower St. Law. Flow**	**Costs of Lower St. Law. Mitigation**	**Max Lower St. Law. Flow**	**Min Lower St. Law. Flow**	**Costs of Lower St. Law. Mitigation**
Base Case	16,000 m3/s (565,000 ft3/s)	4,000 m3/s (141,000 ft3/s)	Not assessed	16,200 m3/s (570,000 ft3/s) An increase of 1,700 m3/s (60,000 ft3/s) over design flows	4080 m3/s (144,000 ft3/s) A decrease of 1,130 m3/s (40,000 ft3/s) over design flows	Approx. $4 to $6 billion	-200 m3/s (-7,000 ft3/s)	-80 m3/s (-3,000 ft3/s)	Unknown
$29B 4-pt	16,100 m3/s (569,000 ft3/s)	4,500 m3/s (159,000 ft3/s)					-100 m3/s (-4,000 ft3/s)	420 m3/s (15,000 ft3/s)	
$6B 4-pt	19,900 m3/s (703,000 ft3/s)	2,600 m3/s (92,000 ft3/s)					3700 m3/s (21,000 ft3/s)	-1,480 m3/s (52,000 ft3/s)	
$23B St. Clair 3-pt	16,800 m3/s (593,000 ft3/s)	1,200 m3/s (42,000 ft3/s)					600 m3/s (21,000 ft3/s)	2,880 m3/s (102,000 ft3/s)	
$2B Niagara 3-pt	19,400 m3/s (685,000 ft3/s)	1,600 m3/s (57,000 ft3/s)					3,200 m3/s (113,000 ft3/s)	-2,480 m3/s (88,000 ft3/s)	

1 Source: LRSB (1993)

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.

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.

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 new structures on the St. Clair and Niagara rivers, to reduce the frequency of occurrence of extreme water levels under possible extreme future NBS 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 so as to 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. 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;
  - evaluating the impacts and mitigative measures required in the lower St. Lawrence River;
  - 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,
  - 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. However, 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.

Chapter 9

Addressing Future Extreme Water Levels: The Role of Adaptive Management

Chapter 9 examines the role that adaptive management can play in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels. It proposes a long-term adaptive management strategy for dealing with extreme water levels in the Great Lakes-St. Lawrence River system.

9.1 The Study's Approach to Adaptive Management[1]

9.1.1 The Purpose of Adaptive Management

Adaptive management is a planning process that provides a structured, iterative approach for improving actions through long-term monitoring, modelling and assessment. Adaptive management allows decisions to be reviewed, adjusted and revised as new information and knowledge becomes available and/or as conditions change. It is not a 'trial and error' process, but one that is built on "learning while doing" (Williams *et al.*, 2007).

Figure 9-1 illustrates the conceptual framework for adaptive management (Colosimo *et al.*, 2006; International Joint Commission [IJC], 2008). Core components are the overarching institutional arrangements (governance) and the need for strong, effective interjurisdictional collaboration. The process involves an ongoing effort to identify and reduce specific uncertainties and test management options and policies (Crawford *et al.*, 2005; Gunderson and Light, 2006). The results of implemented management options are monitored to evaluate their expected performance. The lessons learned are then used to adjust subsequent management decisions. Adaptive management is designed to complete the feedback loop whereby the uncertainties associated with future choices are reduced through the application of new knowledge (Nudds *et al.*, 2003; Williams *et al.*, 2007).

1 This chapter is based on peer-reviewed research for adaptation management by the Study's Adaptive Management Technical Work Group (TWG) (IUGLS, 2012a).

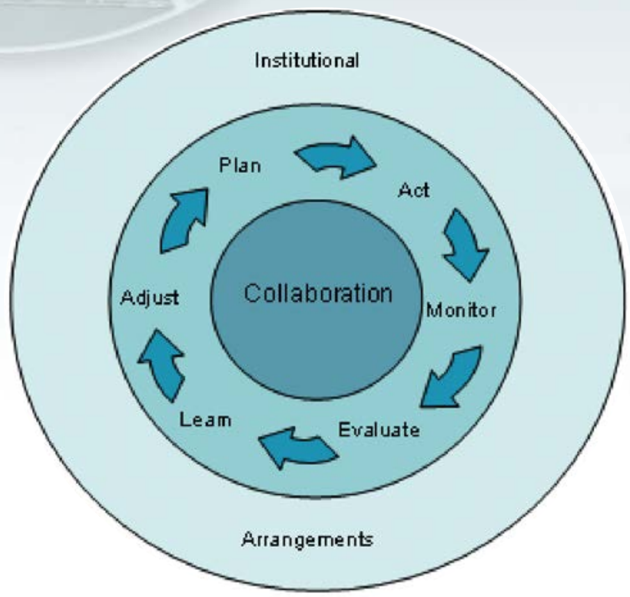

Figure 9-1 ***Adaptive Management Conceptual Framework***
Source: IJC (2008)

It is important to note the distinction between *adaptive management* and *adaptation*. The former is the iterative process for "learning while doing" and adjusting actions as necessary to address changing conditions. *Adaptation* is the broader context of responses taken and actions implemented to address risk. This chapter discusses both concepts, as they are inherently linked. However, the adaptive management strategy emerging from the work of the International Upper Great Lakes Study (the Study) is focused on what is necessary in terms of ongoing monitoring and modelling to gain greater understanding of appropriate adaptive actions and of when and how they should be implemented or adjusted to minimize future risks.

9.1.2 Decision-scaling Process for Risk Assessment

As discussed in **Chapter 4**, recent research indicates that the climate is changing in the Great Lakes region, but that there remains considerable uncertainty in how climate change will affect lake levels in the upper basin. The Study was faced with the challenge of how to assess a regulation plan under a changing climate, together with a wide range of associated uncertainties.

As outlined in **Chapter 2**, the Study identified adaptive management as a viable mechanism for addressing future uncertainty. A separate technical work group (TWG) was established to assess the need for adaptive management and develop a strategy.

As a first step towards developing an adaptive management strategy it became clear that the Study Board needed to better understand the risks of a changing climate and the uncertainties associated with possible future water level conditions. Following consultation with climate experts and resource managers in the upper Great Lakes basin, the Study adopted a *decision-scaling* approach to defining climate risk to help move towards a strategy for adaptive management (Brown *et al.*, 2011). Decision-scaling differs from the more traditional down-scaling approach in that rather than relying on a small suite of scenarios based on Global Climate Models (GCMs)[2] to define system vulnerabilities, the approach begins with stakeholders. It determines the domain of vulnerabilities and then assesses whether those conditions are possible or plausible based on the available climate science (Figure 9-2). This approach allows for incorporating data and models from a broader array of information sources than just GCM outputs.

A seven-step process for defining and managing risk was developed to form the basis for an adaptive management work plan (Figure 9-3):

1. Define system vulnerabilities for each of the interests (*How vulnerable are the various interests?*).
2. Develop risk scenarios (*What are possible future scenarios?*).
3. Define plausibility of risks (*How plausible are high-risk events?*).
4. Develop Lake Superior regulation strategies to address future risks (*Will changing the existing regulation plan help?*).
5. Evaluate new water level control structures (*Would additional structures help?*).
6. Identify other adaptive means of addressing risk that are or could be used, through an institutional analysis (*Are there other adaptive means?*).
7. Identify long-term monitoring and modelling needs that support an adaptive management strategy for understanding future risk, minimizing uncertainties and adjusting management actions as new information and knowledge are incorporated and/or as conditions change (*What monitoring and modelling are needed to support adaptive management?*).

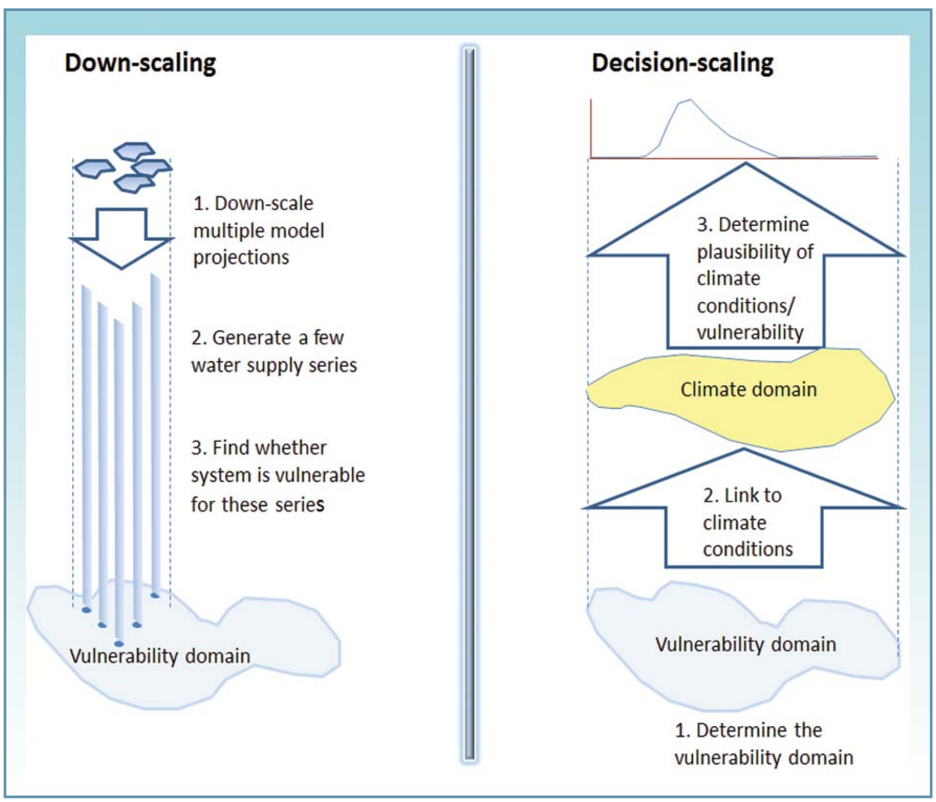

Figure 9-2 Comparison of the Down-scaling and Decision-scaling Approaches
Source: Brown et al.*, 2011*

2 Also known as General Circulation Models or Global Circulation Models.

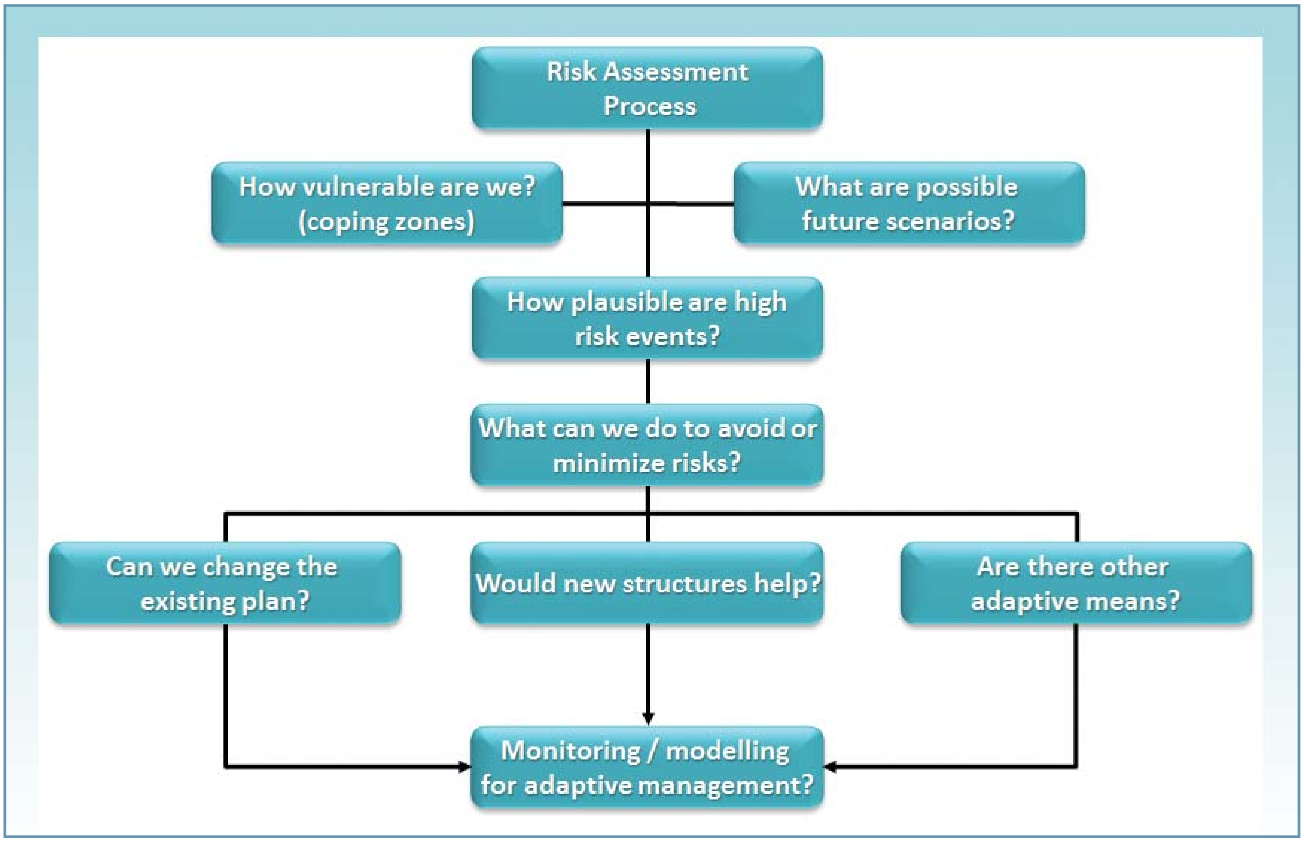

Figure 9-3** **Adaptive Management Work Plan Process

1. Defining System Vulnerabilities

As described in **Chapter 3**, the Study established TWGs based upon the various interests that might be affected by the regulation of Lake Superior levels. The TWGs were tasked with the job of identifying examples where those individuals, businesses, communities and organizations within their specific area of interest were vulnerable to lake level fluctuations.

Chapter 3 provides background information on the key interests considered in the Study. Table 3-1 summarizes the vulnerabilities of each interest group to water level fluctuations. The Study found that vulnerabilities to water level fluctuations varied from interest to interest, by geographic location within a lake and among the lakes, and by local conditions. In addition to the range in water levels, other important factors include the frequency, duration and rate of change. Rapid changes in lake levels generally result in more damages than gradual changes because the key interest has less time to adjust to the change.

Each TWG developed a range of "coping zones" for its specific interest that assessed vulnerability to water level fluctuations as well as confounding factors such as glacial isostatic adjustment (GIA), wind/waves/storm surges and precipitation patterns. Each TWG identified three levels of progressively more challenging water level conditions for the interest:

- *Zone A:* a range of water level conditions that the interest would find tolerable;
- *Zone B:* a range of water level conditions that would have unfavourable though not irreversible impacts on the interest; and,
- *Zone C:* a range of water level conditions that would have severe, long-lasting or permanent adverse impacts on the interest.

Figure 9-4 illustrates the coping zone results. It shows a single point based on the most conservative minimum and maximum water level provided by the TWGs for each interest and for each lake (the mean annual threshold was used in the case of Coastal Zone interests).

A critical aspect in defining the coping zones is determining the thresholds that mark the transitions between zones. The TWGs determined the factors that can push their interest from one zone to another and assessed the ability to recover should the levels return to more acceptable conditions. These thresholds are not only defined by water levels, but also by duration, frequency and rate of change.

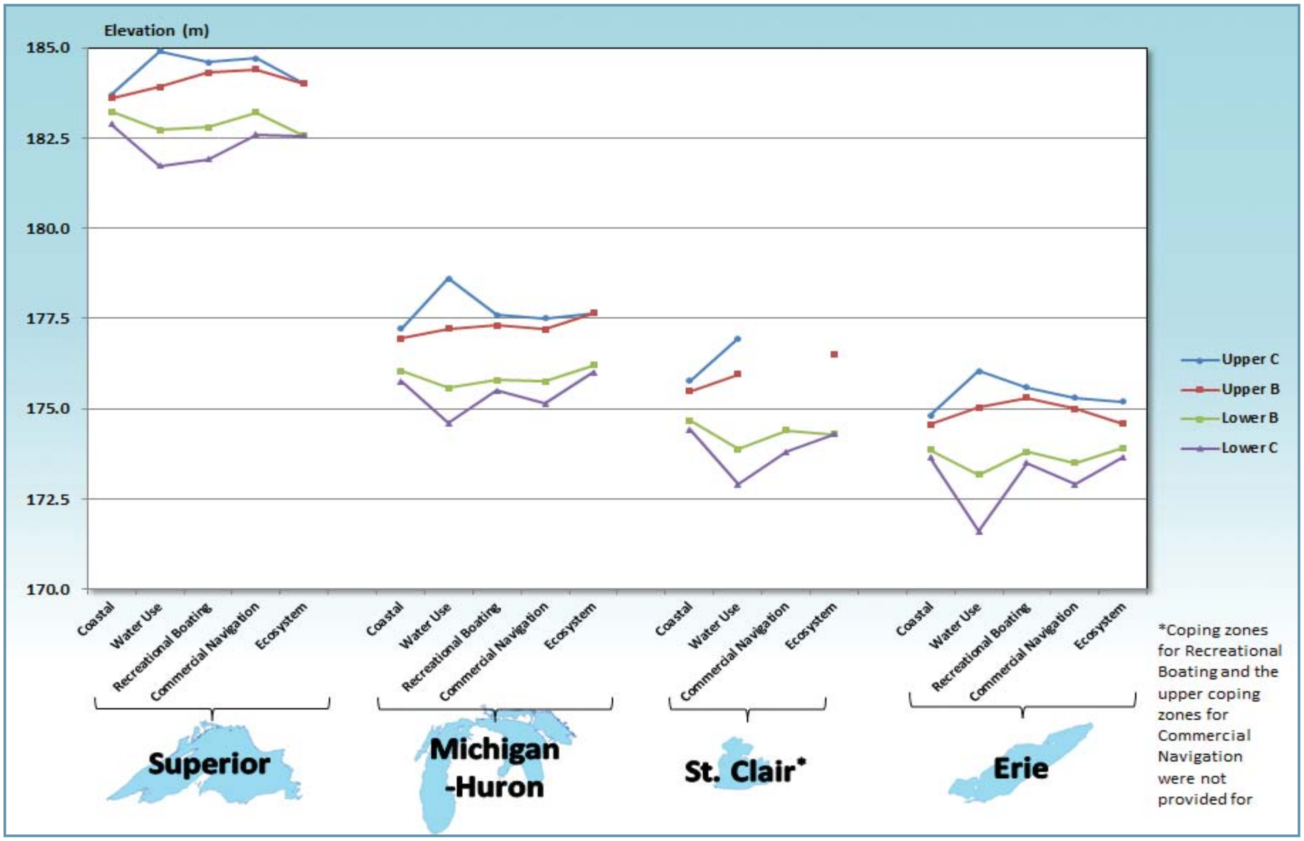

Figure 9-4 ***Lake Coping Zone Definitions by Sector***

Coping zone by interest and by lake, for lakes Superior, Michigan-Huron, St. Clair and Erie.

*Note: Ecosystem zones are only surpassed if combined with a consecutive sequence (*e.g.*, above or below a mean level during the growing season for five or more consecutive years) (DePinto,* et al.*, 2011).*

The thresholds recognize that persistent conditions at or near the zone thresholds could lead to long-term damage within any one interest.

2. Developing Risk Scenarios and Defining Plausibility of Risks

As described in **Chapter 4**, the Study developed a series of possible future water supply scenarios, using a variety of techniques. The objective was to assess the range of possible future water supply scenarios to which a regulation plan might be exposed and assess whether a candidate plan could perform adequately under those conditions.

Study researchers developed a model to estimate the frequency of negative impact occurrences as a function of changes in climate, using the coping zones to define *negative impacts* (Brown *et al.*, 2012). Given that it was not possible to estimate probabilities of future climate conditions, the researchers instead developed subjective probabilities of future climate states, based on a compilation of climate information. These subjective probabilities were termed *plausibilities* and were used for sensitivity analysis in place of formally evaluating risk.

The analysis began with a "hazard discovery," an exploration of the stochastic[3] simulation to identify problematic climate conditions (*i.e.*, the climate conditions that resulted in unacceptable impacts as defined by the coping zones). A model developed by the Study estimated the number of coping zone occurrences for a given regulation plan and climate condition. For this analysis, climate was defined using a 30-year estimate of mean net basin supplies[4] (NBS) to represent mean climate, and the standard deviation of NBS and serial correlation of NBS were used to represent climate variability. Thus for any climate change, and regulation plan, the impacts could be directly estimated based on the changes in those three statistics. Finally, the

3 *Stochastic* – Statistics involving or showing random behaviour. In a stochastic simulation, a model is used to create a new 'synthetic' series of plausible flows and lake levels, based on historical data. The synthetic series will, on average, preserve important properties of the historical record, such as the mean and standard deviation, while generating new combinations of high and low flow conditions that could represent more severe conditions than those seen in the past.

4 Net basin supply (NBS) is the net amount of water entering a lake, consisting of the precipitation onto the lake minus evaporation from the lake, plus groundwater and runoff from its local basin, but not including inflow from an upstream lake.

impacts of any NBS future scenario for a given regulation plan could be estimated using the model by calculating the three statistics from that particular source.

With the future positive or negative impacts estimated for each alternative regulation plan from each separate source of future NBS, the plausibility of those impacts could be estimated. In this application, the plausibility serves as a risk prioritization or weighting scheme for risks. The plausibility concept is based on the premise that the more sources of climate information (*e.g.*, paleo-, GCMs, stochastic, trends) that indicate impacts are probable, the greater the consideration that impact should be given in the overall determination of which plan is the 'best' or most robust for the given range of conditions. This process also helps identify the limitations of the regulation plans in addressing plausible risk. At the same time, events that are highly unlikely, but that could result in relatively large adverse impacts in any future scenario, should not be ignored, given that plausible risks only outline a range of irreducible uncertainty but not necessarily the entire range of uncertainty.

General guidelines were developed for estimating plausible risk. The guidelines were that if the impact is: *likely in multiple futures*, then it is considered a high risk and should be addressed; *likely in a single future*, then consider the source before addressing; and, *unlikely in any future, but severe if it occurred*, then it would make sense to consider contingency planning.

In the historical 109-year record for the coastal zone interest, there were six occurrences of low water level Zone Cs and five occurrences of high water level Zone Cs. Figure 9-5 shows an example of the plausibility estimates for Lake Michigan-Huron of the climate conditions that would cause coastal riparian Zone C occurrences to *double relative to the historical number of occurrences* (1900-2008) (*i.e.*, the probability of twice as many Zone Cs as in the historical record, as estimated from each of the climate information sources).

Overall, the Study's analysis of risk plausibility indicated that extremes (both high and low) outside of the historical record are plausible, with far greater frequency of Zone C incursions arising from extreme low level conditions. The Study's analysis suggests that the magnitude and timing of these risks are highly uncertain and that plausibility estimates for the individual lakes vary widely. While the increased risk of Zone C incursions associated with low levels on Lake Michigan-Huron stand out as more plausible, as shown in Figure 9-5, impacts due to high lake levels should not be ignored, given that the occurrence of such levels cannot be ruled out and that the magnitude of socio-economic impacts may be greater for high lake levels.

For a more complete discussion of the modelling of risk plausibilities and the results for each interest in each of the upper Great Lakes, see the report of the Adaptive Management TWG (IUGLS, 2012a).

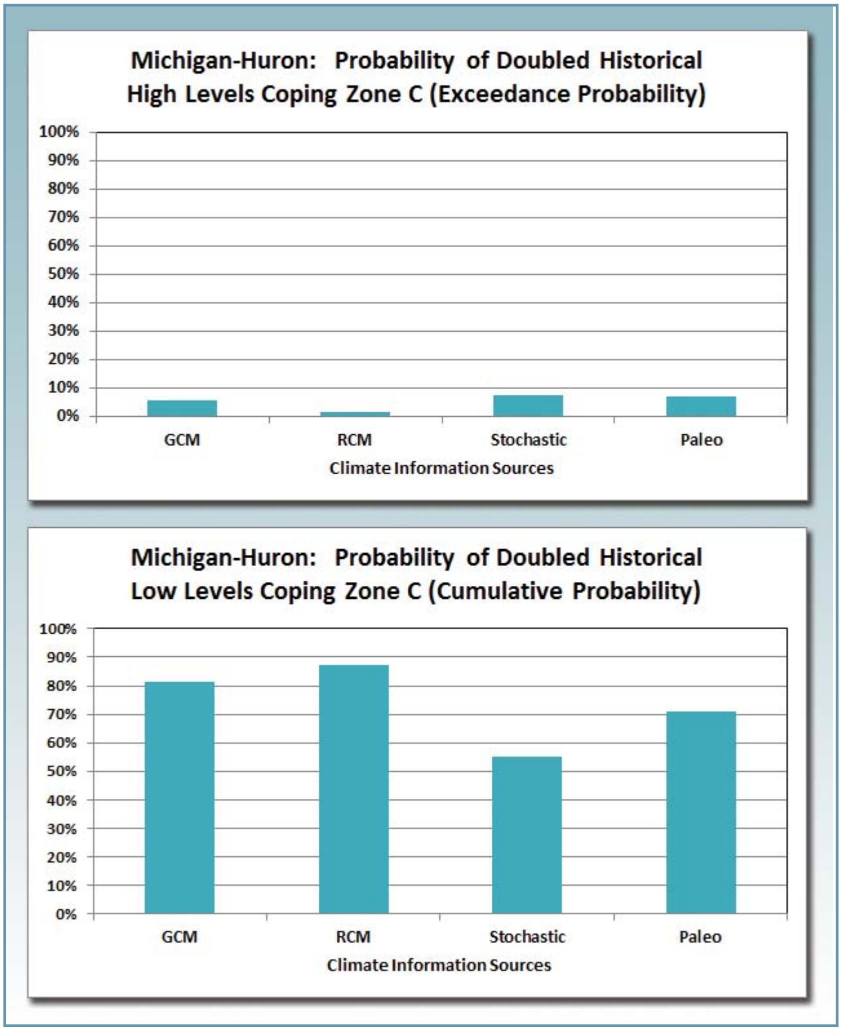

Figure 9-5 Example of Plausibility Estimates for High and Low Water Level Zone C Occurrences for Lake Michigan-Huron

*(based on the Coastal Zone interest threshold under existing regulation plan **1977A**)*

*Note: GCM: Global Climate Models; RCM: Regional Climate Models. See **Chapter 4** for a detailed discussion of the different climate information sources.*

3. Developing Lake Superior Regulation Strategies to Address the Risks

Regulation using the existing control structures on the St. Marys River has limited capacity to reduce extremes, particularly downstream of Lake Superior. As described in **Chapter 6**, the evaluation of alternative regulation plans, and in particular a series of "fencepost plans" that tested the limits of regulation under a series of extreme water supply conditions, revealed that none of the regulation plans reviewed could influence the water levels of Lake Michigan-Huron by more than a few centimetres without exacerbating the historical extreme lake level conditions on Lake Superior. Thus, any Lake Superior regulation plan will have limited ability to moderate lake levels, most notably extremes in the downstream lakes.

While water level regulation plans can do little to minimize risk downstream of Lake Superior, the analysis does indicate that some additional work is warranted on testing the regulation plans under extreme conditions (outside the historical range) to see if adjustments under these conditions could be made in time to improve plan performance for Lake Superior without harm downstream. Study analyses have shown that improvements in short to mid-term NBS and lake level forecasting could improve regulation plan performance on Lake Superior without harm downstream (Brown and Moody, 2011). Tests using the stochastic supplies showed that to reduce the highest levels of Lake Superior to the preferred limit of 183.86 m (603 ft), releases would have to be increased from the normal plan releases to the maximum possible release from 12 to 18 months prior to the peak. For every rare occasion the larger releases would be useful, there would be many more when the high levels would resolve themselves and the decision to make maximum releases would be seen as having caused unnecessary damage downstream. Forecasting this prescient will not happen in the foreseeable future; until it does, regulation will not be effective in avoiding record high Lake Superior levels. Regulation was found to help mitigate the lowest Lake Superior levels, however, because doing so did not require near perfect long-term forecasting. (IUGLS 2012b).

4. Evaluating New Water Level Control Structures

As described in **Chapters 7 and 8**, the Study investigated the potential for addressing future water level conditions in the upper Great Lakes basin through additional structures, by means of restoration-type structures in the St. Clair River and additional multi-lake regulation in the Great Lakes-St. Lawrence River system.

The analysis found that new structures for restoration would generate a mix of benefits and adverse impacts for various sectors and locations. For example, higher water levels from these structures likely would benefit commercial navigation in the lakes, as well as shoreline property and wetlands in Georgian Bay, but adversely impact hydroelectric generation and shoreline property and wetlands along Lake St. Clair and Lake Erie. The analysis also concluded that multi-lake regulation can help mitigate but cannot fully eliminate risk of water level extremes outside the historical range. In addition, restoration structures and multi-lake regulation would be costly and would require many years to review, approve and construct.

5. Reviewing the Potential for other Adaptive Measures

Successful implementation of adaptive management is dependent upon the ability of institutions and agencies to be adaptive themselves. Institutional adaptations can range from modest efforts (*e.g.*, new collaborative arrangements, establishing new priorities, exercising unused authorities, redirecting or seeking additional funding) to more ambitious efforts (*e.g.*, securing new legislative or regulatory authority, establishing a new international agreement and/or institution, establishing/ funding major new monitoring and modelling programs).

An institutional analysis undertaken by the Study on implementing non-regulation adaptive response to water levels found that the legal, regulatory and programmatic "institutional infrastructure" varies considerably from one jurisdiction to the next (Donahue, 2011). Federal, state and provincial governments generally provide the policy and regulatory framework, while site-specific selection and application of adaptive risk management measures is generally a local government responsibility. Efforts to coordinate approaches and promote consistency across jurisdictions have been limited. The primary focus of the existing "infrastructure" is on accommodating seasonal lake level fluctuations and the occasional extreme high and low water event. Little focus to date has been placed on long-term implications of climate change-induced impacts and the associated need for new adaptive risk management measures.

Integrated coastal management strategies at the local and regional level are an effective means for identifying important vulnerabilities and possible solutions. Better coordinated data and information related to hydroclimate and climate change is required by coastal zone managers and decision makers to identify and advance means to induce and promote adaptive actions. Applying adaptive actions, in turn, implies a commitment to monitoring, modelling, observing changes and regularly evaluating strategies to manage resources in light of uncertainty and new conditions.

Finally, information and education are powerful components of adaptive management. They contribute to both anticipating and preventing lake level-induced damage, particularly when focused on understanding risk, the limits of regulation, inherent uncertainties and system vulnerability.

9.2 Elements of an Adaptive Management Strategy for Addressing Extreme Water Levels

Long-term policies that ignore uncertainty tend to, over time, lead to unsatisfactory outcomes (Granger *et al.*, 1990). As noted above, the Study Board concluded that it may not be possible to design a regulation plan for Lake Superior outflows that is optimal for all future conditions and the various interests potentially impacted, particularly given the dynamic nature of the Great Lakes system and the uncertainties created by climate change. In addition, regulation of Lake Superior outflows alone can do little to reduce risks downstream of Lake Superior. Managing potential risks under an uncertain future is a challenge both for managers of water levels and flows and for those adapting to water levels and flows. The more they can anticipate what to expect, the better prepared they can be.

Regardless of the Lake Superior regulation plan adopted by the IJC, ongoing efforts for monitoring, modelling and research will be required to continue to assess risk, address uncertainties and changing conditions and identify appropriate adaptive actions. The Study identified the following six core elements of an adaptive management strategy to address future water level extremes in the upper Great Lakes basin (Figure 9-6):

1. **bi-national Great Lakes hydroclimatic monitoring and modelling;**
2. **ongoing risk assessment;**

Figure 9-6 ***Elements of an Adaptive Management Strategy***

3. **information management and outreach;**
4. **tools and processes for decision makers to evaluate their actions;**
5. **a collaborative regional Great Lakes-St. Lawrence River system adaptive management study for dealing with water level extremes; and,**
6. **integration of water quality and quantity modelling and activities.**

This section explores each of these core elements in more detail. It is important to note that the six elements are common to other Great Lakes initiatives (e.g., the Great Lakes Water Quality Agreement [GLWQA]) that are also considering adaptive management in light of climate change. In addition, as outlined below, administration of these six core elements would require a modified governance structure.

9.2.1 Bi-national Great Lakes Hydroclimatic Monitoring and Modelling

1. Monitoring and Modelling Priorities

The Study identified specific needs and priorities for hydroclimatic monitoring and modelling to improve decision making by reducing uncertainties in the various components of the Great Lakes water budget. These uncertainties exist due to inadequate spatial coverage of monitoring networks, inconsistent data gathering methodologies, temporal data gaps or insufficiently long records, failure to seamlessly present data from different networks and incomplete use of new or emerging technology.

The following were identified as priority needs over the near-term (five years).

(i) Improved Measurement of Component NBS

Precipitation: The first priority should be the introduction of a metadata[5] management system for Great Lakes precipitation gauges, which would improve the usability of currently monitored data and any additional data collected in the future. An improved monitoring network is also needed, including an expanded gauge network in northern Ontario and an improved network of snow accumulation gauges.

5 Metadata: Data (information) about the characteristics of data such as content, quality, date of capture, user access restrictions and ownership.

Overlake evaporation: Under the Study, the first eddy covariance gauges were installed to measure overlake evaporation on the Great Lakes, with two stations, one each on lakes Superior and Michigan-Huron. The station located at Stannard Rock on Lake Superior has proven to be of particular value in reducing uncertainty in modelled evaporation estimates. The Study has provided funding to establish these gauges and operate them for several years. The Study is in the process of funding an additional two gauges in the near-term, one on Lake Michigan and another on Lake Erie. These gauges will aid in future event-based monitoring of winter storm events on these lakes, which was also identified as a key task for reducing uncertainty in the measurement and modelling of overlake evaporation and precipitation.

Runoff: Multiple methods and estimates of Great Lakes runoff are now available through various agencies, partly as a result of the work of the Study. About a third of the drainage area into the Great Lakes is not gauged, and the United States Geological Survey (USGS) estimates the uncertainty in total runoff basin-wide is now between 15 and 35 percent. A comprehensive evaluation and coordination of Great Lakes runoff estimates is a priority. Estimates of runoff would benefit from an improved and possibly expanded streamflow network. The first step for achieving this should be a comprehensive streamflow gauge network evaluation.

(ii) Improved Measurement of Residual NBS

Change in lake storage/volume: Thermal expansion and contraction of lake volume is not accounted for in estimates of residual NBS, resulting in a seasonal, systematic error in these estimates. Therefore, a priority must be the investigation of the use of hydrodynamic/thermodynamic lake models and other means of estimating thermal expansion and contraction.

Connecting channel flows: The Study implemented new index velocity flow gauges on the St. Marys, St. Clair and Detroit rivers. These gauges provide a more accurate means of measuring flow in the connecting channels. This approach is expected to be more effective than current methods, particularly during less than ideal monitoring conditions, such as when flows are affected by ice. Therefore, ongoing maintenance of these gauges is a high priority. Furthermore, the first part of the Study, on the St. Clair River, demonstrated the importance of ongoing monitoring of channel conveyance through data collection and analysis (IUGLS, 2009). Given the uncertainty in the causes of conveyance changes in the St. Clair River, ongoing monitoring of connecting channel conveyance capacity is considered a top priority. The first step will be developing a sustainable framework for continuous conveyance monitoring, which should include a combination of frequent analysis of hydrometric data and hydrodynamic modelling, and periodic bathymetric surveys that follow established protocols to ensure the collection of accurate data. Additionally, further investigations into the cause of conveyance changes observed are necessary, and it is proposed that a study of ship-induced hydrodynamics be pursued to investigate the possible impact of commercial ships on bed morphology.

(iii) Integration of Great Lakes Water Balance Estimates

Ongoing maintenance of and improvements to Great Lakes basin hydroclimatic models will lead to improved water balance estimates and insight into closure of the water budget. Closure of the water budget requires that all the inflows and outflows across defined spatial and temporal boundaries, as well as the change in storage within those boundaries, equate to zero. However, there are inherent uncertainties and biases in Great Lakes water balance estimates as a result of imperfect information on the different components being estimated. Uncertainty results from a number of factors, including: data accuracy limitations and limited spatial/temporal coverage of monitored data; incomplete knowledge of the true physical processes being observed; the need to represent complex physical systems with simplified models; and, natural variability and randomness. A study focused on reconciling water balance estimates over all lakes simultaneously through application of an integrated state-space model will allow for assessing uncertainty and tracking changes and systematic differences in water balance components on an ongoing basis. This is a priority for reducing uncertainty across the entire basin.

Improvements in these areas will help lead to the elimination of bias in NBS estimates, and considerably reduce uncertainty in each of the components of the Great Lakes water balance. This in turn will allow greater accuracy in balancing Lake Superior and Lake Michigan-Huron water levels through the regulation plan and will help distinguish incipient climate change effects from errors in the data, allowing an earlier response to such effects.

2. Improved NBS Forecasting

With greater certainty in the Great Lakes components of NBS, improvements can be made to NBS forecasting both in the short-term (two to four weeks) and mid-term (six to 18 months). Study findings indicated that improvements in forecasting could help improve regulation plan performance if accurate forecasts are developed and utilized as part of the regulation plan (Brown and Moody, 2011). In addition, efforts through the Lake Ontario-St. Lawrence River Study (LOSLR, 2006) indicated that the greatest potential benefit appears to be for forecasting Lake Ontario outflows about six months in advance. This should be identified as a priority for NBS forecasting research. Reductions in the uncertainty of the components of NBS through improved hydroclimatic monitoring and modelling will help improve forecasting capabilities, making further research in this area more productive.

It is proposed to improve both Environment Canada's Modélisation Environnementale Couplé: Surface et Hydrologie (MESH) modelling system currently under development and the Great Lakes Advanced Hydrologic Prediction System (AHPS) system of the National Oceanic and Atmospheric Administration (NOAA). The latter model has been in use for nearly 20 years. The AHPS system was recently evaluated (Gronewold *et al.*, 2011) and is targeted for a series of critical improvements. This system is currently used by the United States Army Corps of Engineers (USACE) in an operational forecasting framework. It is proposed that the MESH system be coordinated with AHPS and other tools to improve daily ensemble forecasts.

3. Improved Climate Change Prediction for the Great Lakes Basin

The analysis in **Chapter 4** indicated that while some impacts of climate change are evident in the Great Lakes Basin (increased temperature, and wind speeds), there is uncertainty associated with regional projections of climate into the future, particularly with respect to precipitation patterns. The Study's analysis of future climate change scenarios found that while low water extremes appear to be more likely, high water level extremes over the coming century are also plausible and should not be dismissed. Decision making for addressing these potential risks into the future needs to be informed by improved science and outputs from GCMs and RCMs, better attribution of observed trends in climate, as well as improved understanding of the extent of current and future climate related risks.

9.2.2 Ongoing Risk Assessment

1. Tracking Key Performance Indicators

As outlined in section 9.1.1, one of the major purposes for adaptive management is to verify, through ongoing monitoring and assessment, that a particular management decision is achieving its intended results and to determine whether any modification is needed. Based on plan formulation and evaluation efforts outlined in **Chapter 6**, the Study identified few performance indicators that would be greatly improved or degraded as a result of a new regulation plan. This suggests that minimal follow-up of performance indicators will be required in the near-term, though ongoing assessment of emerging issues and changes in vulnerabilities to water levels may identify additional performance indicators over the longer term.

As an initial priority, follow-up analysis will be needed to assess the implications of the new regulation plan on just a few performance indicators isolated to the St. Marys River area. The St. Marys River provides critically important wetland, fish spawning, and nursery habitat for many species in the upper Great Lakes. The Study developed ecological criteria to identify flows and water level regimes that will adversely affect or enhance the St. Marys River ecosystem. During the development of these criteria, considerable effort was made to protect or enhance vulnerable habitat areas and species, including vulnerable lake sturgeon spawning habitat.

Opportunities have been identified to improve the St. Marys River ecosystem by manipulating flows and implementing operational changes at the compensating works and/or the St. Marys River hydropower plants. In addition, concerns have been raised regarding the stability of the St. Marys compensating works under rare, though possible, high water levels. These issues require follow-up monitoring and analyses on behalf of the International Lake Superior Board of Control, as follows:

- Approximately 90 percent of the sea lamprey in the upper Great Lakes spawn in the St. Marys River. Based on data collected by the Great Lakes Fishery Commission (GLFC), sea lamprey are attracted to high flow. Operational changes at the hydropower plants may increase trapping efficiencies (thus eliminating more sea lamprey) and allow GLFC control agents to better assess the number and distribution of sea lamprey in the rapids and St. Marys River. If changes to the flow are successful in improving trapping efficiencies, then ongoing assessment and monitoring would be required to develop changes in the flow operation.
- Significant environmental benefits may result from operational changes at the compensating works. By slowing the rate of water level change to less than 10 cm (about 4 in) per hour, flushing and dewatering effects in the St. Marys River rapids are minimized, thereby enhancing fish production within the rapids. These changes, however, would have planning and timing implications for the hydropower companies. Therefore, follow-up monitoring would be required to ensure that the operational changes were having the intended results.
- The St. Marys River is a critical spawning area for a genetically distinct population of lake sturgeon.[6] Lake sturgeon mature at about 20 years and the females reproduce every four to nine years. Lake sturgeon spawning is very sensitive to habitat conditions. Studies indicate that periodically flows need to exceed 1,700 m^3/s (about 60,000 ft^3/s) in June to flush the substrate. This flow will be accommodated through operational adjustments to the outflows under the new regulation

6 As discussed in Chapter 7, the St. Clair River is primary spawning habitat for another population of lake sturgeon.

plan. Follow-up monitoring and verification of the flow requirements would be needed over time to verify results, with the information fed back into regulation decision process as part of an adaptive management effort.

- A 1987 IJC task force study on high water levels in the Great Lakes basin concluded that Lake Superior water levels should not be raised above 184.1 m (603.8 ft) above sea level without a detailed study to identify any necessary modifications to the compensating works on the St. Marys River (Great Lakes Water Levels Task Force, 1987). Through the Study's analyses of multiple future scenarios, it has been determined that, while rare, there is the potential risk for water levels to exceed this level under all the regulation plan options evaluated. Therefore, a preliminary stability analysis of the compensating works was performed as part of the Study, but a more detailed assessment should be done as part of the adaptive management process.

This work should be coordinated with any additional tracking of performance indicators as part of the Lake Ontario-St. Lawrence River effort.

2. Tracking Changes in Vulnerability

Changes to the physical characteristics of the Great Lakes system, from both natural processes and human activities, are expected to continue in the future. These changes can be large scale, such as the impact of GIA, or small scale, such as the building of a shore protection structure in front of a single property. However, these changes cumulatively can influence the vulnerability of interests to fluctuating water levels and flows. Tracking changes in the vulnerability of interests over time is important to understanding potential water level risk. The following were identified as priority needs over the near-term:

(i) GIA Monitoring

Ongoing monitoring of GIA effects, through the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD), is needed to gauge the extent to which the land is adjusting and to inform future changes in vulnerabilities that may result. There is a need to ensure that data and information on GIA are incorporated into hydrological and shoreline models. From a regional perspective, GIA can exacerbate the adverse anticipated impacts of global warming-related lake level changes for specific areas, such as Georgian Bay (where the land is rising relative to the lake's outlet) or Duluth, MN (where the land is subsiding relative to the lake's outlet).

(ii) Monitoring and Modelling Nearshore Processes

Tracking natural erosion and depositional processes is important at more regional and local scales to help inform local decisions and better understand vulnerabilities. Improved understanding and modelling of shoreline processes will need accurate nearshore bathymetric data and shoreline profile data over a number of years to investigate how systems respond to changes in water level conditions.

A related priority is monitoring changes in ice conditions as well as storm patterns and wind direction to track trends and assess implications to shoreline vulnerabilities as well as linkages between nearshore processes and water quality.

(iii) Tracking Shoreline Modifications and Wetland/Ecosystem Changes

There is a need to undertake a comprehensive and coordinated approach to tracking shoreline modifications in the Great Lakes basin as they affect vulnerabilities. Related monitoring measures include:

- recording permit applications for shoreline modification (*e.g.*, dredging, dock extensions);
- documenting land use changes around particular sites to assess whether encroachment is likely to impact vulnerabilities to shoreline property and ecosystems;
- monitoring reported shoreline damages, to provide a context for the overall assessment of water-related damages in the basin;
- tracking changes in wetlands and ecosystems to monitor changes in the type and extent of various ecosystems; and,
- linking nearshore process models with water quality monitoring and modelling.

Initially, these items could be addressed on a site-specific basis as proposed below in section 9.2.5.

9.2.3 Information Management and Outreach

Information collected and generated by the Study, as well as ongoing hydroclimatic monitoring and modelling afterward will support coastal zone management efforts. This information is also highly relevant to other Great Lakes initiatives such as the GLWQA and the Great Lakes-St. Lawrence River Basin Sustainable Water Resource Agreement.[7] As well, the ongoing hydroclimatic monitoring, modelling and data management systems of different agencies can be utilized to inform the learning culture that is needed to support coastal zone management and other Great Lakes resource management programs.

At present, there are numerous agencies involved in generating hydroclimatic information, with different though occasionally overlapping roles. These agencies include: NOAA, USACE, the USGS, Environment Canada, Fisheries and Oceans Canada, Natural Resources Canada, state and provincial

7 For information on the Great Lakes Water Quality Agreement, see: www.ijc.org/en/activities/consultations/glwqa/agreement.php

For information on the Sustainable Water Resource Agreement, see the website of the Council of Great Lakes Governors: www.cglg.org/projects/water/CompactImplementation.asp resource management agencies, local and regional non-government agencies, conservation authorities, the private sector and academia. In the absence of a bi-national study, Great Lakes hydroclimatic information management is agency-based and generally not driven by the needs of resource managers and decision makers. Coordination and oversight is required to develop an effective and efficient means of compiling, vetting, coordinating and distributing hydroclimatic data and information to those who need it.

Effective management and distribution of hydroclimatic information will require information management infrastructure. Distribution also may need data sharing agreements and staff support from partner agencies. The organization responsible for distributing the information should have formal status under the IJC or be supported by the two federal governments to give it the necessary authority and a reporting structure. Funding of this group would also be required. Coastal zone managers and regulatory agencies would need to take steps to incorporate the information into their decision-making processes. In addition, outreach would be required to ensure that the information is trusted, easy to use and access, meeting the needs of the target audience, and providing a coordinated and clear message.

The proposed effort could build on existing initiatives such as the efforts that are underway by NOAA and the Great Lakes Observing System to develop portals to Great Lakes hydroclimatic information.

9.2.4 Tools and Processes for Decision Makers to Evaluate their Actions

As outlined in Chapter 6, the Study sought to develop as robust a regulation plan as possible by testing options under a wide variety of possible water supply scenarios. However, the future remains unknown. The recommended plan, however robust, may not be resilient under all possible future conditions. As a result, ensuring the continued maintenance of the tools and processes for monitoring plan performance and making necessary changes into the future are important to an adaptive management process.

1. Maintenance and Updating of Evaluation and Modelling Tools

A number of evaluation tools were developed in the Study to support plan evaluation and ranking that are critical to assessing the effectiveness of any given regulation plan. These tools should be maintained and updated or replaced as new information and knowledge are acquired and as software and hardware are improved. The tools include:

- Shared Vision Model (SVM);
- Structures analysis tool (for shore protection);
- Integrated Ecological Response Model 2 (IERM2) for the upper Great Lakes;
- Multi-lake optimization modelling tool;
- Great Lakes Navigation Model (GL-SAND);
- IJC Flooding Sites Excel Tool; and,
- Low water impact analysis tool.

All of these models were developed by outside experts under contract to the Study. To support the ongoing use and updating of these tools, full documentation (*e.g.*, manuals, process flow diagrams, data specifications, sample data bases) is required, particularly for the SVM and IERM2. Training for United States and Canadian agency staff is necessary so that they could apply, update, revise and continue to expand on and improve these tools. Integration of these tools with similar tools developed for the management of the Lake Ontario-St. Lawrence River system will permit system-wide analyses that will be of particular importance in future climate change analyses.

2. Incorporating Adaptive Management into a New Regulation Plan

There are questions as to how an adaptive management plan can be incorporated into a new regulation plan. Any new objective for Lake Superior regulation to achieve a different purpose from that approved by the IJC in the 1914 Orders would require new authorities from the two national governments. This was the procedure followed with respect to the adoption of the principle of systematic regulation and a change to the Lake Superior regulation plan to implement the **1977A** plan. This change in regulation had been recommended by the International Great Lakes Levels Board in its report to the IJC in 1973 (International Great Lakes Levels Board, 1973). This recommendation was reviewed by the IJC, along with comments received at public hearings. The IJC subsequently forwarded this recommendation in its report to the governments in 1976 and in 1979 issued a Supplementary Order that adopted the objective of systematic regulation and changed the way Lake Superior's outflows are regulated (Brown, 2011).

The Orders of Approval should include a periodic review of the operating plan to adjust for changed conditions. The IJC has issued such a procedure in its 2001 letters approving peaking and ponding guidelines, which are subject to periodic review and approval by the IJC. Alternate contingent regulation objectives to address different future conditions such as climate change would be difficult to address through Supplementary Orders. However, it may be possible to provide greater flexibility in the Orders to allow for changing conditions. For example, decision protocols could be included to identify when and how to change the regulation plan (Brown, 2011). A decision protocol would have to be established for how information is reviewed, assessed and brought forward to the International Lake Superior Board of Control for its attention, and a determination made as to who can decide to change a regulation plan.

Proposed improvements to the monitoring and modelling of hydroclimatic factors would address the second purpose of an adaptive management plan – determining if the decision should be adjusted to address future conditions. Efforts will be required to understand when and if a change is necessary and what change should be made. Given that Lake Superior regulation is more effective in regulating Lake Superior levels and has a much smaller effect on levels below the St. Marys River, the most likely decisions relative to very high or very low levels will be whether to hold more or less water on Lake Superior. Past experience has shown that despite the inability to affect levels to any great degree on the lower lakes, public pressure will be to try to minimize adverse impacts to downstream interests because the great majority of Great Lakes residents live below Lake Superior. For example, during the record high 1985-1986 water levels, the IJC directed the International Lake Superior Board of Control to hold back water on Lake Superior to reduce Lake Michigan-Huron levels, even though Lake Superior was also very high and the hold back affected water levels on Lake Michigan-Huron by only a few centimetres.

It will be important to revisit the plan's objectives during extreme conditions to ensure the objectives for the plan are still appropriate under these conditions and to test the hypotheses that "it will be possible to improve future outcomes under extreme conditions." To that end, three scenario objectives should be tested as part of an adaptive management strategy: to compress Lake Superior levels; to compress Lake Michigan-Huron levels; and, to address an additional (*e.g.*,10 cm [about 4 in] drop) in Lake Michigan-Huron levels as a result of unforeseen increases in St. Clair River conveyance.

Critical impact thresholds could be established to isolate the problem water level regimes (including range, frequency, duration and rate of change). Next steps would then be to:

- relate these water level regimes to potential hydroclimatic indicators/triggers and/or socio-economic and environmental triggers;
- test plan adjustments under extreme conditions using perfect forecasting to formulate alternative plan rules to address extremes, then testing plans without perfect forecasting;
- link plan adjustments to hydroclimatic and/or impact triggers;
- clarify the limitations of regulation for addressing risks; and,
- establish an emergency contingency plan for addressing extreme levels.

9.2.5 A Collaborative Regional Adaptive Management Study

Integrated coastal zone management initiatives have been identified as a potential means of identifying and advancing methods to induce and promote adaptive actions on a regional scale. This implies a commitment to monitoring, modelling, observing changes, and regularly evaluating strategies to manage resources in light of uncertainty and new conditions.

A collaborative regional study of the feasibility and effectiveness of such a coastal zone management initiative to address specific local and regional vulnerabilities is a priority. Such a study would enable the identification of possible solutions and mechanisms for ongoing adaptive management to address changing conditions. The Study's work on climate change impacts under a wide variety of possible scenarios indicated that neither future high lake level scenarios, nor very low water level scenarios can be readily dismissed. The Study also showed that the current two-lake water regulation system is inadequate to deal with extreme climate scenarios. Hence, the Study Board recognized the need for an adaptive management study that builds on the work that the Study initiated at four specific areas (Duluth, MN, Chicago, IL, Lake St. Clair and Georgian Bay), and expand that analysis to additional sites for each of the lakes, downstream through the St. Lawrence River to Montreal, QC. This research should:

- critically assess vulnerabilities of the key interests and potential costs and benefits of lake level extremes;
- assess regional objectives and potential adaptive actions that could address specific issues and minimize risk;
- identify costs and specific institutional requirements for implementing such actions; and,
- establish the long-term adaptive management processes for ongoing assessment of any implemented actions including costs avoided by actions taken.

9.2.6 Promoting the Integration of Water Quality and Quantity Modelling and Activities

Great Lakes water quality is undeniably linked to water quantity. Climate change and its implications on the Great Lakes water balance will have implications for water quality. Water levels, water temperature, changes in storm activity and ice cover could all impact water quality, particularly in the nearshore. The linking of water quality and quantity models and nearshore processes is important to understanding these potential impacts. With the renegotiation of the GLWQA, the need for the integration of these two disciplines is more pertinent than ever. The implementing agencies for the GLWQA will be looking for coordinated hydroclimatic and climate change science for the Great Lakes basin.

The efforts proposed under this adaptive management strategy should be linked with those of the GLWQA to ensure a common understanding on the state of climate change science and the linking of nearshore water quality and quantity models where possible to support a greater understanding of the system's dynamics.

9.3 Application of an Adaptive Management Strategy for Addressing Future Water Level Extremes

The adaptive management strategy outlined above is intended to assist water level managers, coastal zone managers and others having to adapt to future extreme water levels. Through a structured, collaborative, iterative approach to improved monitoring, modelling and assessment, these decision makers can be better equipped to anticipate changing water levels and better prepared to respond. They will be able to implement, review, adjust and revise actions to address future extremes as new information and knowledge become available and/or as water level conditions change.

Adaptive management clearly requires a collaborative bi-national effort, as various components of the adaptive management strategy fall under jurisdictions and agencies in the United States and Canada. However, in the absence of an IJC Study, there is no formal coordination or bi-national responsibility for undertaking these efforts related to water levels and flows. No existing bi-national organization is responsible for overseeing an ongoing coordinated adaptive management effort in the Great Lakes basin.

The Study focused on the upper Great Lakes, reflecting the geographical influence of Lake Superior regulation. However, adaptive management should encompass the entire Great Lakes-St. Lawrence River system from Lake Superior down through Trois Rivière on the lower St. Lawrence River. There are important system-wide issues and linkages to be addressed, particularly associated with the impacts of climate change.

A successful adaptive management program requires a proper governance structure and funding mechanism to ensure its application and operation for the Great Lakes-St. Lawrence River system. This is particularly important for ensuring that the data and information generated through an adaptive management program are being properly utilized in the decision process for addressing future extreme water level and flow regimes.

9.3.1. A Great Lakes-St. Lawrence River Levels Advisory Board

Recognizing the importance of governance to the application and operation of an effective adaptive management strategy, the Study reviewed several options with respect to governance. The objective was to identify a governance mechanism that would have bi-national authority, would build on existing mandates and responsibilities, would be accepted by the Great Lakes-St. Lawrence River community, and would provide the ongoing support required to effectively administer and operate the adaptive management program. The options examined included:

- an adaptive management committee reporting directly to the International Lake Superior Board of Control;
- the expansion and formalizing of the existing CCGLBHHD; and,
- a new advisory board under the IJC responsible for implementing a Great Lakes-St. Lawrence River system perspective and responsible for administering the adaptive management strategy.

The third option, a new advisory board, was identified by the Study as the preferred approach in keeping with the objectives and given the restricted mandates and composition of the first two options.

A new advisory board could champion and coordinate and administer a bi-national basin-wide adaptive management strategy for the Great Lakes-St. Lawrence River system. The advisory board, tentatively named the *Great Lakes-St. Lawrence River Levels Advisory Board*, would report directly to the IJC. Building on and complementing existing institutions, the advisory board would coordinate with all the Boards of Control, the CCGLBHHD and other appropriate Great Lakes-St. Lawrence River institutions. It would be responsible for:

- coordinating, vetting and managing Great Lakes-St. Lawrence River hydroclimatic data and science;
- advising on required hydroclimatic monitoring and modelling needs to:
  - improve Great Lakes-St. Lawrence River water budget estimation;
  - recommend on observing system requirements;
  - support improved forecasting; and,
  - improve climate change prediction and track hydroclimatic triggers;
- ensuring distribution of water level and hydroclimatic information to users;
- maintaining and updating plan evaluation tools and monitoring critical performance indicators;
- supporting the periodic review of regulation plans;

- addressing special water level management related issues;
- undertaking outreach and education;
- promoting integration of water quantity and quality modeling and activities; and,
- considering alternative adaptive actions.

Membership of the advisory board should reflect that water management in Canada and the United States is a shared jurisdiction. Members could be drawn from federal, state and provincial governments, academia, non-government organizations, and the public.

The advisory board would be mandated to identify and work with the appropriate agencies in the United States and Canada to ensure that required monitoring and modelling needs are met to support improved short-term and long-term forecasting and climate change projections in support of all the IJC Boards. It would coordinate forecasting and climate change research for the Great Lakes-St. Lawrence River and be the primary authority for Great Lakes-St. Lawrence hydroclimatic data. Technical sub-groups could be established to coordinate necessary performance indicator monitoring and modelling in support of the adaptive management program. These sub-groups would maintain the tools necessary for ongoing assessment by the Boards of Control of their regulation plans and address other water management and science related questions that arise through governments or the IJC. They would also support information management and distribution for Great Lakes-St. Lawrence River hydroclimatic data and information, consult with the users of the data and information distribution system to ensure a direct link to the advisory board's activities, and integrate water quantity and water quality initiatives particularly related to the GLWQA.

Figure 9-7 illustrates the structure and key relationships of the proposed levels advisory board.

9.3.2. The Role of the IJC

The IJC has undertaken numerous water level studies over the past 50 years. These studies have generated considerable data and knowledge, and have helped inform governments on courses of action. However, there has been limited continuity between these studies. The data and information gathered for one study are not necessarily maintained for the next. Rather, the monitoring, data gathering, information management and data to decision protocols generally have been issue-specific and not designed for long-term continuity and decision making.

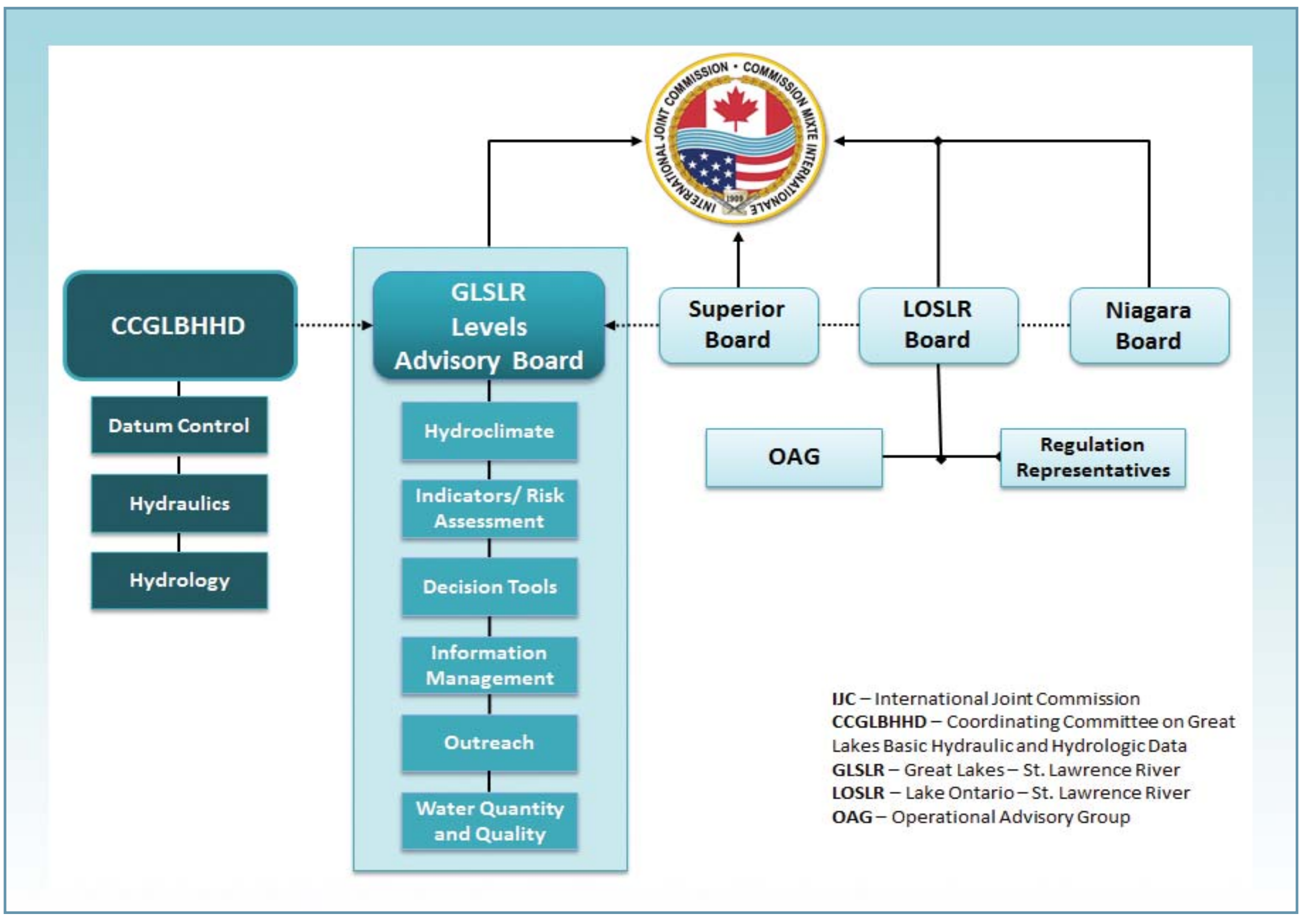

Figure 9-7 ***Governance Option for the Proposed Great Lakes-St Lawrence River Levels Advisory Board***

The IJC is working with governments to establish a new approach to managing the outflows of Lake Ontario while continuing to provide benefits to other interests in the Lake Ontario-St. Lawrence River system. An adaptive management program is being developed as an essential component of this new approach. Coordination between this effort and the Study's efforts on the upper Great Lakes would be a more effective use of resources and provide an overall coordinated program for the whole Great Lakes-St. Lawrence River system.

While the IJC has a Water Quality Advisory Board and a Science Advisory Board, it does not currently have a board to advise on Great Lakes-St. Lawrence River system-wide water quantity management issues. The IJC did have a Great Lakes Levels Advisory Board between 1979 and 1983 in concurrence with a 1977 Reference Letter from the Governments of Canada and the United States to the IJC (The Secretary of State for External Affairs Canada, 1977). However, the IJC disbanded the board in 1983 (IJC, 1984).

In the early 1990s, the IJC's Levels Reference Study recommended that a Great Lakes-St. Lawrence River Advisory Board be created to coordinate, review, and provide assistance to the IJC on issues relating to water levels and flows of the Great Lakes and St. Lawrence River (Levels Reference Study Board, 1993). However, the IJC did not act on this recommendation.

Such an advisory board is even more relevant today, given the uncertainties associated with climate change and the identified need for adaptive management. It could provide the oversight for administering an adaptive management program for the entire Great Lakes-St. Lawrence River system and provide coordination and guidance for all cross-over issues among the existing Boards of Control and the CCGLBHHD. Lessons can be learned from past attempts. It is apparent, for example, that a specific mandate with clearly identified roles and responsibilities for the advisory board and any sub-committees is a necessary requirement. The 1977 reference to the IJC from Governments, while dated, may provide the authority to the IJC to re-establish a water levels advisory board relatively easily.

9.3.3. Funding Considerations

A structured long-term adaptive management program aimed at minimizing the risks of adverse water level-related impacts through ongoing hydroclimatic monitoring and modelling and through protocols for informing the appropriate decision makers would be an effective mechanism of addressing future risks. In addition, the monitoring and modelling proposed by the Study would support other initiatives that must consider the implications of fluctuating water levels and uncertain future conditions in the Great Lakes, such as the GLWQA and the Great Lakes-St. Lawrence River Basin Sustainable Water Resources Agreement and state and provincial coastal zone management activities. The success of an adaptive management program will depend on the commitments of the IJC, federal and state/provincial governments in securing the necessary resources required to support the program. In the long run, a coordinated adaptive management program as outlined in this chapter could have considerable cost savings, and provide immeasurable benefits.

Initial cost estimates for the adaptive management program outlined here suggest an initial investment of five years at $1.5 to $2.5 million ($U.S.) a year, with ongoing requirements at a more reduced level. (For a detailed discussion of funding issues, see IUGLS [2012a].)

9.4 Key Points

With respect to the role of adaptive management in addressing future extreme water levels in the upper Great Lakes, the following points can be made:

- Adaptive management is a process of "learning while doing." It provides a structured, iterative approach for improving actions through long-term monitoring, modelling and assessment, so that decisions can be reviewed, adjusted and revised as new information and knowledge become available and/or as conditions change.
- The Study's approach to considering climate risk assessment was based on *decision-scaling*. The approach begins with stakeholders rather than climate models. It determines the domain of vulnerabilities and then assesses whether those conditions are plausible based on the available climate science. This was a valuable step in developing a long-term adaptive management strategy for addressing future risks.
- Adaptive management has an important role to play in addressing the risks of future changes in water levels in the upper Great Lakes. Lake Superior regulation on its own can do little to address risks of extreme lake levels downstream of Lake Superior. Nor can multi-lake regulation fully eliminate the risk of extreme lake levels outside the historical range. New structures in various parts of the Great Lakes Basin could take decades to implement and cost billions of dollars. Therefore, regardless of the Lake Superior regulation plan adopted by the IJC, ongoing monitoring and modelling efforts will be required to continue to assess risks and address uncertainties and changing conditions.
- Information and education are powerful components of adaptive management. They contribute to both anticipating and preventing lake level-induced damage, particularly when focused on understanding risk, the limits of regulation, inherent uncertainties and system vulnerability.

- The Study identified six core elements of an effective adaptive management strategy:
  - bi-national Great Lakes hydroclimatic monitoring and modelling;
  - ongoing risk assessment;
  - information management and outreach;
  - tools and processes for decision makers to evaluate their actions;
  - a collaborative regional adaptive management study for addressing water level extremes; and,
  - promotion of the integration of water quality and quantity modelling and activities.
- Application of a comprehensive adaptive management strategy would require a new approach to institutional involvement and coordination. Existing legal, regulatory and programmatic efforts related to adaptive management vary considerably from one jurisdiction to the next. Federal, state and provincial governments generally provide the policy and regulatory framework, while site-specific selection and application of adaptive risk management measures is largely a local government responsibility. To date, efforts to coordinate approaches and promote consistency across jurisdictions have been limited and generally have focused on accommodating seasonal lake level fluctuations and the occasional extreme high and low water events. Furthermore, little focus has been placed on long-term implications of climate change-induced impacts and the need for new adaptive risk management measures.
- No bi-national organization is currently responsible for overseeing an ongoing coordinated adaptive management effort in the Great Lakes basin. A 1977 reference to the IJC from Governments may provide the authority to the IJC to re-establish an adaptive management advisory board relatively easily. Lessons from past experiences should be identified and applied.
- Adaptive management to address future levels in the upper Great Lakes basin has direct relevance to several important initiatives in the Great Lakes-St. Lawrence River system, including:
  - adaptive management efforts in the Lake Ontario-St. Lawrence River part of the system;
  - the GLWQA; and,
  - the Great Lakes-St. Lawrence River Basin Sustainable Water Resource Agreement.

9.5 Recommendations

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

1. *An adaptive management strategy should be applied to address future extreme water levels in the Great Lakes-St. Lawrence River basin through six core initiatives:*
   - *strengthening hydroclimatic monitoring and modelling;*
   - *ongoing risk assessment;*
   - *ensuring more comprehensive information management and outreach;*
   - *improving tools and processes for decision makers to evaluate their actions;*
   - *establishing a collaborative regional adaptive management study for dealing with water level extremes; and,*
   - *promoting the integration of water quality and quantity modelling and activities.*
2. *The IJC should seek to establish a Great Lakes-St. Lawrence River Levels Advisory Board to champion and help administer the proposed adaptive management strategy for the entire Great Lakes-St. Lawrence River system.*
3. *The IJC should work with governments to pursue funding options and coordinate adaptive management efforts with the Lake Ontario-St. Lawrence River Working Group, the renewal of the Great Lakes Water Quality Agreement, and the implementation of the Great Lakes-St. Lawrence River Basin Sustainable Water Resource Agreement.*

Chapter 10

Public Engagement in the Study

Chapter 10 describes the public engagement activities undertaken during the Study and summarizes public concerns regarding Lake Superior regulation and other issues related to water levels in the upper Great Lakes.

10.1 Study's Approach to Public Engagement[1]

10.1.1 The Need for Public Engagement

Water levels in the Great Lakes affect millions of residents of Canada and the United States – from shoreline property owners, recreational boaters, marina operators and municipal governments, to major industries such as commercial navigation and energy producers relying on hydroelectric and thermal power plants. Water levels are also critically important to many wetlands and aquatic ecosystems in the Great Lakes, and are central to the lives of a number of Native American communities and First Nations.

All of these interests are rightly concerned about future water levels in the upper Great Lakes, particularly if those levels approach or exceed historical highs or lows. All have a legitimate right to be heard in any deliberations about plans to regulate those water levels.

Article XII of the *Boundary Waters Treat of 1909* requires that the public "be given a convenient opportunity to be heard."   This commitment to public engagement has been a hallmark of the work of the International Joint Commission (IJC) throughout the last 100 years. The views of the public play an important role in helping the IJC and its advisory bodies strengthen policy recommendations so as to increase the likelihood such recommendations will reflect public concerns and be understood, accepted and implemented.

1 This chapter is based, in part, on the final report of the Public Interest Advisory Group (PIAG) to the International Joint Commission (PIAG, 2012).

10.1.2 Public Interest Advisory Group

Reflecting the 1909 Treaty's commitment to public involvement and recognizing the many interests concerned with the future of water levels in the upper Great Lakes, the IJC appointed a bi-national Public Interest Advisory Group (PIAG) at the start of the International Upper Great Lakes Study (the Study). The mandate of the PIAG, as established in its Terms of Reference from the IJC (IJC, 2007), was to:

- provide advice to the Study Board relating to the planning and management of its public involvement and communications activities;
- provide advice to the Study Board on how to increase the effectiveness of its communications and information dissemination to the public;
- provide advice to the Study Board on issues related to the Study; and,
- carry out specific activities that the Study Board may request from time to time.

In appointing PIAG members (see **Annex**), the IJC drew from a wide range of groups with an interest in the Great Lakes, including those of shoreline property owners, boaters, anglers, governments, Native Americans, hydroelectric power producers, and environmental and shipping organizations. The group consisted of 20 members. The PIAG co-chairs, one each from Canada and the United States, served as members of the Study Board. Other members served as liaisons to the Study's technical work groups (TWGs) that addressed issues in which they had particular experience or interest.

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10.2 Public Engagement Activities

Throughout the course of the Study, the PIAG assisted the Study Board in developing and implementing a comprehensive public information and engagement program, using a range of media.

10.2.1 Study Progress Report

With the support and input of the PIAG, the Study Board issued a progress report on the Study in the summer of 2011. The report, *Addressing Future Water Levels on the Upper Great Lakes: Toward a New Regulation Plan*, was prepared to help build awareness of the Study and to notify interested members of the public of the upcoming public meetings (Figure 10-1).

The progress report:

- reviewed the Study's objectives;
- provided background on the challenges to developing a new Lake Superior regulation plan, such as the uncertainty in future water supplies arising from climate change and variability;
- described how the Study was applying a "shared vision" approach to balancing the many interests of water users in the upper Great Lakes basin;
- summarized how the Study was considering other approaches beyond Lake Superior regulation to address uncertainty in future water levels, such as levels restoration structures, multi-lake regulation and adaptive management; and,
- provided information on the upcoming public meetings scheduled for cities and towns throughout the upper Great Lakes.

The progress report was included as an insert in five newspapers in Canada and the United States with a total circulation of more than 100,000. It was also available online on the Study's website[2]. Additional copies were distributed at the public meetings.


Upper Great Lakes

Addressing Future Water Levels on the Upper Great Lakes:

Toward a New Regulation Plan

Summer 2011 | Progress Report: International Upper Great Lakes Study

contents

for more information

If you would like more information on the Study or want to provide comments on the Study's preliminary findings, please visit the Study web site at www.iugls.org, at www.facebook.com/iugls or twitter.com/IUGLS.

Highlights

In 2007, the International Joint Commission launched a five-year study to look at future water levels in the upper Great Lakes and the options for regulating those levels to support the region's economic and environmental interests. In the entire upper lakes basin, water levels are currently influenced through a regulation plan at the St. Marys River control structures at Sault Ste. Marie, where Lake Superior outflows have been regulated since 1914.

Over long periods of time, a regulation plan can generally affect the balance between Lake Superior and Lake Michigan-Huron (considered as one lake, since they are at the same water level). However, the ability to influence high and low water levels through regulation is severely limited by the natural variation in climate conditions, the risks that climate change could introduce more extreme conditions in the future, and the physical geography of the lakes and connecting channels. Moreover, the natural shifting of the earth's crust has serious implications for both water regulation and coastal interests.

There is a high degree of uncertainty about how climate change will affect future water levels over the next several decades. In response, the Study has undertaken the most comprehensive and balanced analysis ever made of climate change in the Great Lakes basin. The Study concludes that future water levels are likely to remain within a relatively small range around their long-term averages. While lower water levels in the future are likely, water users around the lakes have to be prepared for episodes of higher levels, too. Any new regulation plan, therefore, must be *robust* – effective and flexible enough to perform well in an uncertain future.

A new regulation plan also must recognize and balance the needs of the *key economic and environmental interests* in the upper Great Lakes. Some of these interests, such as recreational boating and ecosystems, were not specifically listed in the original 1909 treaty between Canada and the United States that established a co-management approach to boundary waters. The Study's *shared vision planning* exercise has allowed representatives of these key interests to provide information regarding their needs and preferences related to Great Lakes water management.

Given the limited ability to regulate the lakes, the Study also has looked at:

- the feasibility of building new control structures to either restore water levels on Lake Michigan-Huron to conditions that existed prior to channel modifications or regulate the entire Great Lakes-St. Lawrence River system; and,
- adaptive management measures, such as strengthened monitoring and information sharing, that can help water managers and property owners know what to expect in terms of changing water levels so that they can take action to reduce risks.

From the start, public involvement has been an important part of the Study. This summer, Study experts and members of a Public Interest Advisory Group will be holding a series of informational meetings to provide background information, present preliminary findings and invite public comments *(see schedule on page 4)*.

In the fall, the Study's management board will complete its evaluation of the regulation plan options, taking into account public input. The Study's final report will be submitted to the International Joint Commission by March 2012.

The International Joint Commission will conduct public hearings after the Study is completed and put forward a new regulation plan to the governments of Canada and the United States.

Pictured right: The St. Marys River, where outflows from Lake Superior have been regulated since 1914 under an International Joint Commission Orders of Approval. Today, the control structures consist of three hydropower plants and a gated dam at the head of the rapids known as the Compensating Works.

Progress Report: International Upper Great Lakes Study —Summer 2011 | www.iugls.org

Page 1 of 4

***Figure 10-1* Study Progress Report Cover**

10.2.2 Public Meetings

The Study Board, in conjunction with the PIAG, convened 12 public meetings around the Great Lakes basin during the summer of 2011 (Figure 10-2). Members of PIAG were involved in organizing, publicizing, and facilitating the meetings. The meetings were structured to present preliminary findings, respond to questions and receive public comments.

Study presentations addressed: the potential to improve the regulation plan for Lake Superior outflows at Sault Ste. Marie; the need for ongoing monitoring to allow for adaptive management; an exploratory analysis of restoration scenarios for Lake Michigan-Huron water levels; new information on potential climate change impacts for the Great Lakes; a discussion of the ongoing impacts of glacial isostatic adjustment (GIA); and, options for multi-lake regulation.

In addition to the 12 public meetings, Study Board and PIAG members participated in several meetings with specific interest groups in Michigan, Ohio and Ontario, including the Indigenous Water Forum in Sault Ste. Marie, ON.

More than 1,200 people attended the 2011 summer public meetings and additional interest group sessions.

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2 www.iugls.org

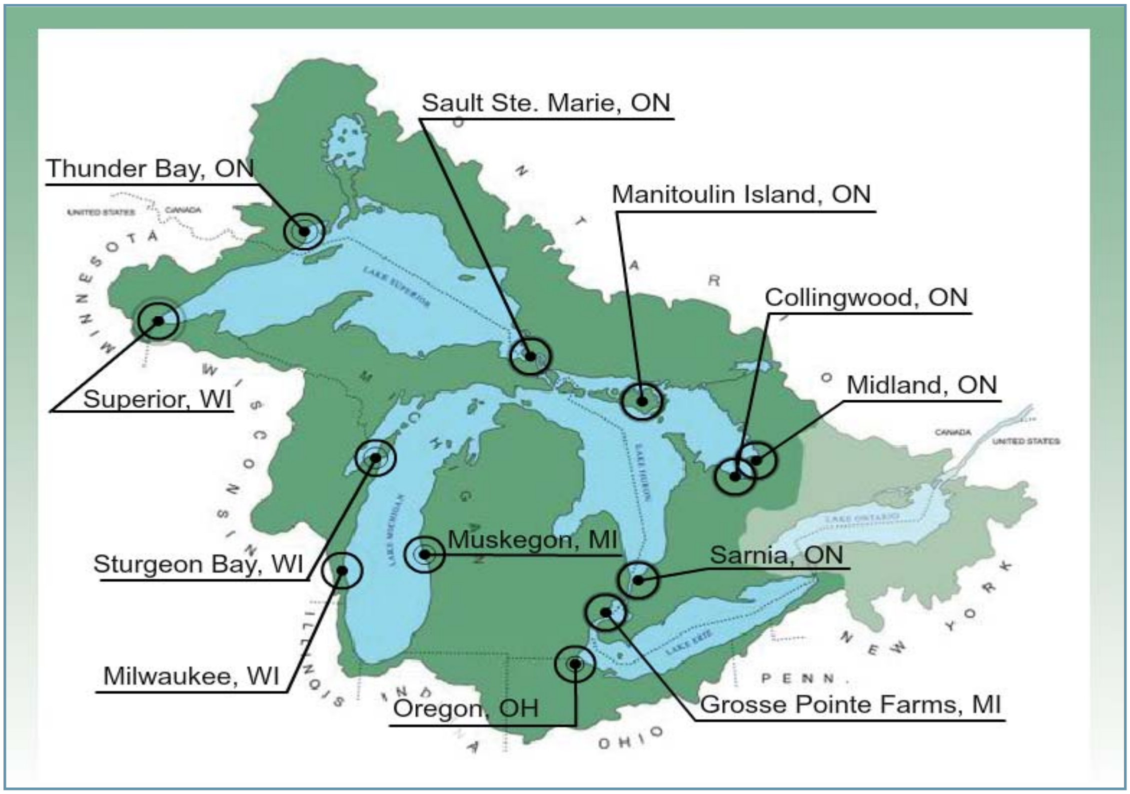

Figure 10-2 ***Location of Public Meetings***

10.2.3 Written Comments

In addition to comment cards available at the public meetings, the Study Board solicited written comments from the public during the summer of 2011, with opportunities to comment via an online form at the Study's website, by email and by traditional mail.

The Study received about 100 written comments from individuals and organizations. These included submissions from the Shipping Federation of Canada, Canadian Shipowners Association, Ducks Unlimited Canada, National Wildlife Federation, Georgian Bay Foundation/Georgian Bay Association, the International Great Lakes Coalition, the Alliance for the Great Lakes, and the Sierra Club of Ontario.

10.2.4 Social Media and Other Web-based Resources

The PIAG made extensive use of social media, including Facebook, Twitter and other web-based resources such as the Study's website, email lists, and Internet advertising. Based on advice from the PIAG, the Study Board established Facebook and Twitter accounts to expand the scope of the Study's communications efforts. These accounts helped build awareness of the Study and allowed the PIAG to forward regular updates on the Study's progress to interested parties. The Study's Facebook page provided information on meeting times and locations, public comment opportunities, and a copy of the Study's PowerPoint presentation given at the public meetings. The page had more than 900 followers by the time the public meetings were held in the summer of 2011.

The Study's website was also linked to Facebook, providing easy access to official Study news and outside reports on general Great Lakes issues. A Study Twitter page, created in September 2010, had nearly 500 followers by the end of 2011.

Five advertisements on Facebook targeted readers in Ohio, Wisconsin, Michigan and Ontario by various interests: shorelines; recreational boating and fishing; government; hydroelectric power; environment; commercial shipping; and, Native Americans and First Nations. The campaign brought in about 90 new followers to the Study's Facebook page, and resulted in more than 900 "hits" to pages that included information on specific meetings and the comment period.

10.3 Public Concerns and Priorities

The various public engagement activities helped the PIAG and Study Board gain a sound understanding of public concerns and attitudes regarding Lake Superior regulation and, more generally, issues relating to water levels in the upper Great Lakes.

10.3.1 Public Views on Lake Superior Regulation

There was general support among individuals and organizations participating in the public engagement initiatives for an improved regulation plan for the Lake Superior outflow. Those who commented on the existing regulation plan, **1977A**, believed that it had done a good job of balancing lake levels. Due to the minor changes expected to be achieved by a new regulation plan, the issue was not considered controversial and did not generate a large number of comments.

Among supporters of an updated regulation plan, there were numerous positive comments regarding improvements for fisheries and sea lamprey control on the St. Marys River. Concerns expressed in the Lake Superior basin about a possible new regulation plan included objections to using Lake Superior as a "holding pond" for the lower lakes, or draining too much from Lake Superior to feed downstream lakes.

10.3.2 Public Views on Lake Michigan-Huron Water Level Restoration

By far, the issue receiving the most public attention through the public engagement activities was the possible restoration of Lake Michigan-Huron levels to offset the effects of past dredging. Overall, the majority of comments received opposed water level restoration by means of new structures in the St. Clair River, though public views related strongly to geographical location.

Many individuals who attended public meetings in the Georgian Bay region of Ontario expressed support for restoring the water levels of Lake Michigan-Huron by means of the new structures. For example, Georgian Bay Association members expressed concern that important wetlands in Georgian Bay will be lost unless some form of water level restoration is achieved for that area (Figure 10-3). Some Georgian Bay residents also expressed doubts about the seriousness of negative effects of new structures in the upper St. Clair River on habitat for lake sturgeon and other fish species. In addition, some residents upstream of the St. Clair River expressed doubt that Lake St. Clair would be as severely impacted by water level restoration as suggested in the presentations. There was also some support for restoration from residents of Door County, WI.

Figure 10-3 ***Impacts of Changing Water Levels on Wetlands***

The Study concluded that restoration of Lake Michigan-Huron levels could help protect wetlands in the Georgian Bay region, upstream of the new structures, but at the cost of damaging fish habitat and wetlands downstream in the St. Clair River and Lake St. Clair.

In contrast, many individuals residing along the shorelines of Lake Michigan and the western and southern shorelines of Lake Huron expressed concerns about the impacts of higher water levels on shorelines. Some shoreline property owners in western Michigan said they did not understand why the IJC would consider raising lake levels to compensate for past dredging, as record-high water levels in 1986 occurred after dredging in 1962. In addition, individuals living downstream of the upper St. Clair River, including along Lake St. Clair and Lake Erie, as well as some First Nations and Native American communities, expressed concerns about the environmental impacts of temporarily lower water levels, which would for a time follow construction of any new control structure in the St. Clair River. Some residents along Lake Erie said they were not confident that serious attention was being paid by the Study to their interests.

PIAG Views

The divided public views on restoration measures for Lake Michigan-Huron were reflected in the views of PIAG members. They acknowledged that restoration would generate benefits to commercial navigation, but at high costs to other economic and environmental interests. Some PIAG members supported local measures to preserve and restore key wetlands in the lakes, including in the Georgian Bay area, if full lake level restoration is not undertaken. A few members also favoured further exploration of the flap gate option as a pilot project in the St. Clair River. Other PIAG members strongly opposed the flap gate option and expressed reservations about restoration in general, noting that restoration could exacerbate high water levels in parts of the basin upstream of structures in the St. Clair River and create lower water levels downstream for a period. Some PIAG members expressed the need to maintain as close to the naturally fluctuating water levels of the past 50 years as practicable, so as to foster healthy wetlands and their associated ecosystem services. It was noted that while some wetlands in the basin have been negatively affected by low water levels, those same low water levels can rejuvenate wetlands in other areas.

10.3.3 Public Views on Multi-lake Regulation

Multi-lake regulation did not generate as much interest among members of the public as the issue of restoration of Lake Michigan-Huron water levels. Views on multi-lake regulation tended to reflect those on restoration, generally differing depending on geographical location. In addition, some attendees and commenters had difficulty separating Lake Michigan-Huron restoration from system-wide multi-lake regulation options.

Some interest was expressed in further exploring multi-lake regulation scenarios for the lakes, and in support of using a basin-wide water levels advisory board to better monitor lake levels in the future and disseminate information more widely. For example, many commenters in Sault St. Marie, ON and the Georgian Bay area said that the multi-lake option appears to be promising and should be studied further. Among those concerned about climate change impacts, there was some interest in multi-lake regulation as a potential engineering solution in future decades. This was suggested as part of adaptive management techniques, including the idea of a water levels advisory board.

In contrast, many respondents along the shorelines of Lake Michigan, the western and southern shorelines of Lake Huron, Lake St. Clair, Lake Erie and on the St. Clair River did not want impediments to flow installed in the St. Clair River. Others opposed to multi-lake regulation said the approach was too expensive to be practical and unlikely to be funded in the near future.

PIAG Views

Some PIAG members expressed the view that multi-lake regulation could be one form of adaptive management.

10.3.4 Public Views on Proposed Water Levels Advisory Board

With respect to the concept of a water levels advisory board as part of adaptive management, information presented at the public meetings and during the public comment period stated the proposed board would, among other tasks, provide coordination and management for Great Lakes hydroclimatic data and science, ensure distribution of water level and hydroclimatic information to appropriate users, maintain and update plan evaluation tools, and monitor critical performance indicators. There was general support for a proposed water levels advisory board as presented at the meetings.

PIAG Views

PIAG members supported the establishment of a water levels advisory board, but stressed the need for any such board to include public membership and/or involvement. The PIAG also strongly endorsed the Study's recommendation that the Canadian and United States governments fund the monitoring necessary for adaptive management measures.

10.3.5 Other Issues of Public Concern

Some public comments received over the course of the public engagement activities were on water-related issues that were either misconceptions or beyond the scope of the Study's mandate. For example, concerns were expressed about the influence of water withdrawals on lower lake levels, including the Chicago diversion[3], and the bottled water industry.

PIAG Views

The PIAG concluded that these comments suggest that despite efforts to provide accurate information on the factors affecting Great Lakes water levels, considerable misinformation is prevalent on both sides of the border regarding the causes of high or low water levels and the relative magnitude of the influencing factors. Further sustained action by the IJC should be taken to help reduce such misinformation, such as an educational program targeted at K-12 students.

10.4 Public Engagement Benefits

The PIAG and the public information and engagement plan it developed and implemented for the Study Board contributed a number of important benefits to the Study.

1. A Sound Understanding of Public Concerns and Priorities

Public engagement over the course of the Study allowed the Study Board and the PIAG to better understand public concerns and priorities with regard to water levels in the upper Great Lakes. Through the public meetings, briefings and public feedback, areas of public consensus and disagreement became clear (Figure 10-4).

Such an understanding of public concerns and priorities is extremely important as the IJC considers the Study's recommendations regarding a new Lake Superior regulation plan, adaptive management and multi-lake regulation. It identifies areas where the IJC and governments may need to focus in future efforts, such as improving public

***Figure 10-4* Understanding Public Concerns**

The public meetings provided an opportunity to gain a sound understanding of public concerns. Here, residents attend a meeting in Kagawong, on Manitoulin Island, ON.

3 For more information on the impact of major water diversions on lake levels in the upper Great Lakes, see Chapter 2 of the first report of the Study, *Impacts on Upper Great Lakes Water Levels: St. Clair River*, available at the Study's website: www.iugls.org

understanding of the factors affecting water level changes in the Great Lakes, and encouraging greater dialogue among interests and residents of different regions to promote a shared basin-wide understanding of the possible impacts of extreme water levels and regulatory options.

2. Strengthened Analysis

Public engagement and the advice of PIAG members led to improvements in the Study's approaches and analyses, resulting in an overall strengthened final report. As participants in the Study and as members of the Study Board, PIAG members were able to provide specific recommendations and ideas that improved the scope and interpretation of the Study's analyses. For example, PIAG members recommended that the Study include an analysis of the economic effects of low water levels on shoreline property values, and identified the need for additional analyses on climate change.

Members also directly assisted in the development of specific performance indicators that served as inputs into the Study's shared vision planning work for evaluating candidate regulation plans. In addition, PIAG members served as liaisons to the TWGs, addressing issues in which they had particular experience or interest, and providing local or specialized knowledge. They carefully monitored the results of technical studies on navigation impacts, recreational boating, hydroelectric power, and municipal and industrial water supply, acting as an additional level of internal review.

3. A More Transparent Study Process

Through the public information and engagement plan, the Study met and exceeded the standard under the *Boundary Waters Treaty of 1909* that the public "be given a convenient opportunity to be heard." The comprehensive range of public engagement activities contributed to a more transparent Study process and final report. Through public engagement activities, members of the Study Board and the PIAG were able to convey important information to the public on the Study's objectives, options and findings. At the same time, interested organizations and individuals across the entire upper Great Lakes basin were given a variety of opportunities to review the Study's progress, seek clarification and provide feedback on issues that affected their lives, businesses and environment.

10.5 Key Points

With respect to the role of public engagement in the Study, the following points can be made:

- Public engagement has been an important part of the Study from the beginning. Reflecting the commitment to public involvement embodied in the *Boundary Water Treaty of 1909* and recognizing the many interests concerned with the future of water levels in the upper Great Lakes, the IJC appointed the bi-national PIAG to provide guidance and support to the Study Board at all stages.
- The PIAG assisted the Study Board in developing and implementing a comprehensive public information and engagement program. The program used a range of media and events, including conventional activities such as public meetings and progress reports, and social media such as Facebook, Twitter and Internet advertising. More than 1,200 people attended a series of public meetings and interest group meetings held in the summer of 2011 throughout cities and towns in the upper Great Lakes basin.
- There was general support among participating individuals and organizations for an improved regulation plan for the Lake Superior outflow. However, the issue did not generate extensive comment, as there was general agreement that any new plan would mean only marginal changes from the existing plan.
- Public views on other key water level issues within the Study's mandate differed strongly depending, among other factors, on geographical location:
  - Many residents in the Georgian Bay region of Ontario, as well as several other communities upstream from the St. Clair River, supported the construction of new structures in the St. Clair River to restore Lake Michigan-Huron levels or to allow for multi-lake regulation. They expressed concern that important wetlands in Georgian Bay will be lost unless some form of water level restoration is achieved for that area. Some residents also expressed doubts about the seriousness of negative environmental impacts at or downstream of new structures in the upper St. Clair River.

10

   - In contrast, many individuals residing along the shorelines of much of Lake Michigan and the western and southern shorelines of Lake Huron expressed concerns about the negative shoreline effects of higher water levels resulting from restoration structures or multi-lake regulation. Those living downstream of the upper St. Clair River, including along Lake St. Clair and Lake Erie, as well as some First Nations and Native American communities, expressed concerns about the environmental impacts of lower water levels in their areas, even for a few years. Others opposed to multi-lake regulation said the approach was impractical given its high cost.
- The PIAG and the Study's public engagement activities contributed to several important benefits for the Study, including:
   - a sound understanding of public concerns and priorities regarding Great Lakes water levels, which can help guide future IJC work;
   - incorporation of local knowledge and specific recommendations and ideas, which improved the Study's analytical framework and the scope and interpretation of the analyses; and,
   - a more transparent Study process.

Chapter 11

Summary of Findings and Recommendations

Chapter 11 summarizes the key findings and recommendations of the second and final part of the International Joint Commission's five-year International Upper Great Lakes Study.

11.1 The Challenge

The International Upper Great Lakes Study (the Study) was established to examine a recurring challenge in the upper Great Lakes system: *how to manage fluctuating lake levels in the face of uncertainty over future water supplies to the basin while seeking to balance the needs of those interests served by the system.*

Changing water levels can have significant effects on the lives of the more than 25 million people who live in the upper Great Lakes basin. The people around the Great Lakes depend on these waters for a myriad of uses: their livelihoods; drinking water; fishing; recreational boating; and spiritual needs. The economic importance of this region cannot be understated and industries such as navigation, hydroelectricity and thermal power are dependent on water levels. Water levels are also important for maintaining healthy wetlands, fisheries and other ecosystems across the basin.

In the entire upper Great Lakes basin, however, water levels are affected by regulation at only one location upstream from Niagara Falls: at the outlet of Lake Superior on the St. Marys River (Figure 11-1). The International Joint Commission (IJC) issued its first Orders of Approval in 1914 for hydropower development on the St. Marys River and its first Lake

***Figure 11-1* Lake Superior Regulation Control Structures**

The first plan regulating outflows from Lake Superior at the St. Marys River came into effect in 1921. Today, the control structures consist of three hydropower plants and a gated dam at the head of the rapids, known as the compensating works.

Superior regulation plan was implemented in 1921. Since those first Orders, the IJC has sought to incorporate new knowledge, data and modelling strategies to address the challenge of regulating water levels in the upper Great Lakes. In that sense, the existing Lake Superior regulation plan, **1977A**, in effect since 1990, represents the culmination of nearly 75 years of regulation experience responding to changing economic, environmental and social conditions.

The rationale for reviewing the existing plan is based on several important factors that have emerged over the past 20 years since the current plan was implemented:

- First, there is considerable uncertainty about water supplies or net basin supplies[1] (NBS) and corresponding water levels in the Great Lakes basin in the future as a result of natural climate variability and human-induced climate change. Compounding uncertainty about NBS are the impacts of glacial isostatic adjustment (GIA), the differential adjustment of the earth's crust that has the effect of gradually "tilting" the Great Lakes basin over time.
- Second, there is better information available today than 20 years ago about the hydrology and hydraulics of the Great Lakes. Researchers have more confidence in the newer models that describe how the system performs under a variety of conditions. New knowledge has also been gained through recent investigations, such as the Study's own analysis of the changes in the conveyance of the St. Clair River (IUGLS, 2009).
- Finally, there is improved information about the different sectors and public interest concerns that any new regulation plan must address. Under the *Boundary Waters Treaty of 1909*, *domestic and sanitary water uses, navigation*, and *power*[2] *and irrigation* are given order of precedence. These uses must be taken into account in developing regulation plans. However, it is now recognized that the needs of other interests, such as ecosystems, coastal zone uses and recreational boating and tourism must be taken into account, as well.

1 Net basin supply (NBS) is the net amount of water entering a lake, consisting of the precipitation onto the lake minus evaporation from the lake, plus groundwater and runoff from its local basin, but not including inflow from an upstream lake.

2 In interpreting the Treaty, "power" is taken to mean hydroelectric power.

11.2 The International Upper Great Lakes Study

11.2.1 Mandate of the Study Board

In February 2007, the IJC issued a Directive establishing the Study and appointing a 10-member bi-national Study Board to direct and manage the effort[3]. Members were drawn from the two federal governments, state and provincial governments, universities and the public.

The IJC directed the Study Board to provide it with the information it needs to evaluate options for regulating levels and flows in the upper Great Lakes system in order to benefit affected interests and the system as a whole in a manner that conforms to the requirements of the *Boundary Waters Treaty of 1909*. The Directive further instructed the Study Board to provide options and recommendations for the IJC's consideration. Furthermore:

> *"… in carrying out this mandate, the Study Board is encouraged to integrate as many relevant considerations and perspectives into its work as possible, including those that have not been incorporated to date in assessments of the Upper Great Lakes system regulation, to assure that all significant issues are adequately addressed"* (IJC, 2007).

The Study Board is only authorized to offer non-binding recommendations to the IJC that are consistent with its mandate established in the Directive. The Study Board is not empowered to implement any solutions. The IJC is responsible for making decisions and recommendations to the Canadian and United States governments, including changes in its regulation plans, in accordance with its authority under the 1909 Treaty.

The geographical scope of the Study was the upper Great Lakes basin, from the headwaters of Lake Superior downstream through lakes Michigan, Huron, St. Clair and Erie and the connecting channels (the St. Marys, St. Clair and Detroit rivers, the Straits of Mackinac and the upper Niagara River) (Figure 11-2).

The Study's first report, ***Impacts on Upper Great Lakes Water Levels: St. Clair River***, submitted to the IJC in December 2009, examined the physical processes and possible ongoing changes in the St. Clair River and the effects of such changes on the levels of Lake Michigan-Huron.[4]

3 The full text of the IJC's directive is available at: http://www.iugls.org/en/mandate/Mandate_directive.htm

4 Available at: www.iugls.org

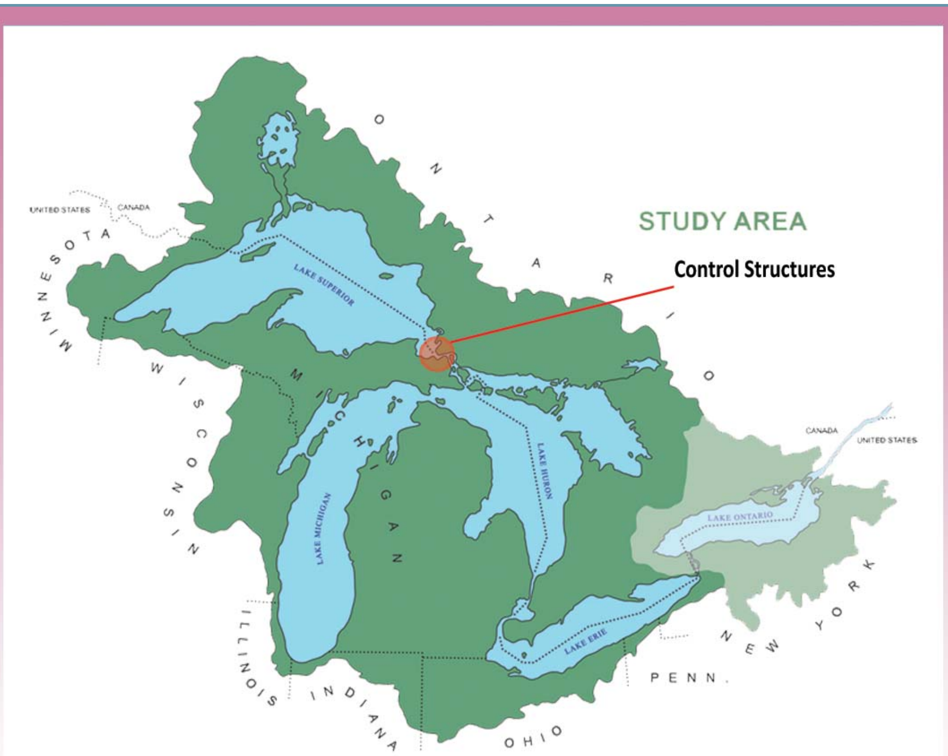

Figure 11-2 ***Study Area***

This second and concluding report of the Study, ***Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels***, focuses on the formulation and evaluation of options for a new regulation plan. It also addresses restoration and multi-lake regulation as alternative approaches for dealing with extreme water levels beyond those addressed by Lake Superior regulation alone, and considers the important role that adaptive management can play to help the interests better anticipate and respond to extreme water levels in the future.

11.2.2 The Study's Strategy

The IJC's Directive to the Study Board called for an understanding of the key interests served by the upper Great Lakes system, an examination of the changing conditions in the water levels of that system, and the identification and evaluation of options to regulate water levels while balancing the needs of the interests. Addressing these closely related issues required a thorough analysis of past, present and projected future hydroclimatic conditions in the system and an effective approach to testing regulation options in relation to impacts on water levels and flows on the key water interests.

The Key Interests

Future changes in water levels in the upper Great Lakes basin will affect a complex and interrelated network of individual, institutional and commercial interests (Figure 11-3). With this in mind, the Study commissioned detailed analyses of the current and emerging conditions and perspectives of six key interests likely to be affected by possible future changes in water levels in the upper Great Lakes basin (**Chapter 3**):

1. Domestic, municipal and industrial water uses;
2. Commercial navigation;
3. Hydroelectric generation;
4. Ecosystems;
5. Coastal zone; and,
6. Recreational boating and tourism.

These analyses summarized the socio-economic context for the interest, including important values and perceptions, and identified the likely consequences, if any, for the interest of changing water levels, together with the prospects for the interest to address these risks through adaptive behavior and response.

Figure 11-3 ***An Integrated View of the Interests Served by the Waters of the Upper Great Lakes***

The Study also recognized that indigenous First Nations in Canada, Native American tribes in the United States, and Métis represent a unique perspective in the upper Great Lakes. With respect to changing water levels, their concerns cut across the Domestic Water Users, Coastal Zone and, in particular, Ecosystems interests investigated in detail. Study Board members engaged a number of First Nations and Native American tribes through workshops and other outreach activities to identify their issues and concerns with respect to Great Lakes water levels. In addition, a member of a Native American tribe with extensive experience in Great Lakes water issues was a member of the Public Interest Advisory Group (PIAG).

Hydroclimatic Analysis

A key task of the Study was to improve understanding of hydroclimatic conditions in the upper Great Lakes system, focusing on the possible impacts of climate variability and climate change on future water levels (**Chapter 4**). The Study addressed two primary science questions:

- *What are the historical estimates of the NBS in the upper lakes and how have any potential changes to the water balance components affected the level of the lakes?*
- *What potential impact could variations in the climate system have on any future regulations of the upper Great Lakes?*

Three themes were central to the Study's approach to the hydroclimatic analysis:

1. understanding the water balance (precipitation, evaporation and runoff) of the Great Lakes;
2. assessing the reliability of historical recorded and estimated data, and increasing understanding of potential NBS conditions through the use of paleo-information[5] and stochastic[6] analysis; and,
3. addressing the plausibility and scope of climate change impacts on water supplies through new modelling work.

Regulation Plan Formulation and Evaluation

A primary objective of the Study was to develop and evaluate possible new Lake Superior regulation plans to determine if a new plan could improve on the performance of **1977A** – particularly in the context of the considerable uncertainty about future climate conditions and corresponding water levels on the upper Great Lakes.

The Study Board established clear objectives for a new Lake Superior regulation plan – and for the upper Great Lakes basin as a whole – based on the IJC's Directive and feedback received at public meetings (**Chapter 5**):

- To maintain or improve the health of coastal ecosystems;
- To reduce flooding, erosion and shore protection damages;
- To reduce the impact of low water levels on the value of coastal property;
- To reduce or maintain shipping costs;
- To maintain or increase hydropower value;
- To maintain or increase the value of recreational boating and tourism opportunities; and,
- To maintain or enhance municipal-industrial water supply withdrawal and wastewater discharge capacity.

5 *Paleo* – a combining form meaning "old" or "ancient," especially in reference to former geologic time periods, used in the formation of compound words, as in *paleo-hydrology*.

6 *Stochastic* –Statistics involving or showing random behaviour. In a stochastic simulation, a model is used to create a new 'synthetic' series of plausible flows and lake levels, based on historical data. The synthetic series will, on average, preserve important properties of the historical record, such as the mean and standard deviation, while generating new combinations of high and low flow conditions that could represent more severe conditions than those seen in the past.

Of the hundreds of NBS sequences generated by the Study's hydroclimatic analysis, 13 were chosen as representative of the range of plausible future conditions that could be used to test the limits of any new proposed regulation plan. This suite of NBS sequences allowed the Study Board to test plans for *robustness* – the capacity to meet particular regulation objectives under a broad range of possible future NBS conditions.

In formulating, evaluating and ranking regulation plans, the Study applied *shared vision planning*, an iterative and collaborative process through which participants can better understand the implications of any regulatory decision. The Study Board used a shared vision model to undertake practice decisions, allowing experts, stakeholders and decision makers a series of opportunities to weigh the results as information developed.

Study plan formulators generated more than 100 alternative regulation plans, using a variety of scientific approaches, so as to ensure a comprehensive search for regulation plan options. The Study Board reduced the list of plans to four. One of the final four plans performed better than or as well as any other regulation plan considered, regardless of the NBS sequence or the decision criterion applied. As a final step in the selection process, plan formulators developed three variations of the preferred plan as part of an optimization analysis. One of the variations was selected as the recommended plan (**Chapter 6**).

The Limits of Lake Superior Regulation

The Study Board recognized that Lake Superior regulation on its own has limited ability to affect the levels of Lake Michigan-Huron or address risks of extreme lake levels downstream of Lake Superior. In addition, the Study Board concluded that the impacts of climate change and climate variability on future water levels would introduce uncertainty to any regulation effort. As a result, 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[7] and consider alternative approaches for managing and responding to uncertain future water level conditions. These alternative approaches were: restoration of Lake Michigan-Huron water levels (**Chapter 7**); multi-lake regulation of the Great Lakes-St. Lawrence River system as a whole (**Chapter 8**); and, adaptive management (**Chapter 9**).

7 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/upper St. Lawrence River, respectively.

Public Engagement and Peer Review

Public involvement was a core element of the Study from the outset. Recognizing the many interests concerned with the future of water levels in the upper Great Lakes, the IJC appointed a bi-national PIAG to provide advice to the Study Board on issues related to the Study and advice and support in the development and implementation of the Study Board's public information and engagement activities (**Chapter 10**). These activities included a series of 12 public meetings around the Great Lakes basin, attended by more than 1,200 people, to present preliminary findings, respond to questions and receive public comments.

Finally, given the diverse public and private interests concerned about Great Lakes water levels and the uncertainty and debate around some of the scientific issues, the IJC and Study Board recognized the need to ensure that the Study was scientifically credible and transparent. As a result, much of the Study's work was subject to a high level of independent scientific scrutiny by external peer reviewers as well as extensive review by internal experts. The peer reviewers operated independently of the Study Board and provided their views directly to the IJC. They reviewed drafts and background studies of several of the Study's scientific and technical chapters. The Study's final report also was reviewed by the co-leads of the independent expert reviewers group. The Study Team considered and responded to each comment from the expert reviewers.

11.3 Summary of Key Findings of the Study

This section summarizes the key findings of the Study in seven major areas.

11.3.1 The Key Interests Served by the Upper Great Lakes System

> ***Key Finding 1:***
> *Most of the key interests have demonstrated their capacity to adapt to changes in water level conditions that have been within historical upper or lower ranges. However, future water levels that are outside these ranges would require some interests to carry out more comprehensive and costly adaptive responses than any undertaken to date.*

The Study undertook a comprehensive analysis of the current and emerging conditions and perspectives of six key interests likely to be affected by possible future changes in water levels in the upper Great Lakes basin. Based on this analysis, the Study Board concluded that:

- Under the *Boundary Waters Treaty of 1909*, the interests of *domestic and sanitary water uses, navigation*, and *power and irrigation* are given order of precedence. Today, it is recognized that other interests, such as ecosystems, coastal zone uses and recreational boating and tourism have rights under the Treaty, consistent with the IJC's balancing principle, which provides for benefits or relief to interests affected by water levels and flows without causing undue detriment to other interests.
- All six interests are experiencing major change as a result of broad, underlying economic, social and environmental forces. The decline in heavy industry and manufacturing in the region has put into motion changes such as declines in income, population, and municipal taxes, which in turn affect demand for shipping, energy and recreation. At the same time, the region's economic transition could see the rise of new, more water-intensive industries, such as irrigated agriculture, biofuels, oilsands refining and electricity production.
- All the interests have a long-established presence in the upper Great Lakes basin, and all represent significant economic value to the region. There are clear expectations across all the interests that water levels will be maintained in the future to support their specific needs.
- All six interests can be adversely affected by both high and low water conditions. Most of the interests have demonstrated their capacity to adapt to changes in water level conditions that have been within historical upper or lower ranges (Figure 11-4). However, future water levels that are outside these historical ranges would require some interests to carry out more comprehensive and costly adaptive responses than any undertaken to date.
- For thousands of years, and continuing into the present, many Native American communities and First Nations have relied on the natural resources of the Great Lakes to meet their economic, cultural and spiritual needs.
  A fundamental ongoing concern of indigenous peoples is the extent to which they are involved in the decisions of governments in the United States and Canada with regard to the Great Lakes.

Figure 11-4 **Shoreline Protection Structure, 2004 – Near Michigan City, IN on Lake Michigan**

11.3.2 Uncertainty in Future Upper Great Lakes Water Levels

> ***Key Finding 2:***
> *Changes in the levels of the upper Great Lakes may not be as extreme in the near future as previous studies have predicted. Lake levels are likely to continue to fluctuate, but still remain within the relatively narrow historical range – while lower levels are likely, the possibility of higher levels cannot be dismissed. Both possibilities must be considered in the development of a new regulation plan.*

The Study undertook extensive analysis to improve understanding of the hydroclimatic forces at work in the upper Great Lakes basin and their likely impacts on future water levels. It also considered how the uncertainties in the hydroclimatic analysis could influence the evaluation and decision-making framework. Based on this analysis, the Study Board concluded that:

- Perhaps most striking from the perspective of effective lake regulation is how little the lake dynamics on inter-annual and decadal timescales are understood. Despite best efforts, the lake levels remain almost entirely unpredictable more than a month ahead. In terms of understanding the lakes system relative to lake levels, the unavoidable conclusion is that the Great Lakes basin is a complex system whose dynamics are only partially understood.
- Without substantially increased confidence in historical NBS estimates and an understanding of the uncertainty associated with these estimates, choosing plausible futures in the context of past events is highly problematical.
- In general, information from global change models (GCMs) introduced more uncertainties that are very difficult to reconcile with historical data.
- Determination of climate change impacts on NBS using regional climate model (RCM) tools provided insights into the dynamics of the hydroclimatic systems that are not possible through statistical down-scaling. Features such as local feedback and recycled evaporation are not captured in any of the GCMs. This work advanced scientific knowledge in this area. Due to the limited number of RCM runs, however, the full range of impacts was not assessed.
- Despite these uncertainties, it is clear that lake evaporation is increasing and likely will increase for the foreseeable future, likely due to the lack of ice cover, increasing surface water temperatures and wind speeds. Analysis indicates that in the Lake Michigan-Huron basin this increased evaporation is being largely offset by increases in local precipitation.
- In the Lake Superior basin, however, increasing evaporation over the past 60 years has not been compensated for by increased precipitation. As a result, NBS have been declining in general in the basin. This trend is consistent with the current understanding of climate change. Unless changes in the precipitation regime occur, which is possible, NBS in Lake Superior will continue to decline, on average, despite the possibility of higher supplies at times. It will be important to ensure that further climate analysis be undertaken to explore these dynamics and provide more certainty of future NBS estimates.
- The very short record of measured evaporation initiated by the Study suggests that earlier evaporation amounts may be over-estimated. However, regardless of differences in absolute evaporation measurements, the trends in increased evaporation rates, inferred from the earlier estimates, are thought to be reasonably reliable.
- As a result, changes in lake levels in the near-term future may not be as extreme as previous studies have predicted. Lake levels are likely to continue to fluctuate, but still remain within the relatively narrow historical range. While lower levels are likely, the possibility of higher levels at times cannot be dismissed. Both possibilities must be considered in the development of a new regulation plan (Figure 11-5).
- Beyond the next 30 years, some projections by GCMs and RCMs of more extreme water levels in the upper Great Lakes may have more validity. However, due to the limitations of these models for this region, there is, at present, no completely satisfying representation of the future water balance.
- Therefore, in terms of water management and lake regulation, the best approach is to make decisions in such a way as to not overly rely on assumptions of particular future climatic and lake level conditions or specific model projections. *Robustness* – the capacity to meet regulation objectives under a broad range of possible future water level conditions – must be a primary attribute of any new regulation plan.

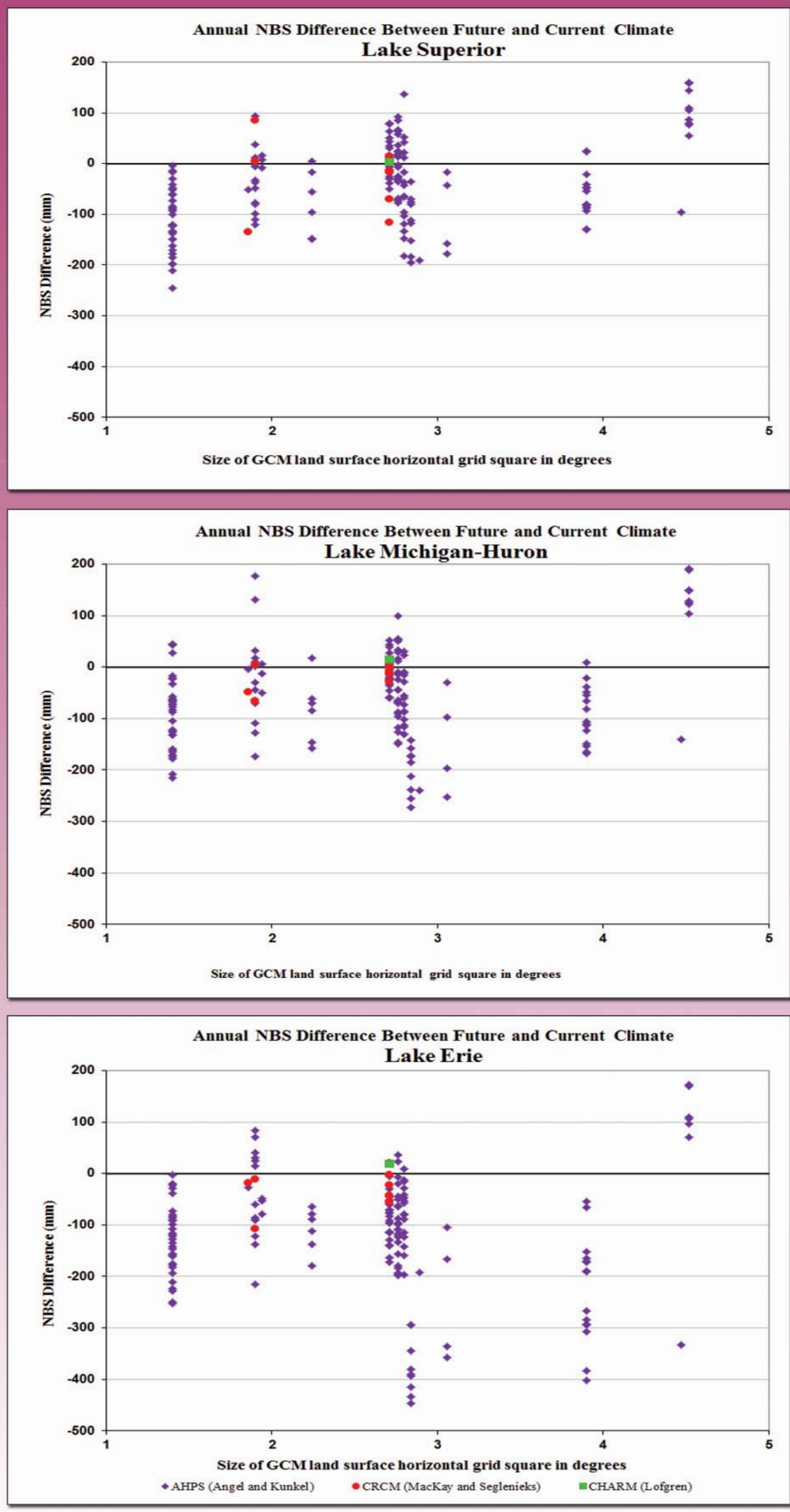

Figure 11-5 Integration of Results of the Study's Hydroclimatic Analysis

This figure shows the ranges in NBS conditions estimated for 2040 above and below long-term averages for lakes Superior, Michigan-Huron and Erie, as projected by several different climate models. The projections suggest that lake levels are likely to continue to fluctuate, but still remain within a relatively narrow range. Lower levels appear to be likely, but there is also the possibility of higher levels at times.

11.3.3 Lake Superior Regulation Plan 2012

> ***Key Finding 3:***
>
> *The Study Board identified a regulation plan that will be more robust than the existing plan and that will provide important benefits related to the maintenance of Lake Superior levels, environmental impacts, economic benefits and ease of regulation.*

Through the shared vision planning process, the Study developed and evaluated numerous Lake Superior regulation plan options to determine if a new plan could improve on the performance of **1977A**. Based on this work:

- Reviewing more than 100 alternative regulation plans, the Study Board identified one plan, named **Lake Superior Regulation Plan 2012**, that, on the basis of the evaluations, performed better than or as well as any other plan considered regardless of the NBS sequence or the decision criterion applied. This performance satisfied the objective of *robustness* in a new plan. Table 11-1 summarizes the evaluation findings of the final four plan options.
- **Lake Superior Regulation Plan 2012** will bring several benefits compared to the existing plan:
  - The recommended plan will perform in a similar manner as the existing plan if future NBS are similar to those that have been experienced since 1900. However, if future NBS become significantly drier under climate change, then the new plan will do a better job preserving water levels on Lake Superior, while taking into account the downstream lakes.
  - If future NBS are much drier than historical conditions, then **Lake Superior Regulation Plan 2012** will still be able to avoid infrequent but serious adverse effects on the spawning habitat of lake sturgeon, an endangered species, in the St. Marys River. Under **1977A**, adverse effects on fish habitat would be more frequent under drier NBS conditions.
  - **Lake Superior Regulation Plan 2012** will provide modest benefits compared to the existing plan for commercial navigation, hydroelectric generation and coastal zone interests, under both wetter and drier NBS conditions. Importantly, under very dry future NBS conditions, commercial navigation through the Sault Ste. Marie locks, as well as hydroelectric generation at the St. Marys River power plants would be threatened with closure under **1977A**, but not under **Lake Superior Regulation Plan 2012**.
  - Month-to-month changes in flow on the St. Marys River with **Lake Superior Regulation Plan 2012** will generally be smaller than with **1977A**, which will give the St. Marys River a more natural flow relationship to Lake Superior levels. Natural river flow frequencies have been identified as an important factor in sustaining riverine ecosystem health. The smaller changes will also help hydroelectric power producers.

Table 11-1: Summary Evaluations of Robustness of Plans

Plan	Strengths	Limitations	Study Board Decision
129	Provides small net economic benefits under historical NBS	Like **1977A**, allows Lake Superior levels to drop too low in severe dry NBS sequences	**Eliminated** because of poor performance in severely dry NBS sequences
PFN3	Compressed the range of Lake Superior levels Maintained Lake Superior levels in a "severely dry" NBS sequence	Compression often caused slightly worse economic and ecological scores	**Eliminated** because of mixed performance and because it compressed Lake Superior levels at the expense of levels on Lake Michigan-Huron
Bal26	Scores on all nine criteria were good and very close to those of Nat64D	Not clearly better than Nat64D and not balanced in extremely dry sequences	**Eliminated** because of limitations under dry NBS sequences
Nat64D[1] (the basis for **Lake Superior Regulation Plan 2012**)	Better than **1977A** for most of the criteria and historical NBS Among the best plans for all NBS	Does not outperform **1977A** for all criteria and every NBS	**Preferred** because of the gained benefits and robustness

1 This plan was further refined through optimization; variation NatOpt 3 selected as the final plan.

– The rules for operating **Lake Superior Regulation Plan 2012** will be much less complex than rules for **1977A**, making the new plan easier to manage, maintain and adapt to a changing climate.

- In reviewing the IJC's Orders of Approval governing how Lake Superior outflows are regulated, the Study Board concluded that there was no need for major revisions to the Orders. However, the Study Board concluded that there is a risk of confusion in having the conditions that are still in force spread between the original 1914 Orders and several much more recent Supplementary Orders, amid many superseded conditions. Implementing a new regulation plan would provide an opportunity for the IJC to integrate various existing Orders and Supplementary Orders and recognize some existing policies or practices within new Orders of Approval.

11.3.4 Restoration of Lake Michigan-Huron Levels

Key Finding 4:

Restoration structures designed to raise Lake Michigan-Huron water levels would result in adverse effects on certain key interests served by the upper Great Lakes system.

At the direction of the IJC, the Study Board considered the feasibility and implications of raising water levels of Lake Michigan-Huron by means of restoration structures in the St. Clair River to compensate for past natural and human-induced changes (**Chapter 7**). The IJC did not request that the Study Board make any recommendation as to implementing a particular restoration option. Based on this analysis, the Study Board concluded that:

- Several of the restoration options reviewed are technically feasible. Construction cost estimates ranged from about $30 million to about $170 million, depending on the technology and level of restoration provided.
- Restoration would reduce the occurrences of extreme low water levels on Lake Michigan-Huron, but also increase the number of occurrences of extreme high lake levels.
- Commercial navigation and recreational boating and tourism interests would benefit, while coastal zone interests, hydroelectric generation and indigenous peoples would be adversely affected.
- Positive environmental effects would be concentrated in the wetlands of the Georgian Bay region, which have suffered significantly during low water levels in the past and would benefit from higher Lake Michigan-Huron levels. In contrast, restoration structures in the St. Clair River would adversely affect important spawning habitat of the lake sturgeon, an endangered species, and would have negative effects on the Lake St. Clair fishery (Figure 11-6).
- Restoration of Lake Michigan-Huron levels would temporarily help to counteract the effects of GIA on lowering water levels in Georgian Bay. However, restoration would compound the effects of GIA in much of the densely populated southern portion of the upper Great Lakes, resulting in more high water impacts.
- Climate change could magnify the impacts of restoring Lake Michigan-Huron water levels. If water levels become generally lower in the future as a result of climate change, then the commercial navigation sector and Georgian Bay wetlands would be adversely affected, and restoration could help mitigate these adverse effects. Conversely, if water levels become higher at times in the future, flood damages would increase, and restoration would exacerbate these adverse effects.
- Restoration structures would require the ongoing commitment and financing of the governments of Canada and the United States, a process that could take 20 years or more for the full range of planning, environmental reviews, regulatory approvals and design steps.

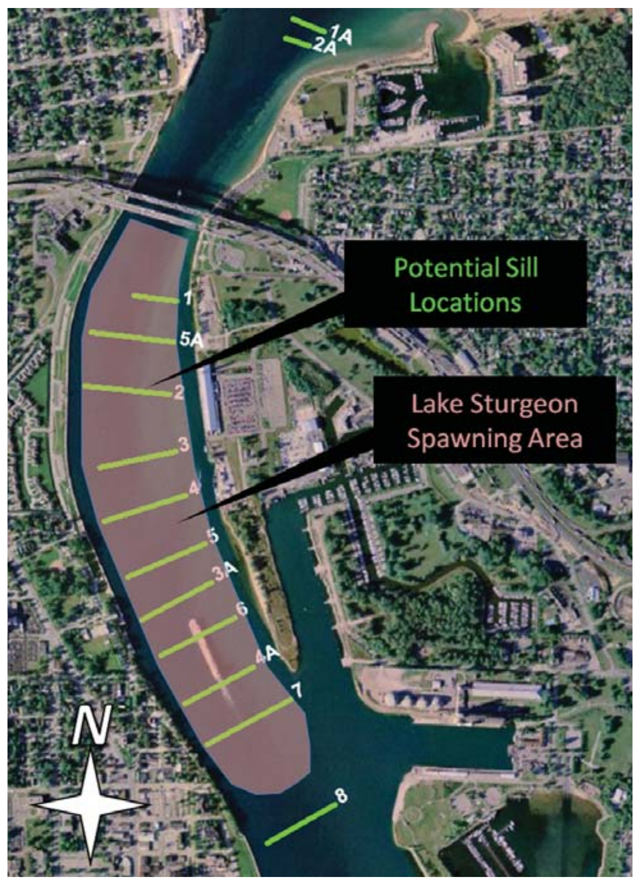

Figure 11-6 Overlapping Zone of Potential Sill Locations and Lake Sturgeon Spawning Habitat in the Upper St. Clair River

The Study's analysis of restoration structures concluded that underwater sills in the St. Clair River would adversely affect important spawning habitat of the lake sturgeon, an endangered species.

11.3.5 Multi-lake Regulation

> ***Key Finding 5:***
>
> *The potential for multi-lake regulation to address extreme water levels is limited by the uncertainty regarding future climatic conditions and NBS, very high costs, environmental concerns and institutional requirements.*

The Study Board considered the feasibility of multi-lake regulation – operating existing and new regulation structures to benefit the Great Lakes-St. Lawrence River system as a whole (**Chapter 8**). The Study analyzed multi-lake regulation plans that used 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 NBS scenarios. Based on this analysis, the Study Board concluded that:

- Multi-lake regulation plans, involving the existing structures as well as new control points on the St. Clair and Niagara rivers, or on the Niagara River alone, could be designed to reduce the frequency of occurrence of extreme water levels across multiple extreme NBS scenarios relative to the existing system of regulation. However, system-wide multi-lake regulation could not eliminate extreme water level events entirely. Extreme water levels in the future may be unavoidable, even with additional regulation capabilities.
- New water level control points are extremely costly, requiring the construction of adjustable control structures, such as a gated 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 normally much greater than the cost of the control structures themselves.
- Many of the environmental impacts and institutional considerations that would arise with restoration structures apply equally to multi-lake regulation.
- 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 the Study's 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.

Figure 11-7 ***Elements of an Adaptive Management Strategy***

11.3.6 Adaptive Management

> ***Key Finding 6:***
>
> *Adaptive management has an important role to play in addressing the risks of future extremes in water levels in the upper Great Lakes, though it requires leadership and strengthened coordination among institutions on both sides of the international border.*

With the concurrence of the IJC, the Study Board expanded the scope of the Study's work to include a more comprehensive consideration of the role of adaptive management in helping interests in the upper Great Lakes basin better anticipate and respond to future extreme water levels (**Chapter 9**). Based on this analysis, the Study Board concluded that:

- Adaptive management has an important role to play in addressing the risks of future changes in water levels in the upper Great Lakes. Lake Superior regulation on its own can do little to address risks of extreme lake levels downstream of Lake Superior. New structures in various parts of the Great Lakes Basin could take decades to implement and cost billions of dollars. Nor can multi-lake regulation fully eliminate the risk of extreme lake levels outside the historical range. Therefore, regardless of the Lake Superior regulation plan adopted by the IJC, ongoing monitoring and modelling efforts will be required to continue to assess risks and address uncertainties and changing conditions.
- Information and education are powerful components of adaptive management. They contribute to both anticipating and preventing lake level-induced damage, particularly when focused on understanding risk, the limits of regulation, inherent uncertainties and system vulnerability.
- An effective adaptive management strategy must include six core elements (Figure 11-7):
  - bi-national hydroclimatic monitoring and modelling;
  - ongoing risk assessment;

– information management and outreach;

– tools and processes for decision makers to evaluate their actions;

– a collaborative regional adaptive management study for addressing water level extremes; and,

– the integration of water quality and quantity modelling and activities.

▶ Application of a comprehensive adaptive management strategy requires a new approach to institutional involvement and coordination. Existing legal, regulatory and programmatic efforts related to adaptive management vary considerably from one jurisdiction to the next. Federal, state and provincial governments generally provide the policy and regulatory framework, while site-specific selection and application of adaptive risk management measures is largely a local government responsibility.

▶ Furthermore, no bi-national organization currently is responsible for coordinating data and information on an ongoing basis for adaptive management efforts in the Great Lakes basin. Efforts to coordinate approaches and promote consistency across jurisdictions have been limited and generally have focused on accommodating seasonal lake level fluctuations and the occasional extreme high and low water events. Little focus has been placed on long-term implications of climate change-induced impacts and the need for new adaptive risk management measures.

▶ Adaptive management to address future levels in the upper Great Lakes basin has direct relevance to several important initiatives in the Great Lakes-St. Lawrence River system, including:

– adaptive management efforts in the Lake Ontario-St. Lawrence River part of the system;

– the Great Lakes Water Quality Agreement; and,

– the Great Lakes-St. Lawrence River Basin Sustainable Water Resource Agreement.

11.3.7 Public Concerns about Upper Great Lakes Water Levels

Key Finding 7:

Public concerns about water levels in the upper Great Lakes differ strongly depending on geographical location.

With the advice and support of the PIAG, the Study undertook a comprehensive public information and engagement program to communicate information about the Study's approach and findings and to gain a better understanding of public attitudes regarding Lake Superior regulation and, more generally, issues related to water levels in the upper Great Lakes (Figure 11-8). Based on the results of these activities, the Study Board concluded:

***Figure 11-8* Understanding Public Concerns about Upper Great Lakes Water Levels**

More than 1,200 people attended the 2011 summer public meetings to hear progress on the Study and provide feedback. Here, residents attend a meeting in Midland, ON.

- There was general support among participating individuals and organizations for an improved regulation plan for Lake Superior outflows. However, the issue did not generate extensive comment, as there was general agreement that any new plan would mean only marginal changes from the existing plan.
- Public views on other key water level issues within the Study's mandate differed strongly depending on geographical location:
  - Many residents in the Georgian Bay region of Ontario, as well as several other communities upstream from the St. Clair River, supported the construction of new structures in the St. Clair River to restore Lake Michigan-Huron levels or to provide for multi-lake regulation. They expressed concern that important coastal wetlands in Georgian Bay will be lost unless some form of water level restoration is achieved for that area. Some residents also expressed doubts about the seriousness of negative environmental impacts at or downstream of new structures in the upper St. Clair River.
  - In contrast, many individuals residing along the shorelines of much of Lake Michigan and the western and southern shorelines of Lake Huron expressed concerns about the negative shoreline effects of higher water levels resulting from restoration structures or multi-lake regulation. Those living downstream of the upper St. Clair River, including along Lake St. Clair and Lake Erie as well as some First Nations and Native American communities, expressed concerns about the environmental impacts of lower water levels even for a few years in their areas. Others opposed to multi-lake regulation said the approach was impractical given its high cost.

11.4 Study Recommendations

On the basis of the Study's analysis and findings, and in accordance with its mandate under the IJC Directive, the Study Board makes the following recommendations to the IJC.

1. A New Lake Superior Regulation Plan

In developing, evaluating and ranking a set of new Lake Superior regulation plans, the Study Board identified a regulation plan that would be more robust than the existing plan, **1977A** and provide important additional benefits. The new plan would perform similarly under historical NBS conditions, but much better if future climatic conditions are either drier or wetter than in the period of historical record (1900-2008).

In considering the need to revise the existing IJC's Orders of Approval governing how Lake Superior outflows are regulated, the Study Board also concluded that the implementation of a new regulation plan provides the IJC with an opportunity to establish new integrated Orders to bring greater clarity and efficiency to the suite of new and existing requirements.

Therefore, the Study Board recommends that:

1. *The IJC should approve* ***Lake Superior Regulation Plan 2012*** *as the new plan for regulating Lake Superior outflow and advise governments that the* ***1977A*** *plan will be replaced with the new plan.*
2. *The IJC should prepare and issue new integrated Orders of Approval that consolidate all of the applicable conditions and requirements of the original and Supplementary Orders, as well as the additional considerations required to implement the recommended new plan,* ***Lake Superior Regulation Plan 2012****.*

2. Hydroclimatic Science

The Study's hydroclimatic analysis has established a new standard that should be used as the starting point for Great Lakes planning and related research conducted in the future. However, considerable work remains – the Study's comprehensive hydroclimatic analyses using a range of approaches showed that assessing the uncertain impacts of climate variability and change on upper Great Lakes water levels will continue to be a challenging task. The Study identified important avenues to be pursued in the near- and medium-term to improve understanding of these impacts and their implications for regulation. To better link this work to planning and decision making across the Great Lakes basin, these scientific initiatives would be most effectively undertaken in a coordinated, bi-national manner as part of the recommended adaptive management measures, led by the proposed new water levels advisory board (see below).

In its first report to the IJC, ***Impacts on Upper Great Lakes Water Levels: St. Clair River***, the Study Board identified a number of specific "legacy" recommendations regarding strengthening data collection, scientific knowledge and institutional capacity. In this final report, the Study Board reaffirms those recommendations and in particular, notes the need for support and expansion of key data collection programs (*e.g.*, evaporation gauges, International Gauging Stations). Long-term data collection continues to be essential for improving scientific understanding of how the Great Lakes system functions and how it is – and is likely to be – affected by both natural forces and human activities.

Therefore, the Study Board recommends that:

3. *The IJC should seek to improve scientific understanding of hydroclimatic processes occurring in the Great Lakes basin and the impacts on future water levels as part of a continuous, coordinated bi-national effort. In particular, the IJC should endorse the following initiatives as priorities and strongly recommend ongoing government support:*
   - *strengthening climate change modelling capacity in the Great Lakes basin in light of the promising preliminary results identified in the Study; and,*
   - *enhancing hydroclimatic data collection in the upper Great Lakes basin.*

3. Adaptive Management

The Study's analysis concluded that adaptive management has an important role to play in addressing the risks of future extremes in water levels in the upper Great Lakes, particularly given the limits of Lake Superior regulation and the high costs and impacts associated with restoration structures and additional multi-lake regulation.

Therefore, the Study Board recommends that:

4. *An adaptive management strategy should be applied to address future extreme water levels in the Great Lakes-St. Lawrence River basin through six core initiatives:*
   - *strengthening hydroclimatic monitoring and modelling;*
   - *ongoing risk assessment;*
   - *ensuring more comprehensive information management and outreach;*
   - *improving tools and processes for decision makers to evaluate their actions;*
   - *establishing a collaborative regional adaptive management study for addressing water level extremes; and,*
   - *promoting the integration of water quality and quantity modelling and activities.*
5. *The IJC should seek to establish a Great Lakes-St. Lawrence River Levels Advisory Board to champion and help administer the proposed adaptive management strategy for the entire Great Lakes-St. Lawrence River system.*
6. *The IJC should work with governments to pursue funding options and coordinate adaptive management efforts with the Lake Ontario-St. Lawrence River Working Group, the renewal of the Great Lakes Water Quality Agreement, and the implementation of the Great Lakes-St. Lawrence River Basin Sustainable Water Resource Agreement.*

4. Multi-lake Regulation

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 NBS conditions, and concluded that multi-lake regulation may have potential to address (though not eliminate) extreme water levels in the upper Great Lakes basin. However, 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, the Study Board recommends that:

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

Annex

Acknowledgements and List of Contributors

Lake Superior Regulation: Addressing Future Water Levels in the Upper Great Lakes represents the final product of a bi-national team effort that has spanned more than five years.

More than 200 scientists, engineers, planners and technical experts drawn from a wide range of disciplines and from governments, academia and the private sector, have contributed to the report's planning, applied research and analysis over the last two years. Their efforts and professionalism have helped produce a comprehensive report based on sound science and peer-reviewed analysis.

The following is a list of the individuals who directly participated in the Study. Their affiliations are also listed, though it is important to note that from the outset the Study was independent of the International Joint Commission or any government agency. All participants served in their personal and professional capacities and did not represent their employer or organization.

The International Upper Great Lakes Study gratefully acknowledges the contributions of these individuals.

Study Leadership and Management

The Study Board was responsible for the overall planning and management of the Study, and supervised the report's preparation. The Study greatly benefitted from the work, insights and commitment of the Study Board and in particular the leadership of its two co-directors and co-chairs, Dr. Eugene Z. Stakhiv and Ted R. Yuzyk.

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Lake Superior Regulation Task Team

The Task Team provided the strategic direction and management oversight for the numerous projects undertaken to address various aspects of Lake Superior regulation and additional approaches to addressing future water levels in the upper Great Lakes. The Task Team also reviewed the analysis and findings of the projects in detail, and supervised the preparation of the final report. The efforts of Task Team co-chairs Dr. Syed Moin and Dr. Anthony Eberhardt were critical to the success of the team. In addition to the co-chairs, the Task Team consisted of the co-leads of each of the technical work groups (see below).

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The Lake Superior Task Team worked directly with 11 technical work groups (TWGs) responsible for conducting the basic studies recommended by the Task Team and approved by the Study Board. The co-leads of the work groups were members of the Task Team.

Six TWGs addressed specific *interests* within the upper Great Lakes affected by water levels and flows. Three *integration* TWGs were tasked with assessing and incorporating relevant information provided by the interest group TWGs to guide the development and evaluation of alternative regulation plans for review by the Study Board. A fourth *integration* TWG was responsible for developing an information management strategy to allow for data sharing among the Study's researchers and to ensure that the Study's literature and data remain available for researchers and managers involved in Great Lakes water management beyond the Study. A special technical work group was established to examine questions related to restoration structures and multi-lake regulation.

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Much of the Study's work was subject to a high level of independent scientific scrutiny by external experts. These peer reviewers operated independently of the Study Board and provided their views directly to the IJC. They reviewed drafts and background studies of several of the Study's scientific and technical chapters. The Study's final report also was reviewed by the co-leads of the independent expert reviewers group.

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Chapter 1: Introduction to the International Upper Great Lakes Study

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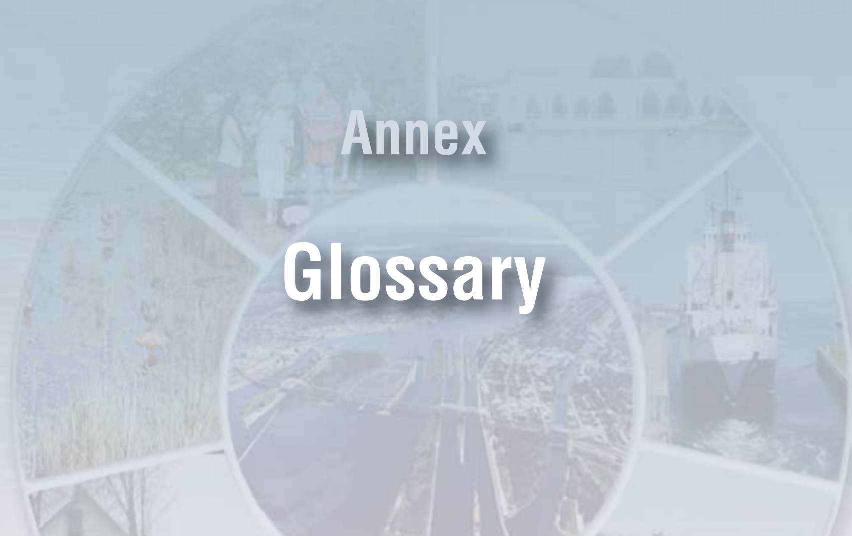
Annex

List of Acronyms

AHPS	Advanced Hydrologic Prediction System
AWRA	American Water Resources Association
BRP	Brookfield Renewable Power hydroelectric generating station
CCGLBHHD	Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data
CEC	Cloverland Electric Cooperative hydroelectric generating station
CGLRRM	Coordinated Great Lakes Regulation and Routing Model
CHARM	Coupled Hydrosphere Atmospheric Research Model
CRCM	Canadian Regional Climate Model
ECNWDAS	Environment Canada's Numerical Weather and Data Assimilation System
ENSO	El Nino Southern Oscillation
GCM	Global Climate Model (also: General Circulation Model, Global Circulation Model)
GIA	Glacial isostatic adjustment
GL-SAND	Great Lakes Navigation Model
GLERL	Great Lakes Environmental Research Laboratory
GLFC	Great Lakes Fishery Commission
GLIN	Great Lakes Information Network
IERM2	Integrated Ecological Response Model 2
IGLD	International Great Lakes Datum
IGLLB	International Great Lakes Levels Board
IJC	International Joint Commission
ILSBC	International Lake Superior Board of Control
IPCC	Intergovernmental Panel on Climate Change
IUGLS	International Upper Great Lakes Study
LRSB	Levels Reference Study Board
LOSLRS	Lake Ontario-St. Lawrence River Study
MESH	Modélisation Environnementale Couplé: Surface et Hydrologie modelling system

NBS	Net Basin Supply
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PI	Performance indicator
PIAG	Public Interest Advisory Group
RCM	Regional Climate Model
SVM	Shared Vision Model
TWG	Technical Work Group
UGLSP	Upper Great Lakes Shore Protection Model
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey



Annex

Glossary

ADAPTATION – The broad context of responses taken and actions implemented to address risk.

ADAPTIVE MANAGEMENT – A planning process that can provide a structured, iterative approach for improving actions through long-term monitoring, modelling and assessment. Through adaptive management, decisions can be reviewed, adjusted and revised as new information and knowledge becomes available or as conditions change.

ACCRETION – An increase by natural growth or addition, used in the Study in terms of increased beach area or wetland.

ADVERSE CONSEQUENCES – Negative implication of fluctuating water levels for social, economic, environmental or political investments.

ANALYTICAL FRAMEWORK – An integrated and systemic approach using science and analytical techniques to understand the physical processes and the relationships between natural forces and human-induced factors, and Great Lakes water levels and flows.

ANTHROPOGENIC – Due to human activities.

AQUATIC VEGETATION GROWTH – Plant growth beneath the surface of water that can generate resistance to water flow in a channel; commonly referred to as weed retardation.

BALANCING PRINCIPLE – In the context of the Study, an important principle in the IJC's regulation plans in which the plans seek to balance the needs of varying interests in the upper Great Lakes basin by providing benefits or relief to interests affected by water levels and flows without causing undue detriment to other interests.

BASIN (UPPER GREAT LAKES) – The focus area of the Study, stretching from the headwaters of Lake Superior all the way downstream to Niagara Falls, an area of about 686,000 km^2 (265,000 mi^2). The area encompasses lakes Superior, Michigan, Huron (including Georgian Bay) and Erie, their drainage basins, and the connecting channels of the St. Marys River, the Straits of Mackinac, the St. Clair River system (including Lake St. Clair and the Detroit River), and the upper Niagara River above the Falls.

BASIN – All land and water within the confines of a drainage basin. Similar term: **Watershed**.

BOUNDARY CONDITIONS – The set of conditions and constraints specified for operating computer models to simulate and analyze water levels and flows in a channel, or other processes, for example, sediment processes.

BOUNDARY WATERS TREATY OF 1909 – The agreement between the United States and Canada that established principles and mechanisms for the resolution of disputes related to boundary waters shared by the two countries. The International Joint Commission was created as a result of this treaty.

BUFFER ZONE – The minimum amount of land needed between a structure and an eroding shoreline before shoreline protection is needed.

CHART DATUM – Water level used to calculate the water depths that are shown on navigation charts. Chart datum for the Great Lakes are selected at an elevation so that the level will seldom fall below it and only rarely will there be less depth available than what is portrayed on the chart. Also known as Low Water Datum in the United States.

CIRCLES OF INFLUENCE – In the context of the Study's public engagement activities, small groups of people whose interest and knowledge on water management issues have gained the trust of others.

CLIMATE – Prevalent weather conditions of a given region (for example, temperature, precipitation, wind speed, atmospheric pressure) observed throughout the year and averaged over a number of years.

CLIMATE CHANGE – A change of climate that is attributed directly or indirectly to human activity, that alters the composition of the global atmosphere, and which is in addition to natural climate variability observed over comparable time periods.

CLIMATE VARIABILITY – Naturally occurring climate phenomenon reflecting the interaction between large bodies of water and the atmosphere for a specified period of time.

COASTAL EROSION – The wearing away of a shoreline as a result of the action of water current, wind and waves.

COMPENSATING WORKS / STRUCTURES – Water control structures placed in the river to offset or compensate the effects of other structures, actions or water diversions on water levels and flows (e.g., the St. Marys River compensating works at Sault Ste. Marie).

COMPONENT METHOD – One of the two methods used to compute Great Lakes net basin supply for a time period (typically monthly) by measuring and/or estimating the components in the water balance – precipitation, evaporation and runoff.

COMPRESSION – In the context of regulating lake levels, the strategy or objective of keeping a lake's water levels within specified upper and lower ranges, typically to provide benefits to one or more interests.

COMPUTER MODELLING – The use of computers to develop mathematical models of complex systems or processes.

CONFIDENCE LEVEL – The degree of likelihood of events or scenarios identified in study findings to occur.

CONNECTING CHANNELS – Natural or artificial waterway linking two bodies of water. Between Lake Superior and Lake Huron, the connecting channel is the St. Marys River. The Detroit River, Lake St. Clair and the St. Clair River comprise the connecting channel between Lake Huron and Lake Erie.

CONSERVATION – The planned management of a natural resource, with the goal of protecting and carefully preserving it from exploitation, destruction or neglect.

CONSUMPTIVE USE – Quantity of water withdrawn or withheld from a water body or basin and assumed to be lost or otherwise not returned, due to evaporation during use, or consumption in manufacturing and other processes.

CONTROL WORKS – Hydraulic structures, such as dams, spillways, canals and channel improvements, built to control outflows and levels of a lake or lake system.

CONVEYANCE – Measure of water flow capacity of a channel.

COPING ZONES – In the context of the Study, a range of water level conditions posing increasing challenge for a particular interest, from "tolerable" to "conditions that would have severe, long-lasting or permanent adverse impacts on the interest." Used in the Study to assess vulnerability to water level fluctuations.

CURRENT – Flow of water described by its velocity or speed and direction.

DECISION-SCALING – In the context of the Study's analysis of the impacts of climate variability and change, an approach to considering interest vulnerabilities and adaptive management. The "bottom up" approach begins with stakeholders, determines the domain of vulnerabilities and then assesses whether those conditions are possible or plausible based on the available climate science.

DESIGN RANGE – The range of factors (including expected water levels) taken into consideration when making an investment decision.

DETERMINISTIC MODEL – A mathematical model or representation in which outcomes are precisely determined through known relationships pertaining to hydraulics, hydrology and water balance.

DIKE – A wall or earth mound built around a low lying area to retard water flow.

DIRECTIVE – An IJC instruction to a new or existing Study Board specifying the study's terms of reference, including tasks and responsibilities.

DISCHARGE – Rate of movement of a volume of water over time, typically expressed in m^3/s and ft^3/s. In this report, the terms discharge and flow are considered interchangeable.

DIVERSIONS – Transfer of water either into the Great Lakes basin from an adjacent watershed, or vice versa, or from the watershed of one of the Great Lakes into that of another.

DRAINAGE BASIN – The area that contributes runoff to a stream, river, or lake.

DREDGING – Removal of lake bed or river bed material to increase water depth for navigation or other purposes.

DYNAMICAL – In the context of climate modelling, dynamical down-scaling approaches use a regional climate model that takes outputs from projections from a global climate model as inputs and simulates climate conditions at a much higher resolution over a smaller area.

ECOLOGY – The science relating living forms to their environment.

ECOSYSTEM – Biological community in interaction with its physical environment, and including the transfer and circulation of matter and energy.

ECOSYSTEM INTEGRITY –State of health of an ecosystem. It encompasses integrated, balanced and self-organizing interactions among its components, with no single component or group of components breaking the bounds of interdependency to singularly dominate the whole.

ENDANGERED SPECIES – A species threatened with extinction.

ENVIRONMENT – The physical setting of air, land and water, together with the plant and animal life, including humans, living in the setting, and the social, economic, cultural, physical, biological and other conditions that may act on an organism or community to influence its development or existence.

ENVIRONMENTAL INTEGRITY – The sustenance of important biophysical processes that support plant and animal life and that must be allowed to continue without significant change. The objective is to assure the continued health of essential life support systems of nature, including air, water, and soil, by protecting the resilience, diversity, and purity of natural communities (ecosystems) within the environment.

EQUITABILITY – The assessment of the fairness of a measure in its distribution of favorable or unfavorable impacts across the economic, environmental, social, and political interests that are affected.

EROSION – The wearing away of river beds, shorelines, and land surfaces through the action of water, waves and wind.

EVAPORATION – Process of liquid water becoming water vapour, including vaporization from water surfaces, land surfaces, and snow fields, but not from plant surfaces.

EXOTIC SPECIES – Non-native species found in a given area as a direct or indirect result of human activity.

FENCEPOST PLAN – In the context of evaluating regulation plan options, a plan in which a single interest is favoured to the exclusion of all other interests.

FLOODPLAIN – The lowlands surrounding a watercourse (river or stream) or a standing body of water (lake), which are subject to flooding.

FLOW – See **DISCHARGE**.

FLUCTUATION – A period of rise and succeeding period of decline of water level. Fluctuations can occur on a short-term basis, seasonally, or over a period of years.

FRAZIL ICE – Stream ice with the consistency of slush, formed when small ice crystals develop in super-cooled stream water as air temperatures drop below freezing. These ice crystals join and are pressed together by newer crystals as they form.

FUNGIBILITY – Something that is exchangeable or substitutable. In this Study, fungibility refers to the degree to which performance indicators are measured in the same units and are comparable.

GENERAL CIRCULATION MODEL (GCM) – See: **Global Climate Model**.

GEOGRAPHICAL INFORMATION SYSTEM (GIS) – An information system used to store and manipulate (sort, select, retrieve, calculate, analyze, model, etc.) geographical data.

GEOSPATIAL –Combination of spatial software and analytical methods with terrestrial or geographic datasets.

GLACIAL ISOSTATIC ADJUSTMENT (GIA) – Gradual rising and subsiding of the earth's crust resulting from the removal of the weight of the glaciers that covered the surface during the last period of continental glaciation (also known as post-glacial rebound).

GLOBAL CLIMATE MODEL (GCM) – A three-dimensional computer representation of climate and its various components, used to predict climate scenarios. Also known as General Circulation Model or Global Circulation Model.

GREAT LAKES WATER QUALITY AGREEMENT (GLWQA) – First signed in 1972, the GLWQA, expresses the commitment of Canada and the United States to restore and maintain the chemical, physical and biological integrity of the Great Lakes basin ecosystem. The Agreement also reaffirms the rights and obligation of Canada and the United States under the *Boundary Waters Treaty*.

GROUNDWATER – Underground water occurring in soils and in pervious rocks.

HABITAT – The particular environment or place where a plant or an animal naturally lives and grows.

HEAD DIFFERENCE – Difference in water surface elevation between two locations (for example, between two lakes, or the upstream end and the downstream end of the river, or the upstream level and downstream level at a hydropower dam).

HINDCAST –Technique used to determine past events based on analysis of data and information related to other past events and processes (*e.g.*, the analysis of geomorphologic features of the Great Lakes shores to generate hydrographs of pre-historic water levels).

HISTOGRAM – In statistics, a graphical representation showing a visual impression of the distribution of data.

HYDRAULIC MODELLING – The use of mathematical or physical techniques to simulate water systems and make projections relating to water levels, flows and velocities.

HYDROLOGIC ATTRIBUTES – Statistics on water levels and stream flows.

HYDROCLIMATIC – Relating to the effects of the components in the water balance of the Great Lakes – precipitation, evaporation and runoff, and the climatic conditions affecting these components.

HYDROCLIMATIC MODEL – Model simulating coupled atmospheric-land hydrologic processes in time and space continuously to generate a quantitative assessment of the Great Lakes water balance under changing climatic conditions and land surface conditions.

HYDROELECTRIC– Electrical energy generated by the action of moving water. Also: **Hydropower**.

HYDROGRAPH – Graph relating water levels or flows over time.

HYDROLOGICAL CYCLE – Cyclic transfer of water vapor from the Earth's surface via evapotranspiration into the atmosphere, from the atmosphere via precipitation back to earth, and through runoff into streams, rivers, and lakes, and ultimately into the oceans.

HYDROLOGICAL MODELLING – The use of physical or mathematical techniques to simulate the hydrologic cycle and its effects on a watershed.

HYDROLOGY –Study of the properties of water, its distribution and circulation on and below the earth's surface and in the atmosphere.

HYDROMETRIC – Pertaining to water discharges or flows, water levels and sedimentation.

INDIGENOUS PEOPLES – In the context of the Study, the Native Americans, First Nations and Métis who make their home in the upper Great Lakes basin.

INTEGRATED ECOLOGICAL RESPONSE MODEL 2 (IERM2) – A model that establishes the framework for evaluating, comparing and integrating the responses for environmental performance indicators.

INTERESTS – In the context of the Study, the key groups or sectors served by the waters of the upper Great Lakes system and most likely to be affected by possible future changes in water levels. Under the *Boundary Waters Treaty of 1909*, domestic and sanitary water uses, navigation, and power and irrigation are given order of precedence. These uses must be taken into account in the development of regulation plans. The Study also addressed three additional interests: ecosystems; coastal zone; and recreational boating and tourism.

INTERNATIONAL GREAT LAKES DATUM (IGLD 1985) – Datum, representing a fixed frame of reference used to measure water levels in a moving environment, currently used to measure water levels in the Great Lakes – St. Lawrence River System. The datum has its zero reference elevation at Rimouski, QC on the St. Lawrence River.

INTERNATIONAL JOINT COMMISSION (IJC) – International independent agency formed in 1909 by the United States and Canada under the *Boundary Waters Treaty* to prevent and resolve boundary waters disputes between the two countries. The IJC makes decisions on applications for projects such as dams in boundary waters, issues Orders of Approval and regulates the operations of many of those projects. It also has a permanent reference under the Great Lakes Water Quality Agreement to help the two national governments restore and maintain the chemical, physical, and biological integrity of those waters.

INTERNATIONAL LAKE ONTARIO – ST. LAWRENCE RIVER STUDY – A study sponsored by the IJC to examine the effects of water level and flow variations on all users and interest groups and to determine if better regulation is possible at the existing installations controlling Lake Ontario outflows. The Study issued its final report in March 2006.

INTERNATIONAL ST. LAWRENCE RIVER BOARD OF CONTROL – Board established by the International Joint Commission in its 1952 Order of Approval. Its main duty is to ensure that outflows from Lake Ontario meet the requirements of the Commission's Order. The Board also develops regulation plans and conducts special studies as requested by the Commission.

INTERNATIONAL REACH – The portion of the St. Lawrence River that is between Lake Ontario and the Moses-Saunders Dam.

LAKE OUTFLOW – The amount of water flowing out of a lake.

LEVEL FLUCTUATION – Changes in water levels in response to natural forces and human activities.

LEVEL (MEAN, MAXIMUM and MINIMUM) – Arithmetic average, highest and lowest values of all past observations of water levels for a specified period of record, or of a set of computer-simulated water levels.

LITTORAL – Pertaining to or along the shore, particularly to describe currents, deposits and drift.

LITTORAL DRIFT – The movement of gravel, sand and other beach material along the coast, caused by waves and currents.

LITTORAL ZONE – The area extending from the outermost breaker or where wave characteristics significantly alter due to decreased depth of water to: either the place where there is marked change in material or physiographic form; the line of permanent vegetation (usually the effective limit of storm waves); or the limit of wave uprush at average annual high water level.

LOWER ST. LAWRENCE RIVER – The portion of the St. Lawrence River downstream of the Moses-Saunders Dam. It includes Lac St. Francis, Lac St. Louis, Montreal Harbour, Lac St. Pierre and the portions of the river connecting these lakes as far downstream as Trois Rivieres, QC.

MARINA – A private or publicly-owned facility allowing recreational watercraft access to water, and offering mooring and other related services.

MARSH – An area of low, wet land, characterized by shallow, stagnant water and plant life dominated by grasses and cattails.

MEAN VELOCITY – Average velocity of water flow in a river at a given cross-section. It is equal to the flow rate divided by the cross-sectional area.

METADATA – Data (information) about the characteristics of data such as content, quality (condition, accuracy), date of capture, user access restrictions and ownership.

METEROLOGICAL – Pertaining to the atmosphere or atmospheric phenomena, including weather and climate.

MITIGATION – In the context of the Study, structural or non-structural measures designed to address future actions that might result in adverse effects.

MODEL –A mental conceptualization, a physical device or a structured collection of mathematical, statistical, and/or empirical statements.

MODEL CALIBRATION – Process of modifying the input parameters to a model until the output from the model matches an observed set of data.

MODEL VALIDATION – Assessment of the ability of a model to generate results that match real-world measurements, including the assurance that the model has been programmed correctly.

MONTHLY MEAN WATER LEVEL – The arithmetic average of all past observations (of water levels or flows) for that month. The period of record used in this Study commences January 1900.

MULTI-LAKE REGULATION – In the context of the Study, the possibility of operating regulation structures to benefit the Great Lakes-St. Lawrence River system as a whole to keep the entire system within observed historical extremes on all lakes under more extreme climate conditions in the future.

NET BASIN SUPPLY (NBS) – Net amount of water entering a lake, consisting of the precipitation onto the lake minus evaporation from the lake, plus groundwater and runoff from its local basin, but not including inflow from an upstream lake.

ORDERS OF APPROVAL – In ruling upon applications for approval of projects affecting boundary or transboundary waters, such as dams and hydroelectric power stations, the IJC can regulate the terms and conditions of such projects through Orders of Approval to maintain specific targets with respect to water levels and flows in the lakes and connecting channels.

OUTFLOW – The quantity of water flowing out of a lake through surface rivers or streams, measured in time units at a given point.

PALEO – A combining form meaning "old" or "ancient," especially in reference to former geologic time periods, used in the formation of compound words, as in paleo-hydrology.

PARAMETERS, MODEL – Mathematical terms, variables and constants, used in computer models.

PEAKING –The process of increasing water flow to generate more electricity when the value of power is high.

PEER REVIEW – Process of subjecting a study method and associated analytical techniques and assumptions to the scrutiny of independent experts.

PERFORMANCE INDICATOR – A measure of economic, social or environmental health. In the context of the Study, performance indicators relate to impacts of different water levels in the upper Great Lakes on the various interests.

PLAN 1958-D – The IJC's current regulation plan for Lake Ontario, in effect since 1963.

PLAN 1977A – The IJC's current regulation plan for Lake Superior outflows, in effect since 1990.

PRECIPITATION – Condensation of atmospheric water vapour that falls to the earth's surface in the form of rain, snow, hail and sleet.

PLAUSIBILITIES – In the context of the Study, subjective probabilities of future climate states, based on a compilation of climate information, that were used for sensitivity analysis in place of formally evaluating risk.

PONDING – The process of storing (or ponding) water upstream when demand for electricity is lower or in response to flood control needs.

PRECAUTIONARY PRINCIPLE – 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."

PUBLIC INTEREST ADVISORY GROUP (PIAG) – Independent advisory group set up by the IJC to assist the Study Board in the development and implementation of a public information and engagement plan over the course of the Study.

PUBLIC INFORMATION AND ENGAGEMENT – A proactive, coordinated process of informing the public throughout the course of the Study and providing opportunities to interested individuals and organizations to make their views known and to review and comment on preliminary findings.

REACH – A segment of a river, typically referring to a segment with fairly uniform physiographic and/or hydraulic features.

REGIONAL CLIMATE MODEL (RCM) – Computer model using mathematical equations from the basic laws of physics, fluid motion and chemistry for weather forecasting, understanding climate and projecting climate change at the scale of a region, such as the Great Lakes basin, rather than globally.

REGIME – A set of physical conditions and relationships, as in hydraulic regime or sediment regime.

REGULATION, WATER LEVEL, OUTFLOW – Artificial changes to lake levels or outflows to achieve certain objectives.

REGULATION PLANS – Control of land and water use in accordance with rules designed to accomplish certain goals. In the context of the Study, the IJC has implemented a series of regulation plans since 1921 to regulate the outflows from Lake Superior to meet the needs of various water-using interests in the upper Great Lakes basin.

REGULATORY STRUCTURES – Adjustable structures, such as a gated dam that can be raised or lowered to adjust water levels and flows both upstream and downstream.

REMEDIATION (REMEDIAL OPTIONS) – In the context of this Study, structural and non-structural measures designed to address past damages or adverse changes.

RESIDUAL METHOD – One of the two methods used to compute Great Lakes net basin supply for a time period (typically monthly) by determining the outflow of the lake and the inflow from the lake upstream of it, and the change in water storage on the Lake.

RESILIENCE – In the ranking of candidate regulation plans, the average amount of time it takes to get back in compliance. It is calculated as the total number of quarter-months of failure divided by the number of failures.

RESILIENCY – The ability to readily recover from an unexpected event.

RESTORATION – In the context of the Study, providing a permanent increase in Lake Michigan-Huron water levels, relative to what they would otherwise be, by constructing structures in the St. Clair River so as to reduce the river's conveyance capacity (*i.e.*, ability to discharge water).

RESTORATION STRUCTURES – In the context of the Study, structures such as submerged sills, dikes and weirs that are designed to restore Lake Michigan-Huron water levels.

RETARDATION, FLOW – Reduction in the flow of water in the channel due to obstructions or the presence of ice or aquatic vegetation in the river.

RIPARIAN – Of, relating to or found along a shoreline.

RIPARIANS – Persons residing on the banks of a body of water.

RIVERINE – Of or relating to a river or a riverbank.

ROBUSTNESS – In the context of the Study, the capacity of a regulation plan to meet particular regulation objectives under a variety of uncertain future water supply and water level conditions.

RUNOFF – Portion of precipitation that falls on a water body's land basin that ultimately reaches the water body.

SCENARIO, CLIMATE – Description of an event or series of events.

SEAWALLS – Structures parallel to the shore designed to protect the land and property behind the wall from damage by storm wave action, and to prevent the land from sliding onto the beach or into the water.

SHARED VISION MODEL – A modelling tool used to assist in the evaluation and comparison of alternative plans. It allows various interests to enter different criteria and learn about potential outcomes under different regulation plans.

SILLS – Underwater obstructions placed to reduce a channel's flow capacity.

STOCHASTIC – Statistics involving or showing random behaviour. In a stochastic simulation, a model is used to create a new 'synthetic' series of plausible flows and lake levels, based on historical data. The synthetic series will, on average, preserve important properties of the historical record, such as the mean and standard deviation, while generating new combinations of high and low flow conditions that could represent more severe conditions than those seen in the past.

STOCHASTIC SUPPLIES – Simulated sequences of net basin supply conditions that reflect variable climatic conditions.

SURFACE WATER – Water open to the atmosphere including lakes, ponds, rivers, springs, wetlands, artificial channels and other collectors directly influenced by surface water.

TECHNICAL WORK GROUP (TWG) – In the context of the Study, a team of scientific and technical experts formed to examine specific issues related to the development of regulatory options, including the key interests served by the waters of the upper Great Lakes basin, hydroclimatic conditions, plan formulation and evaluation, adaptive management, and information management.

TELECONNECTIONS – Study of climate anomalies related to each other over large distances (typically thousands of kilometres).

UPPER ST. LAWRENCE RIVER – The portion of the St. Lawrence River upstream of the Moses-Saunders Dam. It includes the entire river from Kingston/Cape Vincent to the power dam and locks at Cornwall-Massena, including Lake St. Lawrence.

WATER BALANCE – An accounting of the quantity of the water entering and leaving a lake by precipitation, evaporation, runoff, outflow, groundwater flow, diversions, and consumptive uses.

WATER LEVEL – The elevation of the surface of the water of a lake or at a particular site on the river. The elevation is measured with respect to average sea level.

WATER SUPPLY – Water reaching the Great Lakes as a direct result of precipitation, less evaporation from land and lake surfaces.

WATERSHED – See: **BASIN**.

WEATHER – The meteorological condition of the atmosphere defined by the measurement of the six main meteorological elements: air temperature; barometric pressure; wind velocity; humidity; clouds; and precipitation.

WEIR – A natural or human-made overflow dam that raises water levels upstream.

WETLAND(S) – Area characterized by wet soil and high biologically productivity, providing an important habitat for waterfowl, amphibians, reptiles and mammals.

Measurement Unit Conversion Factors

Metric System – United States Customary System Units

(with abbreviations)

Length

1 millimeter (mm) = 0.0394 inch (in)

1 in = 25.4 mm

1 centimetre (cm) = .3937 in

1 in = 2.54 cm

1 metre (m) = 3.2808 feet (ft)

1 ft = 0.3048 m

1 kilometre (km) = 0.6214 mile (mi)

1 mi = 1.6093 km

Area

1 square kilometre (km^2) = 0.3861 square mile ($mile^2$)

1 $mile^2$ = 2.59 km^2

Weight

1 kilogram (kg) = 2.22 pounds (lb)

1 lb = 0.45 kg

1 metric tonne (mt) = 1.1 short tons (2,000 lb)

Volume

1 litre = 0.22 gallon (British) or 0.26 gallon (US liq) or 0.001 cubic metre (m^3)

1 m^3 = 1.308 yard $(yd)^3$

1 yd^3 = 0.7645 m^3

Flow Rate

1 m^3 a second (m^3/s) = 35.315 cubic feet a second (ft^3/s)

1 ft^3/s = 0.02832 m^3/s

Temperature

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$°F=(1.8×°C)+32$


INTERNATIONAL JOINT COMMISSION • COMMISSION MIXTE INTERNATIONALE
1909
INTERNATIONAL
Upper Great Lakes
STUDY