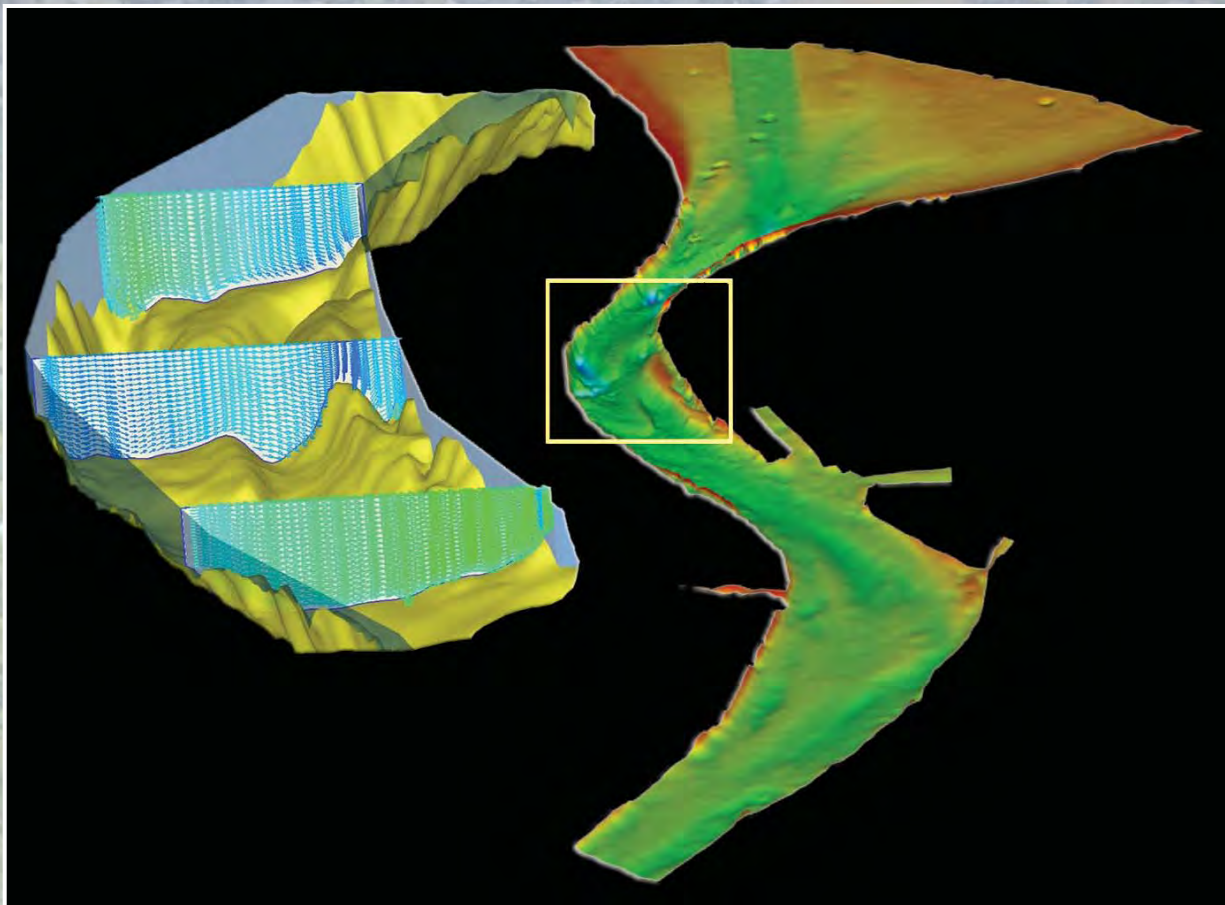




IMPACTS ON UPPER GREAT LAKES WATER LEVELS: ST. CLAIR RIVER



FINAL REPORT TO THE INTERNATIONAL JOINT COMMISSION
DECEMBER 2009

Report Cover

The front cover shows two images of the St. Clair River prepared by the HydroSed2D model and Geographic Information System rendering based on data collected by underwater multi-beam sonar surveys of the river bed in the summer of 2008. The image to the right shows the channel morphology (depth and shape) from the mouth of the St. Clair River downstream for about 10 kilometres (6.2 miles). The yellow areas indicate shallower areas and there is a transition to blue, the deepest areas in the river. The image to the left illustrates typical velocities and flow directions in this first bend of the river. Green reflects higher velocities, while blue indicates lower velocities.

The background image of the cover, taken from an underwater video survey conducted in the summer of 2008 at depths of 12 to 14 metres (39 to 46 feet) shows the mostly gravel material found on the river bed in the upper reach of the St. Clair River.

Using data collected from these types of surveys, and applying the best available models, scientists and engineers have improved our understanding of the hydraulics and morphology of the St. Clair River and, in turn, the effects on the river of natural forces and recent human activities.

Front cover graphic credit: Dr. Syed Moin, Study Co-Manager

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, or to view the Study's 34 scientific/technical reports, please visit the Study's website: **www.iugls.org**

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December 1, 2009

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Ms. Irene B. Brooks
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Dear Chairpersons Gray and Brooks:

On behalf of the International Upper Great Lakes Study Board, we are pleased to submit our final report entitled “**Impacts on Upper Great Lakes Water Levels: St. Clair River.**” This report reflects the scientific findings of more than two years of study conducted under an accelerated schedule. The work represents a truly bi-national effort, with more than 100 scientists, engineers and technical experts involved. This Study has undergone an unprecedented level of peer review, both internally and externally, and extensive public review.

The Study Board made its recommendations after careful consideration of all the scientific information, factoring in the uncertainty of the data and information, and in light of the International Joint Commission’s Directive.

Respectfully submitted,

Ted R. Yuzyk
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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 and writing of the *St. Clair River Report*. Their cooperation, expertise and professionalism enabled the report to be completed under an accelerated and challenging schedule.

Their efforts have helped produce a comprehensive report, based on sound science and peer-reviewed analysis, that greatly strengthens our understanding of the St Clair River system and how it affects water levels in the upper Great Lakes.

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



Members of International Upper Great Lakes Study Board are (left to right):

Ted Yuzyk, Allan Chow, Dr. Syed Moin (Study Co-Manager), Dr. Anthony Eberhardt (Study Co-Manager), Jonathan Gee, Dr. James Bruce, James Bredin, Kay Felt, Dr. Jonathan Bulkley, Dr. Donald Burn, Dr. Eugene Stakhiv. (Missing: Dr. John Boland).

Photo credit: Dr. Paul Pilon, International Joint Commission

Photo taken in Windsor, ON, at the statue of the Right Honourable Herb Gray, Canadian Chairman of the International Joint Commission (2002-2010).

EXECUTIVE SUMMARY

SCOPE AND OBJECTIVES

Impacts on Upper Great Lakes Water Levels: St. Clair River is the first of two major reports presenting the findings and recommendations of the bi-national International Upper Great Lakes Study (the Study). The Study is a five-year investigation launched by the International Joint Commission in 2007 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 (Report 1); 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 (Report 2, to be completed in 2012).

The geographical scope of the Study consists of the upper Great Lakes basin from the headwaters of Lake Superior downstream through Lake Michigan-Huron to Lake Erie and including the interconnecting channels (the St. Marys, St. Clair and Detroit Rivers and the Niagara River to Niagara Falls).

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

STUDY FOCUS

The St. Clair River part of the Study was established to address widespread concerns among governments at all levels, property owners and other interests about the long term economic and environmental effects of low water levels in the upper Great Lakes. Scheduling of the St. Clair River work was accelerated by nearly one year to address these concerns on an urgent basis.

A progressive decline in the lake-to-lake fall or head difference between Lake Michigan-Huron and Lake Erie since measurements of lake levels began in 1860 is well-documented. Figure Ex-1 illustrates how this difference has changed considerably from 1860 to the present day and how it fluctuates from year to year. Records of annual mean water levels recorded at Harbor Beach, Michigan on Lake Huron and Cleveland, Ohio on Lake Erie show that the head difference between the two lakes was about 2.9 metres (m) (9.5 feet [ft]) between 1860 and 1880. The difference then decreased sharply through the turn of the century and generally continued to decline for more than 100 years. In 2008, the head difference was about 1.9 m (6.2 ft). Between 1963 and 2006, the time period on which the Study focused, the head difference declined by about 23 centimetres (cm) (9 inches).

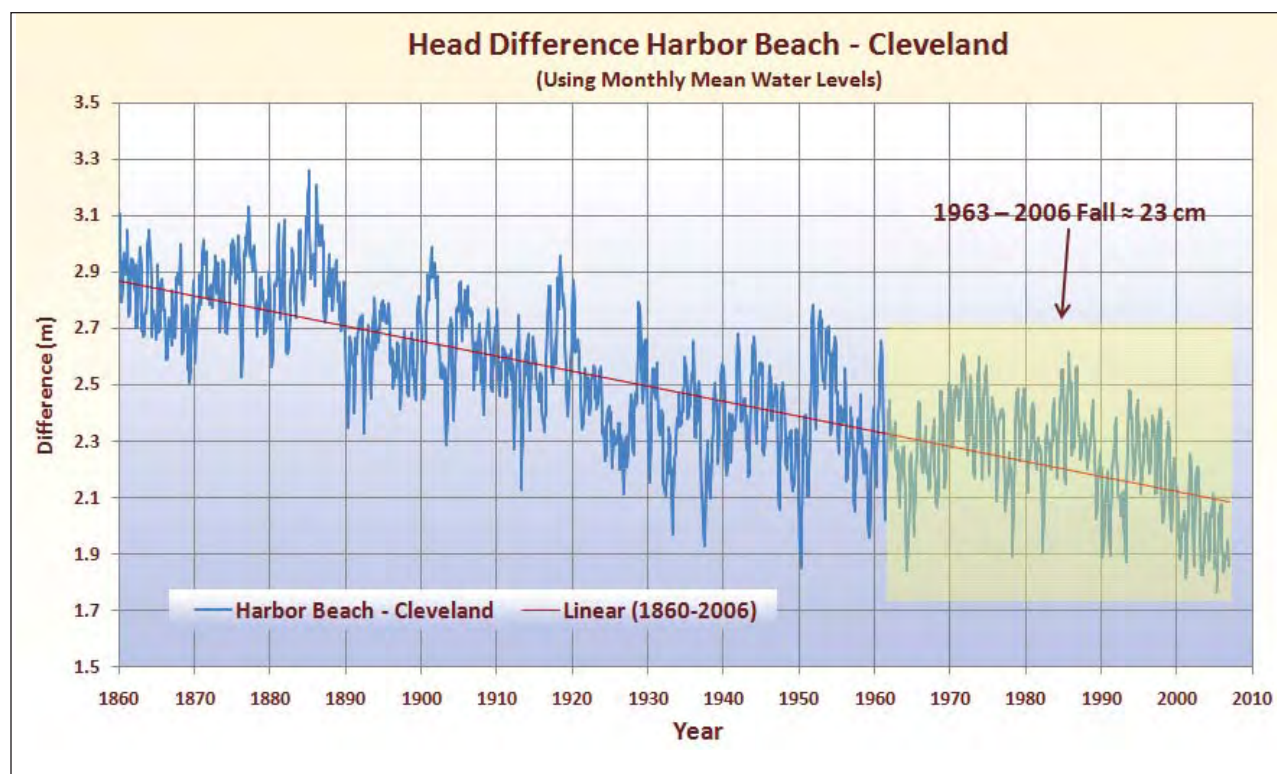
The central challenge of the St. Clair River Study was to determine what factors are responsible for this change in lake-to-lake fall between Lake Michigan-Huron and Lake Erie. Answering this question required an examination of the physical processes and possible ongoing changes in the St. Clair River and the effects on the level of Lake Michigan-Huron relative to Lake Erie.

SCIENCE QUESTIONS

The Study Board formulated a series of core science questions and designed applied research projects to generate information needed to answer the questions. Some of the applied research projects were designed to address more than one science question, so that the Study could address a particular question from a number of perspectives. The core science questions were:

- *Has the “morphology” (the shape and composition of the river bed) of the St. Clair River been altered since the 1962 dredging?*
 - *Is the St. Clair River bed stable or eroding?*
 - *If the bed of the St. Clair River is eroding, what initiated the erosion, and when?*

Figure Ex-1 The Head Difference (Lake-to-Lake Fall) between Lake Michigan-Huron and Lake Erie



► What is causing the declining head difference between Lake Michigan-Huron and Lake Erie?

- Has the conveyance of the St. Clair River changed since 1962?
- If the conveyance has changed, what were the causes?

► How has glacial isostatic adjustment (GIA) affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?

► How has climate affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?

Nearly 100 scientists and engineers from governments, academia and the private sector in both countries worked together, with input from the public, to plan and undertake the necessary investigations, analyze the results and prepare the Study's findings. Their work drew on many disciplines, including engineering, hydrology, hydraulics, geology, sedimentology, physics and climatology.

The Study required data analysis and modelling efforts with a high level of precision and accuracy. One significant challenge identified early on was a lack of reliable historical data and the uncertainty associated with some early

historical data on water levels, flows, and the river bed composition. To address these challenges, the Study collected new field data using the most advanced technology and conducted a critical review of past historical data prior to their use in analytical and modelling tasks. The most recently developed and advanced models also were used.

STUDY APPROACH

The analytical framework for addressing the science questions was structured to examine the issue from four perspectives that are integral to determining whether conveyance changed, when it changed, and how much it changed. The four perspectives were:

- **sediment (morphology) regime**, examining the sediment processes in the St. Clair River to determine whether the river bed is eroding or stable;
- **hydraulic regime**, focusing on understanding the relationships between levels and flows for the St. Clair River, how changes in the river bed (e.g., changes to its geometry, scouring and deposition) have affected conveyance, and the effects on upper Great Lakes water balance;

- **GIA**, addressing the implications on water balance calculations of the rise and fall of the earth's crust across the upper Great Lakes basin; and
- **hydroclimatic conditions and patterns**, examining the components in the water balance (precipitation, evaporation and runoff) to determine how they affect water levels and flows.

STUDY REVIEW PROCESSES

There was an unprecedented intensive, multi-level review process throughout the Study's various stages of planning, analysis and reporting. This review consisted of the following elements:

- members of a peer review group, working independently of the Study, provided their views directly to the International Joint Commission on the draft St. Clair River Report, drafts of the key scientific chapters, and eight of the major scientific/technical reports. They reviewed the methodology of the different perspectives of the Study and the scientific validity of the analyses and findings;
- intensive, systematic internal peer reviews, together with a continuous series of exchanges of data and reviews, were undertaken throughout the Study by the various Study investigators engaged in the technical work groups as well as by the Study Board; and
- a broad series of public consultations on Study strategies and reports were conducted, with the assistance of the Public Interest Advisory Group.

These multiple and continuous levels of review resulted in a dynamic and responsive Study process. Many different hypotheses were tested, results were compared, and analyses were undertaken to accommodate the various public and peer review concerns. In some cases, original hypotheses were adjusted or rejected, while in others, new ones were introduced to explain apparent phenomena that were identified in the projects. Technical work groups met frequently to share information, identify key issues and reconcile any differences. New methods and approaches were frequently proposed and implemented to deal with the uncertainties of the data. These continuous internal and external peer reviews resulted in improved Study outcomes, a higher degree of confidence in the results and a substantially modified and improved final report from the draft report released for comment May 1st, 2009.

ADDRESSING SCIENTIFIC UNCERTAINTY

The Study Board recognized the need to translate the scientific uncertainties embodied in the sources of information, the various physical factors, model outputs and statistical ambiguities, into a coherent set of decisions that displayed degrees of confidence in the various contributing pieces of information. This was important not only for the Study's own internal decision processes and transparency, but also for reporting its findings and recommendations to the International Joint Commission and the public. Therefore, the Study Board adopted an approach that expressed degrees of confidence to deal with the scientific uncertainties inherent in the various sources of information upon which its conclusions were based.

Overall, the Study Board was highly confident or confident in the findings regarding the relative contributions of the key factors to the decline in head difference, and the scientific underpinnings of the quantification of conveyance change. The Study Board had a lesser degree of confidence in attributing the causes of conveyance change. The Board examined several different plausible causes of conveyance change, including maintenance dredging, navigation traffic and ice jams, but could not substantiate any specific cause.

SUMMARY OF CONCLUSIONS

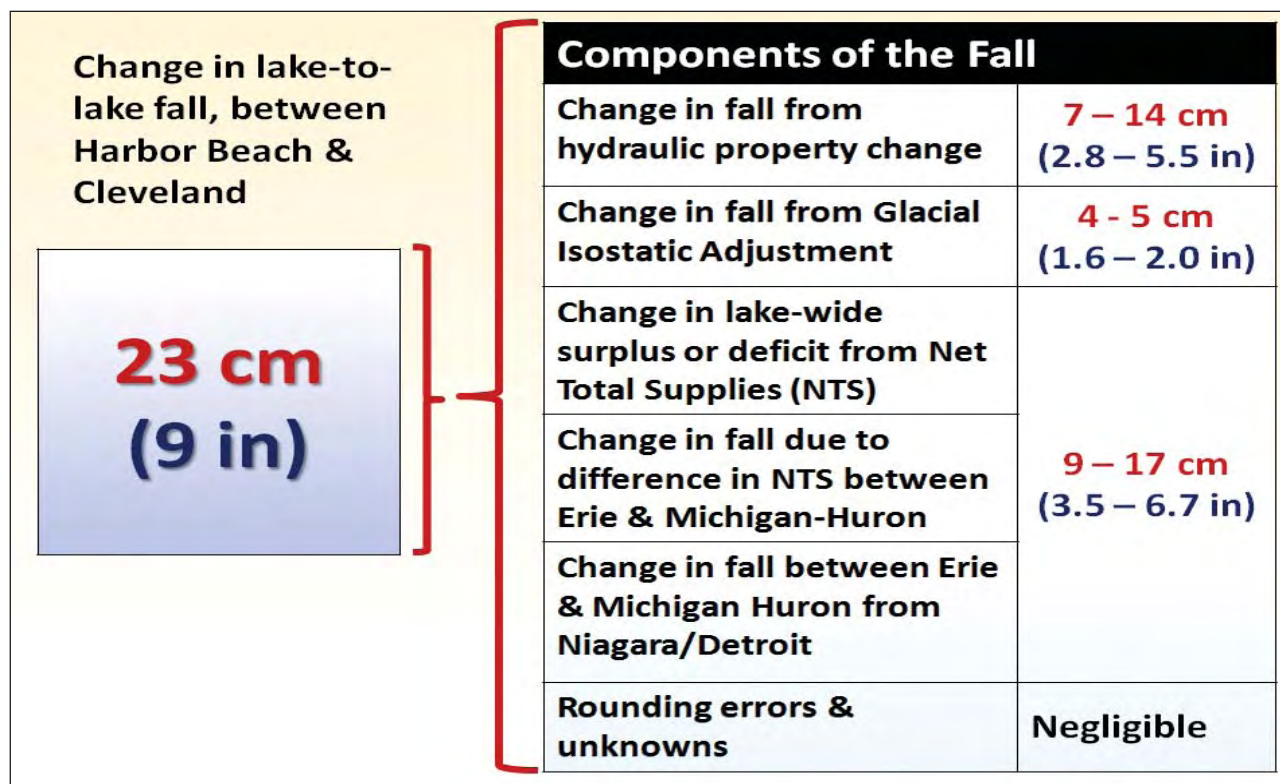
The Study's conclusions are linked to the basic science questions and the findings of the analyses undertaken in the four key areas of study: sediment/morphology; hydraulics; GIA; and hydroclimatology. On the basis of these findings, the Study Board made the following conclusions:

- ▶ The total decline in the head difference between Lake Michigan-Huron and Lake Erie between 1963, following the last major dredging, and 2006, based on a long-term linear trend of data since 1860, is calculated to be about 23 cm (9 inches).
- ▶ There is no evidence of ongoing erosion in the St. Clair River, according to the comprehensive bathymetric surveys undertaken since 2000 and sediment modelling results. It is difficult to state when the period of a stable morphologic regime began, but it may have coincided with the relatively low lake levels of the past decade.
- ▶ Based on 15 different analyses, the decline in head difference specifically due to conveyance changes since 1971 accounts for 7 to 14 cm (2.8 to 5.5 inches) of the 1963 to 2006 decline.

- ▶ Given that there are no bathymetric surveys between 1971 and 2000, it is difficult to determine when the conveyance in the St. Clair River may have changed and whether this change was progressive or episodic in nature. There are three different analyses that suggest that the conveyance change was episodic and occurred in the mid-1980s, followed by a gradual transition to the current regime.
- ▶ Overall, the change in conveyance in the St. Clair River likely has been the result of a combination of several factors. The Study determined that while the record ice jam of 1984 was not the key contributing factor, it did appear to play some role. Fluctuations between extreme highs and lows of upper Great Lakes water levels, such as those experienced in the mid-1980s, also could have contributed to the increase in the river's conveyance. Other possible minor contributing factors to the change in conveyance could include seasonal ice jams, maintenance dredging in the river, shipwrecks and the construction of shoreline protection works.
- ▶ GIA also contributed to the head difference decline. Between 1963 and 2006, it accounted for about 4 to 5 cm (1.6 to 2.0 inches), based on a comprehensive analysis.
- ▶ Changing hydroclimatic conditions (particularly a substantial decline in Lake Michigan-Huron Net Total Supplies) have been major factors in the 23 cm (9 inches) decline in the head difference. Hydroclimatic factors accounted for 40 to 74 percent, or about 9 to 17 cm (3.5 to 6.7 inches), of the decline over this full 43-year period. The influence of hydroclimatic factors appears to be increasing in more recent years, however, accounting for 58 to 76 percent of the decline in the 1996-2005 period.
- ▶ Given the nature of the hydraulic relationship between head and discharge, the relative levels between the lakes adjust to the new hydraulic regime. In an assumed steady state, a new lower water level equilibrium is established, typically within two to three years of any change in conveyance. The St. Clair River is dynamic in nature, however, and the steady state assumption is rarely realized.

Figure Ex-2 summarizes the contributions of the key factors to the decline in head difference between Lake Michigan-Huron and Lake Erie between 1963 and 2006.

Figure Ex-2 Summary Results of Contributing Factors



STUDY BOARD RECOMMENDATIONS

The International Joint Commission has the authority, under the *Boundary Waters Treaty of 1909*, to recommend that the Canadian and U.S. governments undertake compensation measures in boundary waters. Compensation measures can include *remedial measures* to address past damages or adverse effects and *mitigative measures* to address future changes that might result in adverse effects.

The Study Board developed two sets of recommendations on the basis of the findings and in accordance with its mandate.

1. Principal Recommendations

1.1 Compensation Measures

The Study Board recommends that remedial measures not be undertaken in the St. Clair River at this time.

The Study's findings indicated that the increase in conveyance in the St. Clair River is not ongoing, and that, based on bathymetry from 2000 on, conveyance has slightly decreased. In addition, the change is small relative to the degree of scientific uncertainty associated with the various analyses and data measurements. Furthermore, the conveyance change is likely the result of a combination of factors, rather than any single factor.

Given these findings and in accordance with its mandate, the Study Board concluded that remedial measures for the St. Clair River to address changes in the river since the 1962 dredging are not warranted at this time.

1.2 Addressing Effects of Long-Term Climate Change

The Study Board recommends that 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.

Climate change has emerged as a critical but uncertain factor in the future of the upper Great Lakes. There is general world-wide consensus among scientists that climate change, driven by increasing concentrations of greenhouse gases in the atmosphere, is occurring and will continue, though its effects will differ from one region to another. Understanding the effects of climate change is essential to the management of the Great Lakes, including government and community efforts to reduce and adapt to those effects.

The second part of the Study, now underway, is examining current and emerging issues related to the regulation of Lake Superior, including the effects of climate change on water supplies in the upper Great Lakes basin. It is appropriate, therefore, to consider any possible future mitigative measures in the St. Clair River in the context of this broader assessment of future water supplies in the entire upper Great Lakes.

2. "Legacy" Recommendations:

Over the course of the St. Clair River Study, investigators identified serious barriers to their work. These barriers included a lack of reliable data and a lack of standardization of data collection and reporting among the many federal, state, provincial and local agencies and organizations responsible for managing various components of the Great Lakes' waters and related water resources sectors. Together, these barriers reduce our capability to understand and manage the complex systems affecting the Great Lakes.

Recognizing these concerns, the Study Board developed a series of secondary recommendations to the International Joint Commission identifying specific needs in the areas of data collection, modelling and coordination. These include specific recommendations that:

- Bathymetric surveys be conducted every five years to monitor any changes in the bed of the St. Clair River;
- The four new stream flow gauging stations and the two eddy co-variance (evaporation) gauging stations installed as part of the Study be supported following the completion of the Study in 2012; and
- Accountability and coordination in the collection and management of essential data on the Great Lakes be strengthened by formalizing the mandate of the bi-national Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data and having the Committee formally report to the International Joint Commission.

Implementation of these measures by governments will be an important part of the legacy of the Study, helping provide water resource managers and policy makers with the essential information they need to manage the upper Great Lakes more effectively under changing climate conditions.

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CHAPTER 1

INTRODUCTION TO THE ST. CLAIR RIVER REPORT

Chapter 1 provides an introduction to the St. Clair River Report. It presents the objectives, scope, origin and organization of the International Upper Great Lakes Study (the Study), and summarizes the general findings of the peer and public review processes undertaken as part of the preparation of the report.

1.1 INTRODUCTION

1.1.1 Objectives of the International Upper Great Lakes Study

Impacts on Upper Great Lakes Water Levels: St. Clair River (St. Clair River Report) is the first of two major reports presenting the Study's analysis, findings and recommendations. The Study is a five-year investigation launched by the International Joint Commission in 2007 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 (**Report 1**); 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 (**Report 2**, to be completed in early 2012).

The International Joint Commission is an independent bi-national organization created in 1909 to prevent and resolve disputes regarding many of the lakes and rivers along the border between Canada and the United States. This role includes approving the construction and management of works that affect levels and flows in boundary waters. At the request of both governments, the International Joint Commission also has a role in helping the two countries restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes.

The work undertaken in both the St. Clair River and Lake Superior parts was specified in the 2005 Plan of Study for the Upper Great Lakes (Upper Lakes Plan of Study Revision Team, 2005), and reaffirmed by the International Joint Commission in its 2007 *Directive to the International Upper Great Lakes Study Board* (the Study Board). The entire five-year Study is budgeted to cost about \$17.5 million (CDN) or \$14.6 million (US) (at 2005 exchange rates), with this first report on the St. Clair River accounting for about 25 percent of the total. Funding for the Study is shared equally by the governments of Canada and the United States.

Preparation of the St. Clair River Report required the close cooperation of the Canadian and United States governments, state and provincial governments, as well as regional and municipal governments in both countries in the Study area. The work required the integration of a number of disciplines, including engineering, hydrology, hydraulics, geology, sedimentology, physics and climatology. Nearly 100 Canadian and United States scientists and engineers from governments, academia and the private sector worked together, with input from the public, to plan and undertake the necessary investigations, analyze the results, and prepare the report's findings and recommendations.

1.1.2 The Study Setting

From any perspective – economic, social or environmental – the Great Lakes are of tremendous importance to Canada and the United States. The Great Lakes region is home to millions of people who depend on the lakes as the largest single source of surface freshwater in the Western Hemisphere. The Great Lakes support rich ecosystems and diverse animal and plant species, and are the foundation of major industries such as manufacturing, shipping, tourism,

Paragraph 1 of

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

Signed, February 7th, 2007

"1. 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."

power generation and commercial fishing. Many Native American communities and First Nations rely on the natural resources provided by the Great Lakes to meet their economic, cultural, medicinal and spiritual needs.

The Study Area

The entire Great Lakes basin is about 1,100 km (700 mi) long measured north to south and about 1,500 km (900 mi) in width measured west to east (Nicholas, 2003). 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 km² (265,000 mi²) (Figure 1-1). The upper Great Lakes system encompasses Superior, Michigan, Huron (including Georgian Bay) and Erie, and the connecting channels of the St. Marys River, the Straits of Mackinac, the St. Clair River system, and the Niagara River. For the purposes of this Study, Lakes Michigan and Huron are considered a single lake because they have the same surface water elevation due to their shared connection at the broad and deep Straits of Mackinac. In addition, Lake Erie is included in the Study, given its importance in determining the water levels in Lake Michigan-Huron.

Overview of the Geology and Climate of the Study Area

The Great Lakes were formed by complex geological and geomorphologic processes and shaped by successive continental glaciation, the last of which ended about 10,000 years ago. The Great Lakes and their drainage basins are contained generally within three physiographic regions:

- The *Pre-Cambrian* region consists of metamorphic and igneous rocks that surround most of Lake Superior and northern Lake Michigan-Huron. This region is very rocky and has little or no overburden.
- The *Central Lowlands* region is covered mostly by unconsolidated deposits from glaciers and glacial meltwater. The topography is generally flat and rolling. Much of the shoreline consists of till bluffs that can experience severe erosion. Sand beaches and dunes are also found along the shores of Lake Michigan-Huron, and parts of Lakes Erie and Ontario.
- The *St. Lawrence Lowlands* region is the wide flat valley occupied by the St. Lawrence River system. The Niagara Escarpment portion of this region extends northwest from the Niagara River to the Bruce Peninsula and Manitoulin Island, in Ontario.

The climate of the Great Lakes basin varies considerably due to the basin's north-south extent and the effects of the lakes on near-shore temperatures and precipitation. For example, mean annual snowfall ranges from about 51 cm (20 in) in the southern areas of the basin, to 355 cm (140 in) in snow-belt areas downwind of Lakes Superior and Ontario (Nicholas, 2003).

Wind is also an important component of the Great Lakes climate. In fall and winter, very strong winds from weather systems moving across the region are common. In near-shore areas, very strong winds can result from the temperature differences between the lakes and the air moving over the water.

Figure 1-1 International Upper Great Lakes Study Area



Measurement Units Used in the Report

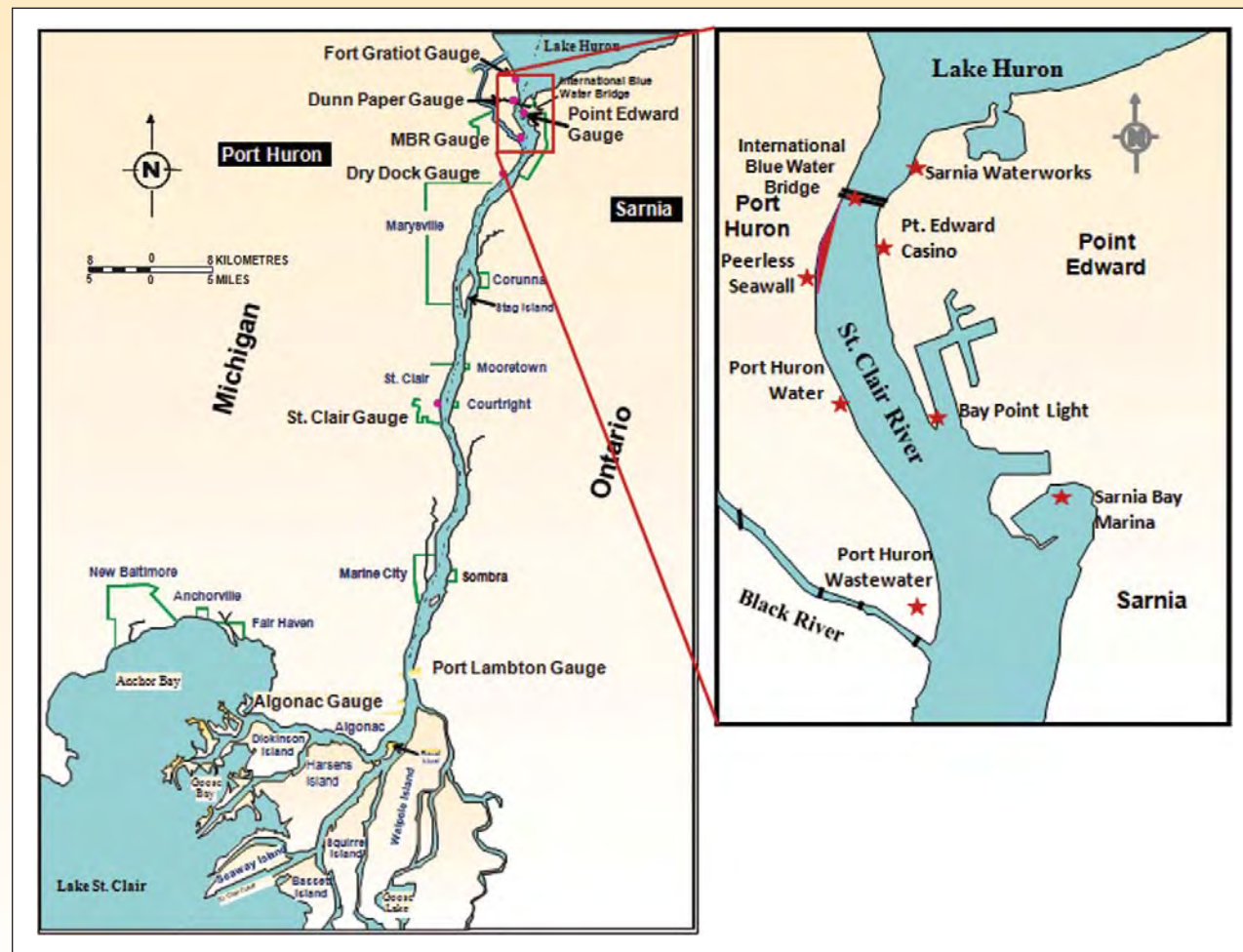
Metric units are presented first in this report, given that most of the collection, modelling and analyses of data undertaken in the Study used the metric system. The equivalent U.S. customary system units are provided (including those from past official documents where only customary system units were used). A table listing the conversion factors between the two systems of units is included in the inside back cover of the report.

1.1.3 Scope of the St. Clair River Report

The St. Clair River system consists of the St. Clair River, Lake St. Clair and the Detroit River. The Study focused on the St. Clair River to Lake St. Clair (Figure 1-2), given the role of the river in affecting water levels in Lake Michigan-Huron and Lake Erie.

The report addressed the question of whether natural and/or human-caused changes in the St. Clair River (after the last major channel enlargement that ended in 1962) have changed the river's conveyance (or water-carrying capacity), and what effects, if any, such a change may have had on the water levels of Lake Michigan-Huron, Lake Erie and Lake St. Clair. In noting that, on average, the levels of Lake Michigan-Huron have fallen relative to those of Lake Erie in recent years, the Study also examined other factors, such as the real and/or apparent effect of glacial isostatic adjustment (GIA) (the gradual rising or 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) on water levels and changes in basin water supplies due to climatic variability or shifting climatic patterns.

Figure 1-2 Focus of the St. Clair River Study



Conveyance

In hydraulic engineering, the term *conveyance* is a measure of the discharge-carrying capacity of a river or channel. It is a function of hydraulic and physical properties of the river or channel. It is also known as *water-carrying capacity*. For the Study, *conveyance* is defined to encompass the St. Clair River reach properties.

Natural changes in the river can include such factors as natural erosion and sedimentation, GIA, vegetation growth, and ice conditions. Human-caused changes in the river can include the effects of dredging, channel shoreline hardening, bridges and other infrastructure, sunken vessels, and ship propeller wash.

1.1.4 Intended Audiences

The St. Clair River Report was prepared for the consideration of the International Joint Commission, which is responsible for recommending appropriate courses of action to the two federal governments.

The findings of the report will be of direct interest to elected representatives in state and provincial governments bordering the upper Great Lakes, federal, state and provincial natural resource agencies, as well as regional and municipal governments in the Study area. The report also will be of interest to other parties with an interest in Great Lakes water management issues, including: residential, recreational and commercial property owners; major industries such as commercial shipping, power generation, and tourism; recreational boaters; First Nations and Native Americans; and environmental and conservation organizations.

The report is primarily *scientific* in focus, in terms of its language, level of scientific and engineering complexity, and presentation of data and conclusions. A stand-alone **Summary Report** has been prepared for general readers.¹

1.1.5 Organization of the Report

The report is organized into nine chapters:

- *Chapter 1* provides an introduction to the Study and the St. Clair River Report, and summarizes the results of the peer review process and the public consultations.
- *Chapter 2* presents an overview of the physical setting of the upper Great Lakes and of the key factors affecting water levels and flows in the lakes.
- *Chapter 3* describes the analytical framework used to guide that part of the Study addressing issues in the St. Clair River.
- *Chapter 4* describes the sediment transport process of the St. Clair River as it relates to the flow capacity of the river.
- *Chapter 5* discusses the past and present hydraulic regimes of the St. Clair River.
- *Chapter 6* discusses how GIA affects water levels in the upper Great Lakes.
- *Chapter 7* examines the hydroclimatic processes and how the various hydrological factors affect water supplies and Great Lakes water levels.
- *Chapter 8* integrates the findings of the work in the focus areas of the Study (sediment, hydraulics, GIA and hydroclimatology) and presents overall findings and conclusions.
- *Chapter 9* presents the key recommendations of the St. Clair River Study.

The Annex provides: acknowledgements/list of contributors; a list of references (by chapter); a list of common acronyms used in the report; and a glossary. A conversion table for comparing metric and U.S. customary units is provided on the back inside cover page.

1.2 BACKGROUND TO THE STUDY

1.2.1 Origins of the Study

Lake Superior, located at the top in the chain of Great Lakes, flows into Lake Michigan-Huron via the St. Marys River. In 1914, the International Joint Commission issued Orders of Approval to two hydropower utilities, one in Canada and the other in the United States, for the use of the waters of the St. Marys River for hydropower generation. The Orders also approved construction of a dam and hydropower works in the river and specified criteria and requirements to be met in the construction and operation of these works. This led to the regulation of the Lake Superior outflows. Pursuant to the *Boundary Waters Treaty* of 1909, the International Joint Commission has an ongoing responsibility for assuring that projects it has approved continue to operate within the provisions of the Treaty. Since 1914, the Commission has made revisions to the criteria and issued supplementary orders. The 1979 Supplementary Order contains the most recent changes and its criteria continue to govern Lake Superior outflow regulation. Plan 1977-A is the present plan used for outflow regulation of Lake Superior resulting from that order and has been used for that purpose since June 1990.

In 1993, the International Joint Commission completed its *Levels Reference Study – Great Lakes-St. Lawrence Basin* (Levels Reference Study Board, 1993). The Levels Reference Study, which was influenced by record high lake levels occurring in the mid-1980s, focused on the question of high lake levels as well as alternative regulation plans for Lake Superior and potential regulation options for Lake Michigan-Huron and Lake Erie. As with previous International Joint Commission studies (International Joint Commission, 1976), the 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 International Joint Commission 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.

¹ The **Summary Report of the Impacts on Upper Great Lakes Water Levels: St. Clair River** is available at the website of the International Upper Great Lakes Study: www.iugls.org

In May 2001, the International Joint Commission informed the Canadian and United States governments of its intention to develop a Plan of Study to review the Commission's Orders and the regulation of the outflows from Lake Superior. The Commission 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.

In October 2001, the team invited a panel of experts from Canada and the United States to conduct a peer review of the draft Plan of Study. Following this review, and a second round of comments from interested organizations and individuals, the team finalized the Plan of Study in January 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 International Joint Commission study, *Options for Managing Lake Ontario and St. Lawrence River Water Levels and Flows* (International Lake Ontario – St. Lawrence River Study Board, 2006).

Across the Great Lakes basin during this time, low lake level conditions continued to be a concern for commercial shippers, property owners and other interests. This was particularly the case in the Georgian Bay region, which features a rocky archipelago of thousands of islands, many of which are inaccessible by boat when water levels are extremely low. There were concerns that low lake levels could reduce property values and tourism revenues, limit access by emergency fire and rescue boats, and adversely affect wetlands.

In 2005, Georgian Bay Forever (formerly the GBA Foundation, a charity that carries out research and education projects related to Georgian Bay) commissioned a study investigating the causes of low water levels in Lake Michigan-Huron (Baird, 2005). Commonly known as the Baird Report, this study concluded that river bed erosion was responsible for what it called “the ongoing and significant drop” in the difference between Lake Michigan-Huron and Lake Erie water levels. It identified a number of possible human-induced causes for this erosion, including dredging in the St. Clair River for a navigation channel and a reduction of sand supplies to the river as a result of shoreline protection works.

1.2.2 2005 Plan of Study

In response to the concerns raised by the findings of the Baird Report, the International Joint Commission established a bi-national team to consider ways to resolve the questions surrounding possible human-induced and natural changes to the St. Clair River. On the basis of the bi-national team's recommendation, the Commission 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. The St. Clair River flow and Lake Superior outflow regulation are interrelated in that the outflow of Lake Michigan-Huron through the St. Clair River, Lake St. Clair and Detroit River depends in part on the level of Lake Michigan-Huron. This latter level, in turn, affects the regulation of the outflow from Lake Superior and how such operation meets the objectives of the International Joint Commission's Orders.

Public comments on the draft revised Plan of Study indicated strong support for the Study, and for the addition of the St. Clair River evaluation. The revised Plan of Study was finalized in October 2005.

1.2.3 2007 Strategic Framework and Work Plan

In February 2007, following approval of the Canadian and United States governments, the International Joint Commission issued a directive establishing a Study Board to initiate the Study. The Study Board began its work in March 2007. 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.

Over the summer and fall of 2007, concerns about the St. Clair River and the near-record low water level conditions on the upper Great Lakes received extensive media coverage. These concerns, in turn, prompted the International Joint Commission to request the Study Board to identify actions that could be taken to accelerate the study of the St. Clair River. In response, the Study Board made further adjustments to the schedule, moving up the completion date for the St. Clair River part by nearly one year, and reducing the number of field seasons for additional observations.

The expedited schedule placed additional burdens on the Study Board, the Public Interest Advisory Group and the teams of investigators. The focus on expediting the St. Clair River Study required a substantial shift in human and financial resources allocation, significantly affecting the schedule of the other part of the Study being undertaken by the Lake Superior Task Team. Although a good deal of the preparatory work of that Team and its techni-

cal work groups had been initiated, the funding for that part had to be reduced, thereby delaying its substantive analyses until Year 3 of the Study. In addition, the timelines and focus of the Study's public information and engagement program and associated resources had to shift markedly towards addressing St. Clair River issues. Independent peer review had to be accelerated, as well, taking into account the need for project investigators to undertake field research as soon as possible.

To ensure the critical questions in the Study could be answered under the expedited schedule, the Study Board developed a strategic framework and work plan that optimized the data collection program and computer model analyses of critical areas (International Upper Great Lakes Study Board, 2007) (see Chapter 3). The Study Board concluded that even with an expedited schedule, the available data and modelling efforts undertaken in the Study were of sufficient level of detail to answer the key science questions concerning the St. Clair River without compromising the Study's scientific foundation.

In December 2008, the Study Board announced a revised schedule calling for the submission of the final report on the St. Clair River to the International Joint Commission in October 2009 (subsequently revised to December 2009). This revised schedule allowed for an extended 90-day public comment period of the draft report, which was released in May 2009. The new schedule also allowed for further examination of hydraulic and sediment modelling results, collection of another partial season of field data to corroborate the results, and more thorough data evaluation, verification and quality control.

1.3 STUDY ORGANIZATION

The organization of the St. Clair River part of the Study consisted of a Study Board, a Study Task Team and a number of technical work groups responsible for specific areas of study (see Figure 1-3). 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.

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

1.3.1 Study Management

The Study Board is responsible for the overall planning and management of both parts of the Study (i.e., the evaluation of the St. Clair River system and the Lake Superior outflow regulation plan). The Study Board reports formally to the International Joint Commission 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 consists of 10 members from Canada and the United States appointed by the International Joint Commission and drawn from the two federal governments, state and provincial governments, universities and the public (see Table 1-1). 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 (see 1.3.4, below) also are members of the Study Board.

The International Joint Commission 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 (Table 1-2).

1.3.2 St. Clair River Task Team

The St. Clair River Task Team provided the strategic direction and management oversight for the numerous applied research projects undertaken to address various aspects of Great Lakes water supplies and the conveyance of the St. Clair River. As described in Chapter 3, these projects were the basis of the 36 scientific/technical and supplemental reports that formed the scientific foundation of this final report.

The Task Team consisted of the co-leads of each of the technical work groups, as well as two co-chairs (one each from Canada and the United States), appointed by the Study Board (see Table 1-3).

Figure 1-3 Study Organization Chart

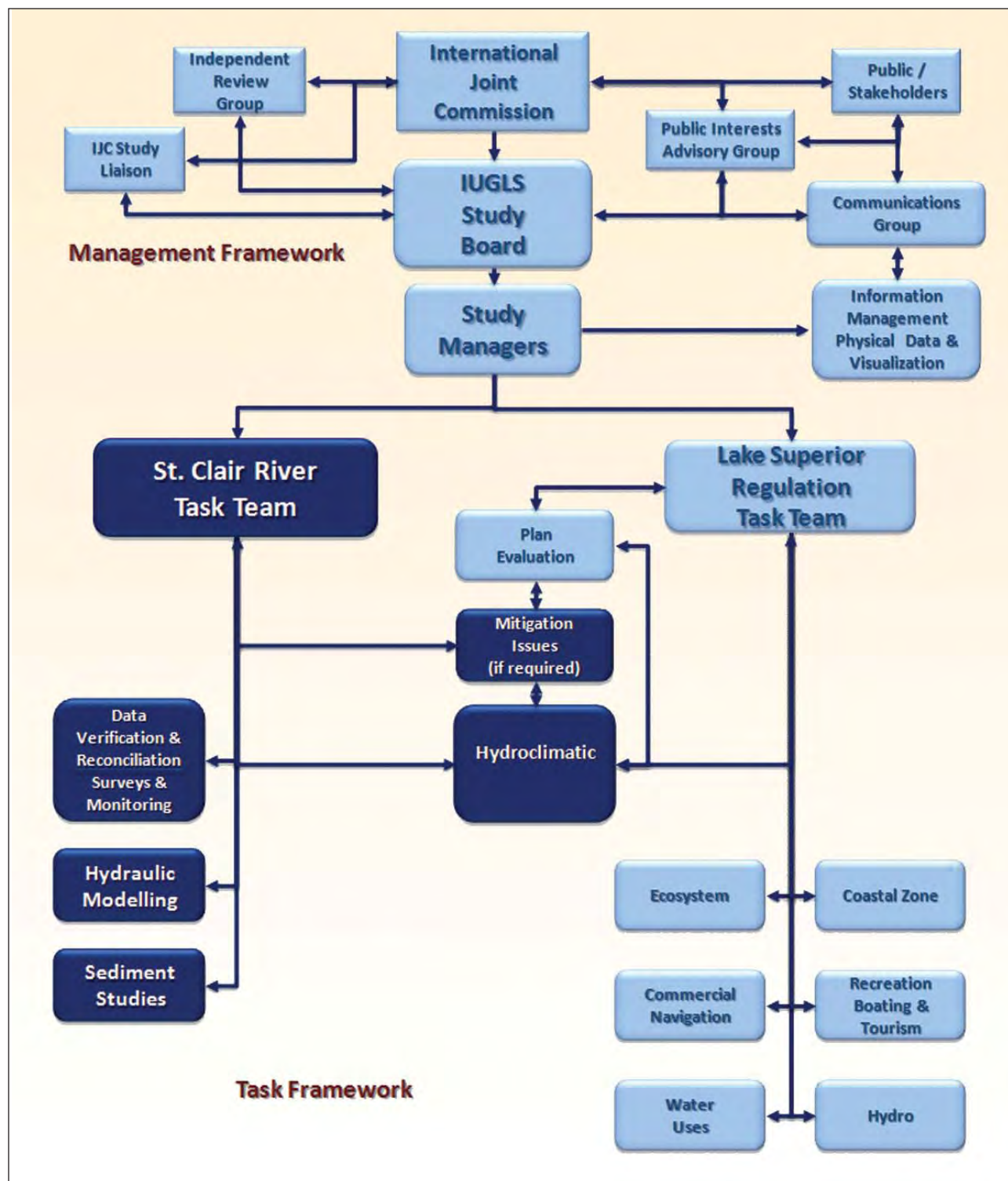


Table 1-1 International Upper Great Lakes Study Board Members

| Canada | United States |
|--|---|
| <i>Co-Chair</i> | <i>Co-Chair</i> |
| Ted R. Yuzyk International Joint Commission Ottawa, ON | Dr. Eugene Z. Stakhiv Institute for Water Resources Alexandria, VA |
| <i>Co-Chair, Public Interest Advisory Group</i> | <i>Co-Chair, Public Interest Advisory Group</i> |
| Dr. James P. Bruce Ottawa, ON | Kay Felt Detroit, MI |
| Dr. Donald H. Burn Dept. of Civil and Environmental Engineering University of Waterloo Waterloo, ON | Dr. John J. Boland (joined in Fall 2008) Dept. of Geography and Environmental Engineering Johns Hopkins University Baltimore, MD |
| Allan Chow Ministry of Natural Resources Thunder Bay, ON | James Bredin Office of the Great Lakes Michigan Dept. of Environmental Quality Lansing, MI |
| Jonathan H. Gee Manager, Great Lakes Areas of Concern Environment Canada Toronto, ON | Dr. Jonathan W. Bulkley School of Natural Resources and Environment University of Michigan Ann Arbor, MI |

**Table 1-2 International Upper Great Lakes Study Board
Co-Managers and International Joint Commission Liaisons**

| Canada | United States |
|---|---|
| <i>Study Co-Manager</i> | <i>Study Co-Manager</i> |
| Dr. Syed M. A. Moin International Joint Commission Ottawa, ON | Dr. Anthony J. Eberhardt Institute for Water Resources Alexandria, VA |
| <i>Engineering Adviser</i> | <i>Engineering Adviser</i> |
| Dr. Paul Pilon International Joint Commission Ottawa, ON | Dr. Mark Colosimo International Joint Commission Washington, DC |

The St. Clair River Task Team was responsible for:

- developing, implementing and overseeing the analytical strategy for answering the Study's key science questions related to St. Clair River issues;
- 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 on investigations;
- directing development of work plans and budgets as input to the Study planning process;
- participating in forums and public meetings held by the Study Board and Public Interest Advisory Group to explain the Study process, seek input and discuss results;
- ensuring that the work plans from the technical work groups are consistent with Study objectives;
- recommending approval of the plans and associated budgets to the Study Board;
- coordinating analytical results and information with the independent review groups;
- scoping and developing remediation and mitigation options for the Study Board's consideration in response to the needs for addressing any erosion-related issues should they arise; and
- interacting with the Lake Superior Task Team, and co-directing work of the technical work groups on hydroclimatic questions and plan evaluation.

Table 1-3 St. Clair River Task Team Members

| Canada | United States |
|---|--|
| <i>Co-Chair</i> Dr. Syed M. A. Moin International Joint Commission Ottawa, ON | <i>Co-Chair</i> James R. Nicholas Director, Michigan Water Science Center U.S. Geological Survey Lansing, MI |
| <i>Co-Leads, Data Verification and Reconciliation/ Surveying and Monitoring Technical Work Group</i> Chuck Southam Environment Canada Burlington, ON | <i>Co-Leads, Data Verification and Reconciliation/ Surveying and Monitoring Technical Work Group</i> Nanette L. Noorbakhsh U.S. Army Corps of Engineers Detroit, MI |
| <i>Monitoring</i> Pat McCurry Environment Canada Ottawa, ON | <i>Monitoring</i> Stephen Gill National Oceanic and Atmospheric Administration Springfield, VA |
| <i>Co-Lead, Sediment and Morphology Technical Work Group</i> Dr. Peter E. Ashmore Dept. of Geography University of Western Ontario London, ON | <i>Co-Lead, Sediment and Morphology Technical Work Group</i> Dr. Marcelo H. Garcia Dept. of Civil and Environmental Engineering University of Illinois Urbana, IL |
| <i>Co-Lead, Hydraulic Modelling Technical Work Group</i> Aaron Thompson Environment Canada Burlington, ON | <i>Co-Lead, Hydraulic Modelling Technical Work Group</i> Eric C. Tauriainen U.S. Army Corps of Engineers Detroit, MI |
| <i>Co-Lead, Hydroclimatic Technical Work Group</i> Dr. Al Pietroniro Environment Canada Saskatoon, SK | <i>Co-Lead, Hydroclimatic Technical Work Group</i> Deborah H. Lee U.S. Army Corps of Engineers Cincinnati, OH |

1.3.3 Technical Work Groups

The St. Clair River Task Team worked with four technical work groups. Technical work groups 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.

Data Verification and Reconciliation/Surveying and Monitoring Technical Work Group

This group was responsible for undertaking a series of priority studies needed in the Study's subsequent modelling efforts. In addition to analyzing existing data, this group gathered new data for 2007 and 2008, including bathymetry, sediment transport and bed material data. This information helped calibrate and verify a variety of mathematical and simulation models used to study sediment processes (erosion, entrainment, transport and deposition), as well as hydraulic and hydrological flow characteristics under different lake level regimes. The group also was responsible for the planning and installation of four new hydrometric (water quantity) stations on the St. Marys,

St. Clair, Detroit and Niagara Rivers; these new stations are expected to be designated International Gauging Stations and will continue in operation after the Study is completed.

Sediment and Morphology Technical Work Group

This group conducted in-situ investigations of sediment transport and bed conditions in the St. Clair River to assess the geomorphologic changes in the river's regime. Group members proposed additional investigations to determine whether the bed is eroding or stable and to provide a more accurate basis for selecting the appropriate sediment transport models and subsequent modelling.

Hydraulic Modelling Technical Work Group

This group addressed the need for an accurate and representative hydraulic modelling system, using one-dimensional (1-D), 2-D or 3-D models. Engineering experts proposed and calibrated models needed to assess the sensitivity of various factors on water level conditions and conveyance. The modelling approach focused on

adapting existing models and on obtaining data that were fundamental for representing the physical conditions more accurately.

Hydroclimatic Technical Work Group

Through a water balance approach, this group determined the relative contribution of net basin supplies (NBS) to water levels in the upper Great Lakes and to St. Clair River flows. The group will continue to work with the Lake Superior Regulation Task Team in the second part of the Study and address the potential impacts from a changing climate.

1.3.4 Public Interest Advisory Group

Recognizing the many interests concerned with the future of water levels in the upper Great Lakes, the International Joint Commission 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 (see 1.5). The Advisory Group is a key component of the International Joint Commission's commitment to ensuring that members of the public are informed throughout all stages and are provided opportunities to make their views known.

Members are drawn from a wide range of public groups with an interest in the Great Lakes (see Table 1-4). Throughout the course of the St. Clair River part 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 serve as liaisons to technical work groups that address issues in which they have a particular interest. The co-chairs of the group, one from Canada and one from the United States, serve as members of the Study Board.

Table 1-4 Public Interest Advisory Group Members

| Canada | United States |
|---|---|
| <i>Co-Chair</i> | <i>Co-Chair</i> |
| Dr. James P. Bruce Ottawa, ON | Kay Felt Detroit, MI |
| James S. Anderson Ducks Unlimited Renfrew, ON | Kate Bartter (joined May 2009) Ohio State University Columbus, OH |
| Doug Cuddy Lake Superior Conservancy and Watershed Council Sault Ste. Marie, ON | Dave Irish Marina Operator, Harbor Springs, MI |
| Dick Hibma Conservation Ontario Newmarket, ON | David L. Powers Save Our Shoreline Bay City, MI |
| Kenneth Higgs Property Owner Port Severn, ON | Roger J. Smithe International Great Lakes Coalition Saugatuck, MI |
| William Hryb Lakehead Shipping Company Ltd. Thunder Bay, ON | Dr. Alan Steinman Grand Valley State University Muskegon, MI |
| John Jackson Great Lakes United Kitchener, ON | Dan J. Tadjerson (until September 2009) Sault Ste. Marie Tribe of Chippewa Indians Sault Ste. Marie, MI |
| Don Marles Lake Superior Advisory Committee Sault Ste. Marie, ON | Dan Thomas Great Lakes Sport Fishing Council Elmhurst, IL |
| Mary Muter Georgian Bay Forever Toronto, ON | Jeff Vito City of Superior Superior, WI |
| First Nations Representative (open) | James H. I. Weakley (until September 2009) Lake Carriers' Association Cleveland, OH |

The Study Board seeks to engage First Nations and Native Americans with an interest in lake levels in the Study area. On the United States side, a Native American participates as a member of the Advisory Group. On the Canadian side, an open letter of invitation was sent to the Chiefs of Ontario and to the Métis Nation of Ontario, and one position remains open with the intention of finding a First Nations representative. Two “circles of influence” workshops were held in the fall of 2008 with a number of First Nations representatives to determine how best to obtain their input to the Study and identify a potential representative.

1.3.5 Information Management

In comparable past studies, there was a risk that important, useful data and analyses from major scientific and engineering investigations would be inaccessible upon completion of the work. The International Joint Commission and Study Board recognized that the Study’s data and publications represent a rich legacy of literature and data about the Great Lakes. To capture this legacy and ensure that it remains readily available to current and future generations of researchers and resource managers, the Study Board developed an information management program at an early stage of the Study.

The Study Board purchased a management software program (SharePoint) and a dedicated server to provide for the sharing of information and data across all the technical work groups, the Task Teams and Study Board. This Study’s scientific/technical reports and accompanying data have been archived and are accessible to interested individuals and organizations.²

1.4 INDEPENDENT PEER REVIEW

1.4.1 The Need for Peer Review

The International Joint Commission 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, the effects of fluctuations on the ecosystems, the complexity of many of the scientific and engineering studies required, and the uncertainty and debate around some of the scientific issues.

As a result, the Study was subject to a high level of independent scientific scrutiny. The St. Clair River Report represented the first time in the history of the International Joint Commission that a bi-national study benefitted from ongoing independent scientific review at all stages, from the development of the Plan of Study through to the completion of its reports.

The International Joint Commission contracted with the Environmental and Water Resources Institute of the American Society of Civil Engineers and the Canadian Water Resources Association to review the work plans and products of the Study. With about 21,000 and 1,300 members, respectively, these organizations also were able to draw upon expertise beyond their membership.

The peer review groups operated independently of the Study Board and provided their views directly to the International Joint Commission.³

1.4.2 Results of the Peer Reviews

Independent peer reviewers reviewed the draft St. Clair River Report, drafts of the synthesis chapters, and eight of the detailed scientific/technical reports. Reviewers were asked to rate the drafts on a range of criteria, including the degree to which:

- objectives were clearly stated;
- methods were valid, appropriate and sufficient; and
- assumptions and mathematical calculations were valid.

Reviewers also were asked to identify and comment on the best, most critical and weakest parts of the analysis, and to offer suggestions on how the analysis could be better explained.

The peer reviewers consistently gave high ratings to the scientific/technical reports, the draft report and the draft chapters on sediment and hydraulics. They also provided specific suggestions for improvement. Reviewers identified a number of concerns regarding the draft chapter on hydroclimatology, including the need for further clarification, re-structuring of the information and additional analysis.

“Overall, we find the analyses, results and conclusions to be technically sound and consistent with the study objectives.”

– Independent Peer Review Co-leads (August, 2009)

² See the website of the International Joint Commission: www.ijc.org

³ Documents relating to the peer review process are available at the American Society of Civil Engineers-Environmental and Water Resources Institute website: <http://content.ewrinstitute.org/committees/IUGLS.cfm>.

Study Board members considered and responded to each comment from the peer reviewers. In some cases, the response required a simple clarification or rewording. In other cases, the responses required additional analysis and substantial revisions to the text. The reports of the independent peer reviewers and the responses of Study investigators are available through the websites of the peer review organizations.

1.5 PUBLIC INFORMATION AND ENGAGEMENT

The Study Board, with the support and advice of the Public Interest Advisory Group, developed and implemented a comprehensive public information and engagement program during preparation of the St. Clair River Report. The program utilized public meetings, workshops, conferences, newsletters, email and the internet.

Details of this program are available in a report prepared by the Public Interest Advisory Group, available through the Study website (Public Interest Advisory Group, 2009).

1.5.1 Public Consultation Activities

The Study Board made the draft St. Clair River Report available for a 90-day period of public review and comment, from May 1st, 2009 to August 1st, 2009. The objectives of the consultations were to:

- inform individuals and organizations with an interest in water level issues in the upper Great Lakes region about the Study and its preliminary findings and recommendations;
- obtain feedback on the preliminary findings and recommendations; and
- obtain feedback on other issues related to the Study's mandate and approach.

Distribution of the Draft Report and Related Information

The Study Board made a number of important documents available on the Study website to help interested individuals and organizations understand the objectives, scope and approach of the Study and the preliminary findings and recommendations. These documents included:

- **Volume 1** of the draft St. Clair River Report, which provided comprehensive information on: the objectives and organization of the Study; factors affecting water levels in the upper Great Lakes; key analyses and findings; integration of Study results and conclusions; and Study recommendations.
Released: May 1st, 2009.

- **Volume 2**, a compendium of summaries of the applied research and related projects commissioned by the Study during preparation of the St. Clair River Report. The project summaries allowed interested readers to learn more about the methodologies and findings that formed the scientific foundation of the Study. *Released: May 15th.*
- A **Summary Report**, in both English and French, summarizing the St. Clair River Report in less technical language for general audiences.
Released: May 1st (French version: May 15th).
- Extensive background reports and planning documents on the Study, including current and past issues of the Study's quarterly **newsletter**, fact sheets, a Microsoft Power Point presentation on the draft report, as well as the Study's 2007 **Strategic Framework and Work Plan**.

Access to Web-based Resources

The website had the most "hits" or viewings (266,429) during May 2009. In particular, May 1, 2009 – the day the draft St. Clair River Report was released – was the most active day, with more than 33,000 hits. Since the beginning of the Study, the website has had nearly 3 million hits (Figure 1-4). On average, following the release of the draft report, the website has approximately 50 visitors each day.

Figure 1-4 Number of Study Website "Hits"/Month



The Summary Report was the most widely referenced document from the website, with more than 1,500 downloads. Volume 1 of the report was downloaded nearly 1,000 times, while Volume 2 was downloaded just over 500 times. Communication products such as the newsletter, *On the Level*, Fact Sheets and various press releases were also referenced fairly extensively. Of the more than 40 technical reports posted, only a few were downloaded more than 50 times.

Briefings

Throughout the St. Clair River Study, the Study Board briefed members of the Canadian and U.S. federal governments, as well as representatives of state, provincial and local governments in the region. Following the release of the draft report, the Board also held web conference briefings for various groups including the Council of Great Lakes Governors, the Great Lakes & St. Lawrence Cities Initiative, non-government organizations, and members of the media.

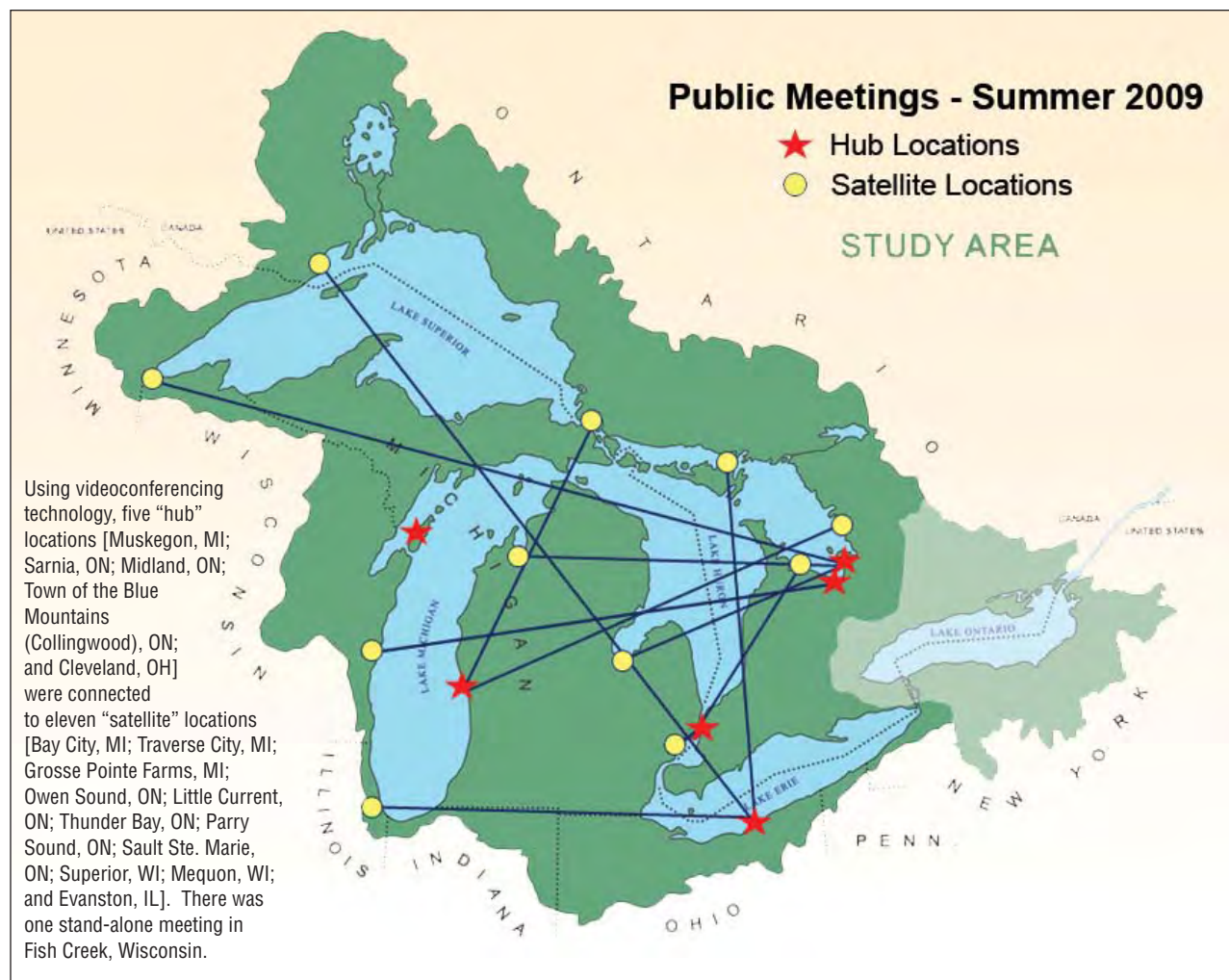
Public Meetings and Related Activities

Since the onset of the Study, the Board has held 34 public meetings throughout the Study region. During the 90-day public comment period (extended from 60 days) following the release of the draft report, the Study provided in-depth briefings and received comments at 17 public meetings held throughout the upper Great Lakes basin (see Figure 1-5). Attendees at each of the public meetings were also asked to fill out a response form to help the Study Board better assess the public's response to the Study, the draft report and the public consultation process.

Members of the public were also encouraged to submit questions and comments regarding the draft report via e-mail, regular mail and a form on the Study website.

This extensive in-person and internet-based outreach effort was complemented by the work of Public Interest Advisory Group members, who were tasked with communicating with members of their respective interest groups and the general public.

Figure 1-5 Public Meetings during the Consultations



1.5.2 Results of the Public Consultations

The results of the public consultation activities suggest that the public was well aware of the report. Over the past two years, nearly 2,000 people attended meetings that were arranged and facilitated by the Study with the support and advice of the Public Interest Advisory Group.

Participating Interests

Attendance at the public meetings on the draft report in mid-2009 was smaller than during the preliminary meetings in 2008 (approximately 400 people in 2009, compared to more than 1,500 in 2008). This trend may have been due to the fact that low water levels in 2008 had generated considerable interest and concern among residents of coastal communities along the lakes, while water levels in the upper Great Lakes were rebounding in 2009, possibly reducing the level of public concern. Moreover, given the intensity of interest in the early phase of the Study, the number of written comments submitted was relatively small (41).

Of the six key interest areas identified in the Plan of Study, the vast majority of comments could be considered as coming from only two groups (Coastal Zone and Ecosystem). By contrast, the other four interests (Commercial Navigation, Recreational Boating and Tourism, Water Uses, and Hydropower), while represented at many of the meetings, did not submit formal comments. As a result, it would be unreasonable to assume that the comments provided were representative of the wide spectrum of interests throughout the upper Great Lakes basin. Indeed, given the general level of awareness about the report and its findings among all groups, the relative lack of comment suggests at least a minimal level of satisfaction regarding the Study's findings and recommendations.

Areas of Consensus

Through the public consultations on the draft report, broad areas of consensus emerged across a wide range of interest groups. During the consultations, consensus emerged in the following areas:

- that decisions at all levels of government be based on sound science;
- that the recommendation that the second phase of the Study, regarding possible improvements to Lake Superior outflow regulation, evaluate mitigation options in the St. Clair River based on additional analysis of the range of potential impacts of climate change;
- that any consideration of remedial options in the St. Clair River take into account the full range of economic, social and environmental interests in the entire upper Great Lakes basin, including Lake St. Clair and Lake Erie;

- the legacy recommendations involving continuing data collection and coordinated monitoring and modelling;
- the importance of maintaining the ability of large vessels to navigate and access ports;
- the need to protect habitat important to native species through natural water level fluctuations; and
- general opposition to a fixed permanent structure in the St. Clair River.

Public commenters also generally agreed that issues regarding fluctuating lake levels are complex, uncertain and merit additional study and further efforts to inform the public. There was also a widespread frustration expressed that the mandate of the Study was too limiting and that the impacts of previous dredging projects and their impacts on lake levels also be considered. Finally, there was general opposition to any permanent structure in the St. Clair River.

Differing Perspectives

The areas in which a consensus did not emerge among the various participating interests were much more limited and were clearly associated with geography. For example, with respect to the Study's recommendation that remedial measures in the St. Clair River not be considered at this time:

- coastal interests on Lake Michigan strongly agreed, citing the potential for costly damages if lake levels were to return to high levels such as those experienced in the mid-1980s; and
- some commenters from the Georgian Bay region strongly disagreed, citing the costly impacts of low water on both the environment and economy.

In the Georgian Bay meetings, there appeared to be support for "flexible" or "temporary" remedial structures, while some environmental interests wanted further examination of nonstructural approaches. At the same time, Lake Superior residents expressed their opposition to any measures that might reduce levels on that lake to compensate for low levels in other lakes.

In addition, some individuals criticized the Study for running the public and peer reviews concurrently and for the delay in posting final versions of the technical reports because of delays in the peer review process. Some individuals also were critical of the Study's initial assessment of and distinction between human-caused or natural-caused changes to the bed of the St. Clair River.

Written Survey Responses

As with those who commented on the draft report, the group responding to the written survey was skewed heavily toward coastal property owners and those who expressed interest in protecting shoreline ecological interests.

The key finding of this survey was that a majority of respondents (52 percent) was confident that the Study would achieve its objectives. Less than one-third (29 percent) was uncertain and only a small minority (11 percent) indicated that it was not confident the Study would achieve its objectives. In addition, respondents expressed a broad range of views regarding the key messages of the Study and general satisfaction with the clarity and technical nature of the presentations at the public meetings. For example, more than two-thirds of respondents noted that their questions had been answered during the meetings.

Conclusion

Based on an analysis of views provided by the public regarding the draft St. Clair River Report, there appeared to be, with some exceptions, general satisfaction on the part of the public that the findings and recommendations were acceptable and the result of a technically sound and unbiased scientific process.

1.6 KEY POINTS

- ▶ The St. Clair River Report presents the findings and recommendations of a major bi-national Study established to consider whether natural and/or human-caused changes in the St. Clair River have increased the conveyance of the river, thereby contributing to the lowering of the levels of Lake Michigan-Huron relative to Lake Erie. The report is the product of a major cooperative multidisciplinary effort nearly 100 Canadian and United States scientists and engineers from governments and academia.
- ▶ The schedule of the St. Clair River part of the Study was accelerated by nearly one year to address growing public and political concerns about low water levels in the upper Great Lakes. Fast-tracking the St. Clair River part of the Study required a substantial shift in human and financial resources allocation within the Study, with effects on planned investigations and modelling efforts. However, the Study Board is confident that the investigations have adequately addressed the key scientific questions concerning the St. Clair River.

- ▶ The International Joint Commission and Study Board recognized the need to ensure that the Study is credible and transparent at all stages, given the diverse public and private interests concerned about Great Lakes water levels and ecosystems, the complexity of many of the scientific and engineering studies required, and the uncertainty and debate around some of the scientific issues. The Study was subject to a high level of independent scientific scrutiny, and represents the first time in the International Joint Commission's history that a bi-national study benefitted from an ongoing independent peer review from the very start of its work.
- ▶ Independent peer reviewers generally gave high ratings to the Study's reports. They identified a number of specific concerns regarding the various draft chapters, including the need for additional analysis and improved clarity of presentation. They also noted the need to quantify scientific uncertainty in the different areas. The Study Board reviewed and responded to all specific suggestions and questions from the peer reviewers.
- ▶ The International Joint Commission and Study Board applied information management measures to ensure that the rich legacy of new literature and data about the Great Lakes resulting from the Study's efforts remains available to current and future generations of researchers and resource managers.
- ▶ The International Joint Commission and Study Board are committed to ensuring that interested members of the public are informed throughout all stages of the Study and are provided opportunities to make their views known. The Study's bi-national Public Interest Advisory Group plays a significant role in this public information and engagement effort.
- ▶ The Study Board made the draft St. Clair River Report available for a 90-day period of public review and comment. Working with the Public Interest Advisory Group, the Study Board undertook a range of outreach activities so that interested members of the public had opportunities, either in person or via the internet, to access information and provide their views on the draft report. Broad areas of consensus emerged on several important issues. With some exceptions, there appeared to be general satisfaction on the part of the public that the Study's findings and recommendations were acceptable and the result of a technically sound and unbiased scientific process.

CHAPTER 2

GREAT LAKES WATER LEVELS AND FLOWS

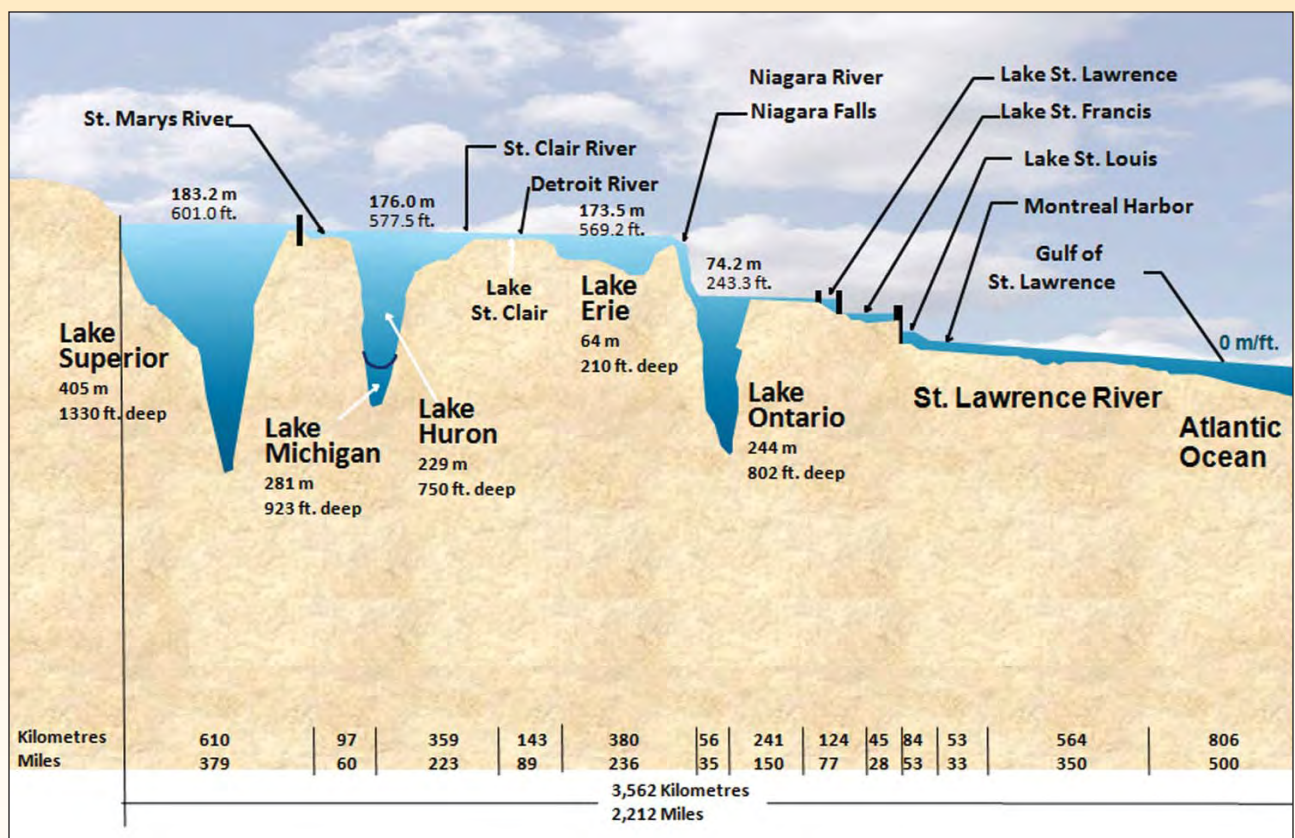
Chapter 2 presents background information on the key factors affecting water levels and flows in the Great Lakes, including the role of connecting channels, climate and human factors. It provides an overview of the factors that can contribute to water levels changes in the upper Great Lakes, and concludes with a description of the flow regime and conveyance of the St. Clair River.

2.1 INTRODUCTION

The upper Great Lakes basin, the focus area of the Study, covers an area of about 686,000 km² (265,000 mi²) (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data [CCGLHHD], 1977). Figure 2-1

shows the general water surface profile of the Great Lakes system, including the St. Lawrence River. About one-third of the upper basin area consists of the water surfaces of the upper Great Lakes and their connecting channels (see Table 2-1).

Figure 2-1 Water Surface Profile of the Great Lakes System



(Source: modified from Great Lakes Commission and U.S. Army Corps of Engineers, 1999)
 Note: Water surface elevations are at chart datum on IGLD (1985).

Table 2-1 Dimensions of the Great Lakes Basins

| | Surface Area | | | | Volume* | | Max Depth* | |
|---|-----------------|--------------------|-----------------|--------------------|-----------------|--------------------|------------|-------|
| | Water | | Land Basin | | km ³ | miles ³ | metres | feet |
| | km ² | miles ² | km ² | miles ² | | | | |
| Lake Superior | 82,100 | 31,700 | 127,700 | 49,300 | 12,100 | 2,900 | 405 | 1,330 |
| St. Marys River | 230 | 90 | 2,600 | 1,000 | - | - | - | - |
| Lake Michigan | 57,800 | 22,300 | 118,000 | 45,600 | 4,920 | 1,180 | 281 | 923 |
| Lake Huron | 59,600 | 23,000 | 131,300 | 50,700 | 3,540 | 850 | 229 | 750 |
| St. Clair River | 55 | 21 | 3,300 | 1,270 | - | - | - | - |
| Lake St. Clair | 1,110 | 430 | 12,430 | 4,800 | - | - | - | - |
| Detroit River | 100 | 39 | 2,230 | 860 | - | - | - | - |
| Lake Erie | 25,700 | 9,910 | 58,800 | 22,700 | 484 | 116 | 64 | 210 |
| Niagara River | 60 | 23 | 3,370 | 1,300 | - | - | - | - |
| Lake Ontario | 18,960 | 7,340 | 60,600 | 23,400 | 1,640 | 393 | 244 | 802 |
| St. Lawrence River (to Cornwall/Massena) | 610 | 240 | 7,190 | 2,780 | - | - | - | - |

* Measured when the lake's water level is at chart datum. Note: No value provided for Lake St. Clair.
(Source: CCGLHHD, 1977)

2.2 UPPER GREAT LAKES WATER BUDGET

2.2.1 Measuring Water Levels in the Great Lakes: The International Great Lakes Datum (1985)

The water levels of the Great Lakes are measured in metres referenced to the International Great Lakes Datum (IGLD) (1985) (CCGLHHD, 1995). This datum represents a fixed frame of reference used to measure water levels in a moving environment. It has its zero elevation reference at Rimouski, Quebec on the south shore of the St. Lawrence River.

The datum needs to be updated every 25 to 30 years, because the earth's crust around the Great Lakes basin is gradually shifting due to glacial isostatic adjustment (GIA). GIA refers to the gradual rising or subsiding of the crust resulting from the removal of the weight of the glaciers that covered the surface during the last period of continental glaciation, which ended about 10,000 years ago (see 2.3.3).

The development of the IGLD is carried out by geodetic agencies in Canada and the United States under the direction of the CCGLHHD. The determination of benchmark elevations for IGLD (1985) used seven years of geodetic and water level data centering on 1985 (hence the specification of the reference year 1985 in its name).

Since 1914, when the International Joint Commission granted the first Orders of Approval related to Lake Superior outflow regulation, several vertical datums have been used in the collection of water level and related hydrographic data. There was a lack of documentation for some historical data, particularly regarding the datums used in their collection. The problem is compounded by the uneven movement in the earth's crust across the Great Lakes, which makes it necessary to use different conversion factors when updating the datum. These factors pose challenges for studies that require a high degree of accuracy and precision. The problem associated with different datums was resolved for data collected after 1962 when the two countries began using the IGLD (1955), the first internationally coordinated vertical system. The IGLD (1955) datum was replaced by IGLD (1985) in 1992.

When a new datum is adopted and new elevations are assigned to the benchmarks and gauges that measure water levels, the same conversions are made to the elevations specified in the Lake Superior regulation plan and to the criteria of the International Joint Commission to maintain the same water level regime for the Great Lakes. The same conversions are used to recalculate the water level data prior to 1985 to make them consistent with the IGLD (1985) datum.

2.2.2 Measuring Net Basin Supplies

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. Groundwater can flow into or out of the lakes and is generally assumed to be part of the runoff component. Water also may flow into or out of the lakes through man-made diversions.

Accurate determinations of net basin supply (NBS) and its components (precipitation, evaporation and runoff) in the water balance of the upper Great Lakes are needed to address both St. Clair River conveyance and Lake Superior outflow regulation issues. Two methods were used in the Study to estimate NBS for each of the Great Lakes. These are commonly referred to as the *component method* and the *residual method* for NBS estimation.

Net Basin Supply and Net Total Supply

Net basin supply (NBS) is the net amount of water entering each Great Lake resulting from overlake precipitation, runoff to the lake (including net groundwater flow), and evaporation from the lake, but not including the inflow from the upstream Great Lake or connecting channel.

Net total supply (NTS) is the sum of the NBS to each Great Lake and the inflow from the Great Lake located upstream.

Component Method

The component method determines NBS directly from overlake precipitation, lake evaporation, groundwater and basin runoff. The mathematical equation for this method is:

$$NBS = P + R - E + G \quad (\text{Equation 1})$$

Where:

- P is overlake precipitation;
- R is basin runoff to a Great Lake;
- E is evaporation from the lake surface; and
- G is net groundwater flux into a Great Lake.

All terms are expressed in m³/s-months (ft³/s) (or other time periods).

Residual Method

The residual method determines NBS indirectly by accounting for the inflow to the lake, its outflow and the net change in storage or water level for a period, using the following equation:

$$NBS = O - I + \Delta S - \Delta ST + D_o - D_i + C_{use} \quad (\text{Equation 2})$$

Where:

- O is the outflow from a Great Lake;
- I is inflow from an upstream Great Lake;
- ΔS is change in water storage of the Great Lake;
- ΔST is change in water storage caused by thermal expansion or contraction of water;
- D_o is diversion of water out of the Great Lake or its basin, and D_i is diversion in; and
- C_{use} is consumptive use of Great Lake water.

All terms are expressed in m³/s-months (ft³/s) (or other time periods).

The consumptive use and thermal expansion/contraction values in the residual method are not considered in most water management studies of the Great Lakes. The former has been determined to be relatively minor compared to the other values, and the latter, though difficult to estimate, is likely to be small.

Ideally, determination of NBS using either method should yield the same values. However, uncertainties in estimating any of the terms can result in large differences between the two methods (Neff and Nicholas, 2004).

The residual method generally has been used for developing and testing outflow regulation plans for the Great Lakes, given the availability of relevant data over a long period. The component method is helpful in estimating the possible effects of a changing climate. Developments in climate and hydrological modelling and remote sensing have enabled greater use of the component method for water management purposes as well.

2.2.3 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 – the higher the level (such as during periods of high water supplies), the higher the outflow. Similarly, low lake levels generate 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.

St. Marys River

Lake Superior flows into Lake Michigan-Huron by way of the St. Marys River. Due to the presence of large islands in the river, the length of the river ranges from 98 to 120 km (61 to 75 mi), depending on the route. Prior to the early 1900s, a rock ledge in the St. Marys Rapids at Sault Ste. Marie acted as a natural submerged weir controlling the outflows of Lake Superior (CCGLHHD, 1970). This part of the river has been altered by hydropower and navigation development and construction of the compensating works, which led to the regulation of Lake Superior outflows beginning in 1916.

Straits of Mackinac

Lakes Michigan and Huron are considered as one lake hydraulically (hence the use of the combined name Lake Michigan-Huron in this report) due to their connection at the broad and deep Straits of Mackinac (Nicholas, 2003). This makes the level of the water surface of the two lakes identical. Owing to its features and size, the Straits of Mackinac is not considered a river.

St. Clair River – Lake St. Clair – Detroit River

Lake Michigan-Huron is connected to Lake Erie by the St. Clair River-Lake St. Clair-Detroit River system (for convenience, this system is called the St. Clair River system in the report). The system measures about 156 km (97 mi) in length (CCGLHHD, 1988). Unlike the St. Marys River, this river system does not have a well-defined single section that plays a dominant role in deter-

mining flow. Rather, the flow depends on a number of factors, particularly the water level of Lake Michigan-Huron at its southern end where the St. Clair River begins, and the relative levels (also called head difference or lake-to-lake fall) of Lake Michigan-Huron and Lake Erie. Other factors affecting the flows in this river system are ice cover and ice jams, vegetation growth, local inflows, precipitation and winds.

The St. Clair River is about 63 km (39 mi) in length, counting the St. Clair Flats delta. It has three distinct reaches (Figure 2-2). The upper reach extends from Lake Michigan-Huron to the confluence with the Black River, about 5 km (3 mi) below the International Blue Water Bridge. Maximum velocities for the river occur in this reach approaching about 2 m/s (6.6 ft/s). The average channel width in this reach is about 450 m (1,500 ft) and depth about 16 m (52 ft). The middle reach, extending downstream from the confluence of the Black River to Algonac, is generally uniform with channel width averaging 650 m (2,100 ft) and an average depth of 13 m (43 ft). Below Algonac, the river extends downstream for the next 14 km (9 mi) to Lake St. Clair, where it divides into a number of channels that flow through the St. Clair Flats.

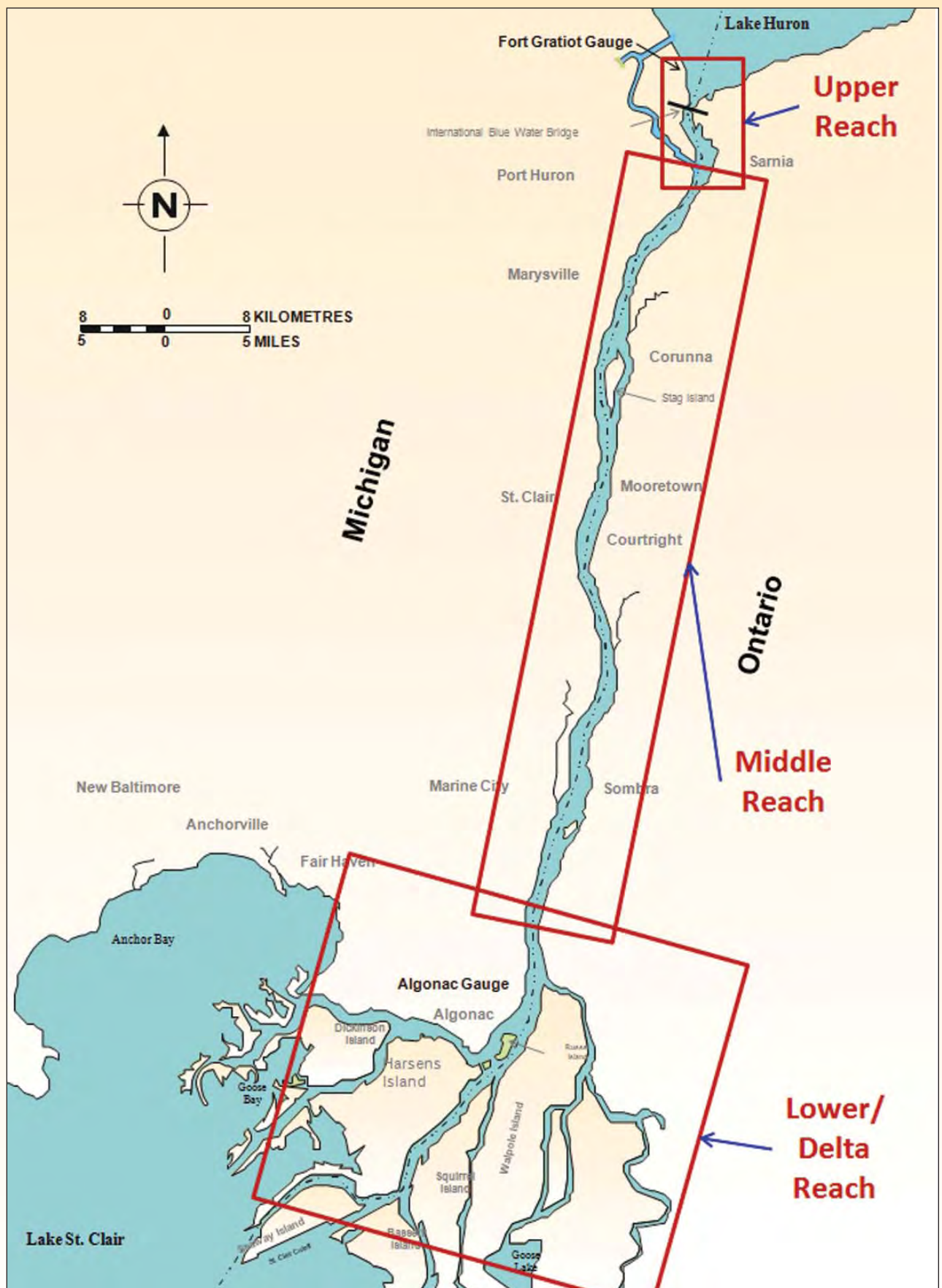
Lake St. Clair is about 42 km (26 mi) in length. It had a maximum depth of only 6 m (21 ft) in its natural state. Dredging currently provides a navigation channel of 8.2 m (27 ft) in depth. Given that the lake is relatively small and shallow, it reacts quickly to wind conditions, ice jams and other meteorological conditions.

The Detroit River is about 51 km (32 mi) long and is characterized by two distinct reaches. The upper reach extends about 21 km (13 mi) from the outlet of Lake St. Clair to the head of Fighting Island. This part of the river is generally deep. The lower reach of the river is broad, with several islands and many shallow expanses. The natural formation of the lower river bed has required very extensive rock excavation and dredging to provide navigation channels of suitable width and depth for large commercial vessels.

Niagara River System

Lake Erie flows into Lake Ontario through the Niagara River. A rock ledge at the head of the river in the vicinity of Buffalo, NY and Fort Erie, ON is the natural control for Lake Erie's outflow (CCGLHHD, 1976). While this ledge is the dominant factor affecting this outflow, the flow is also affected to a very small degree by water level conditions in an area immediately upstream of Niagara Falls known as the Chippawa-Grass Island Pool. To meet the 1950 Niagara River Treaty's objectives of preserving the

Figure 2-2 St. Clair River Reaches



scenic beauty of Niagara Falls while making efficient use of Lake Erie outflow for hydropower purposes, changes in the diversion of water from the Niagara River are made on a daily and seasonal basis. These diversions are made by means of a control structure in the Pool. However, the resulting fluctuations in the Pool's levels have insignificant effects on Lake Erie's outflow or its levels (Lee *et al.*, 1998).

Downstream of the upper Great Lakes, Lake Ontario flows into the St. Lawrence River, which in turn flows into the Atlantic Ocean. Lake Ontario levels and regulation of its outflows cannot affect the upper Great Lakes water levels due to the almost 100 m (328 ft) drop in elevation between Lake Erie and Lake Ontario, most of it located at Niagara Falls and the cascades in the Niagara River.

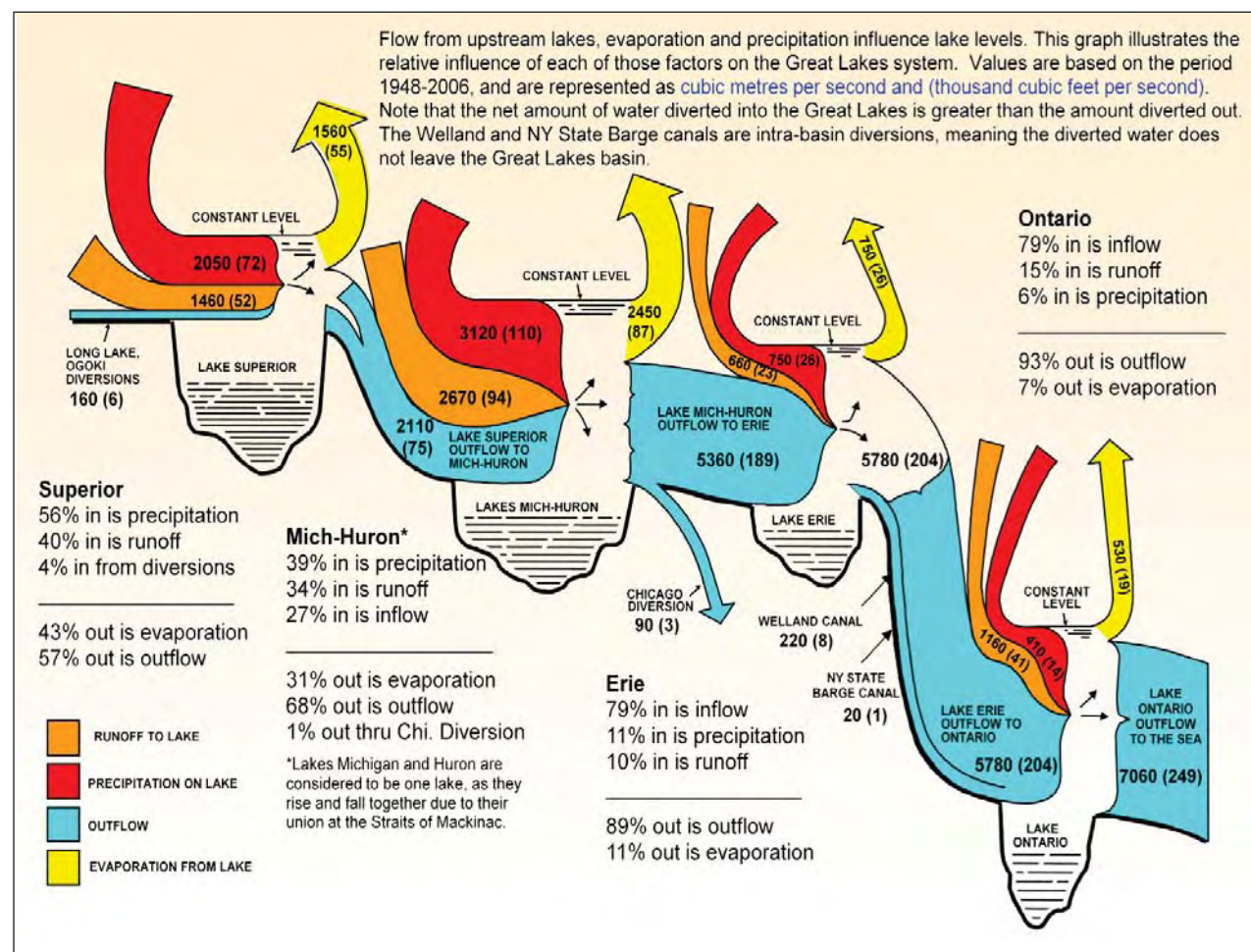
2.2.4 Water Balance

Figure 2-3 shows the relative magnitudes of the factors affecting NBS in the Great Lakes under typical conditions, using the recorded average values for the period 1948-

2006. For example, during this period, overlake precipitation on Lake Superior averaged 2,050 m³/s (72,400 ft³/s) or 56 percent of the water supplies to the lake. The average runoff to Lake Superior for this period was 1,460 m³/s (51,600 ft³/s) or 40 percent, while the remaining 4 percent (160 m³/s or 5,700 ft³/s) consisted of the waters diverted to the Lake Superior basin from the Long Lac and Ogoki watersheds (see 2.2.6 for a discussion on major water diversions in the upper Great Lakes). During this period, water left the lake by evaporation at a rate of 1,560 m³/s (55,100 ft³/s), while the outflow to Lake Michigan-Huron averaged 2,110 m³/s (74,500 ft³/s).

As Figure 2-3 illustrates, NBS is the dominant factor in water supplies to Lakes Superior and Michigan-Huron, making their levels fluctuate more in periods of extended drought or above-normal precipitation. For Lakes Erie and Ontario, the dominant factor is the inflow from the upper lakes.

Figure 2-3 Hydrological Components of Water Supply to the Great Lakes



2.2.5 Human Factors

While the Great Lakes have a high degree of self-regulating capability, their water levels and flow regime have been affected, to some extent, by human activities over the years. Many of the activities have been relatively small in scale with only minor effects.

Lake Superior Outflow Regulation

Since 1916, Lake Superior outflows have been regulated in accordance with the criteria and requirements specified in the Orders of Approval of the International Joint Commission. Full outflow regulation was possible beginning in 1921, when the hydropower projects and related works in the St. Marys River were completed. The Orders have been updated several times to address the evolving needs of interests (such as commercial navigation, recreational boating and tourism, water uses, coastal zone, ecosystem and hydropower) and the changing physical conditions within the upper Great Lakes basin. Under a 1979 Supplementary Order, the present regulation plan, Plan 1977-A, specifies monthly mean outflows designed to: maintain the lake's monthly mean levels between 182.76 and 183.86 m (599.61 and 603.22 ft); reduce the occurrence of high water levels downstream of the works at Sault Ste. Marie; and guard against unduly low levels in Lake Superior. In accordance with the principle of systemic regulation adopted by the International Joint Commission, the monthly Lake Superior outflow is set at the beginning of each month taking into consideration the water level conditions on both Lake Superior and Lake Michigan-Huron.

The ability to regulate the outflow from Lake Superior does not mean that it is possible to control lake levels completely. Major factors affecting the water supply to the Great Lakes – overlake precipitation, evaporation and runoff – cannot be controlled, nor can they be accurately predicted for the long-term. Moreover, the natural variability of water supplies to the Great Lakes basin far exceeds the degree of control that regulation can provide. As a result, little can be done through regulation to alter water levels during periods of extremely high or low water supplies.

The regulation of Lake Superior is the focus of Report 2 of the Study, to be issued in 2012.

Major Water Diversions

There are several large-scale water diversions in the upper Great Lakes (Figure 2-4) (International Joint Commission, 1985; Nicholas 2003). Table 2-2 shows the computed effects of these diversions on the long-term mean water levels of the lakes. The values are generated using computer models that route historical water supply data and assume the state-of-nature for Lake Superior outlet conditions.

- The *Long Lac* and *Ogoki diversions* into the upper Great Lakes system direct southward to Lake Superior a portion of water that otherwise would have flowed north into the Hudson Bay drainage system. Since 1943, these two diversions have averaged about 154 m³/s (5,400 ft³/s). These two projects increase water supplies to the Great Lakes system, raising the long-term mean water levels by 9 cm (3.5 in) on Lake Superior, 11 cm (4.3 in) on Lake Michigan-Huron and 7 cm (2.8 in) on Lake Erie. As noted in Table 2-2, the Long Lac and Ogoki diversions into the Great Lakes more than offset the Lake Michigan-Huron diversion out of the system.
- The *Lake Michigan diversion* out of the upper Great Lakes system consists of water withdrawn from Lake Michigan-Huron at Chicago, and runoff from the Chicago area that in its natural course formerly drained into Lake Michigan-Huron. The water is used for domestic, sanitary, and navigation purposes in the Chicago area and is discharged into the Mississippi River. Although water has been diverted from Lake Michigan-Huron at Chicago since 1848, it was not until 1900 that completion of the Chicago Ship and Sanitary Canal and related control structures allowed for the reversal of the Chicago and Calumet Rivers. This diversion reached a peak of more than 300 m³/s (10,600 ft³/s) in the 1920s; however, a 1967 U.S. Supreme Court decree (amended in 1980) limits the long-term average diversion to no more than 91 m³/s (3,200 ft³/s) and allows some variations in any year within certain specified limits. This diversion lowers the long-term mean levels by 6 cm (2.4 in) on Lake Michigan-Huron and by 4 cm (1.6 in) on Lake Erie, but has no effect on Lake Superior levels.
- The *Welland Canal* was built in 1829 to connect the Welland River and Lake Ontario. In 1881, the canal was extended to Lake Erie and the diversion was made directly from Lake Erie. Since then, the canal has undergone several improvements to accommodate large commercial vessels. The diverted water is used for navigation, hydropower generation, and municipal and industrial uses. In its current configuration, the average diversion is about 244 m³/s

Figure 2-4 Major Water Diversions in the Upper Great Lakes



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

Table 2-2 Summary of Effects of Major Diversions in the Upper Great Lakes
(Increases/decreases in the long-term mean water levels of the lakes)

| Great Lake | Long Lac/Ogoki | Lake Michigan/Chicago | Welland Canal |
|----------------|------------------|-----------------------|------------------|
| Superior | + 9 cm (3.5 in) | 0 | 0 |
| Michigan-Huron | + 11 cm (4.3 in) | - 6 cm (2.4 in) | - 4 cm (1.6 in) |
| Erie | + 7 cm (2.8 in) | - 4 cm (1.6 in) | - 12 cm (4.7 in) |

(Source: Levels Reference Study Board, 1993)

(8,620 ft³/s). Higher and lower flows have occurred, depending on the water level conditions on Lake Erie and water requirements along the canal. While this diversion does not alter the long-term net total water supplies to either Lake Erie or Lake Ontario, it does increase Lake Erie outflow conveyance and thus lowers the long-term mean levels on Lake Erie by 12 cm (4.7 in) and, to a lesser extent, by 4 cm (1.6 in) on Lake Michigan-Huron.

- The *New York State Barge Canal* withdraws water from the upper Niagara River and returns the diverted water to Lake Ontario at several points in upstate New York. Given the location of the point of withdrawal on the upper Niagara River and the relatively small volume (about 31 m³/s or 1,100 ft³/s on an average annual basis), this diversion has negligible effects on Lake Erie and Lake Ontario levels.

Consumptive Uses

Consumptive uses of water represent withdrawals of water from a natural system. Consumptive uses in the Great Lakes basin are relatively small, compared to the natural inflow and outflow of the lakes. An estimate of consumptive use for the Great Lakes States was made for the year 2000, based on median consumptive-use coefficients (Shaffer 2008). The results show that total consumptive use for that year was only about 185 m³/s (6,530 ft³/s). Of this amount, public water supply and thermo-electric power accounted for 28 percent and 26 percent, respectively. Other major consumptive uses were irrigation (20 percent) and industrial uses (15 percent). Livestock, self-supplied domestic and mining uses accounted for the balance.

Alterations to Connecting Channels

Over the years, some obstructions have been placed in the upper Niagara River. These include placement of fill material, the support for the International Peace Bridge, the International Railway Bridge, and the Bird Island Pier separating the Black Rock Canal from the main channel. The cumulative hydraulic impacts of these obstructions can affect Lake Erie levels.

The report by the Levels Reference Study Board (1993) recommended to the governments that steps be taken to ensure that further land filling does not occur in the connecting channels where it can affect lake levels and flows. The report also stated that removal of some of the identified fills from the Niagara River could lower Lake Erie's long-term average level by 3 to 6 cm (0.1 to 0.2 ft).

2.3 UPPER GREAT LAKES WATER LEVELS

2.3.1 Variability and Trends in Water Levels and Flows

Variability

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).

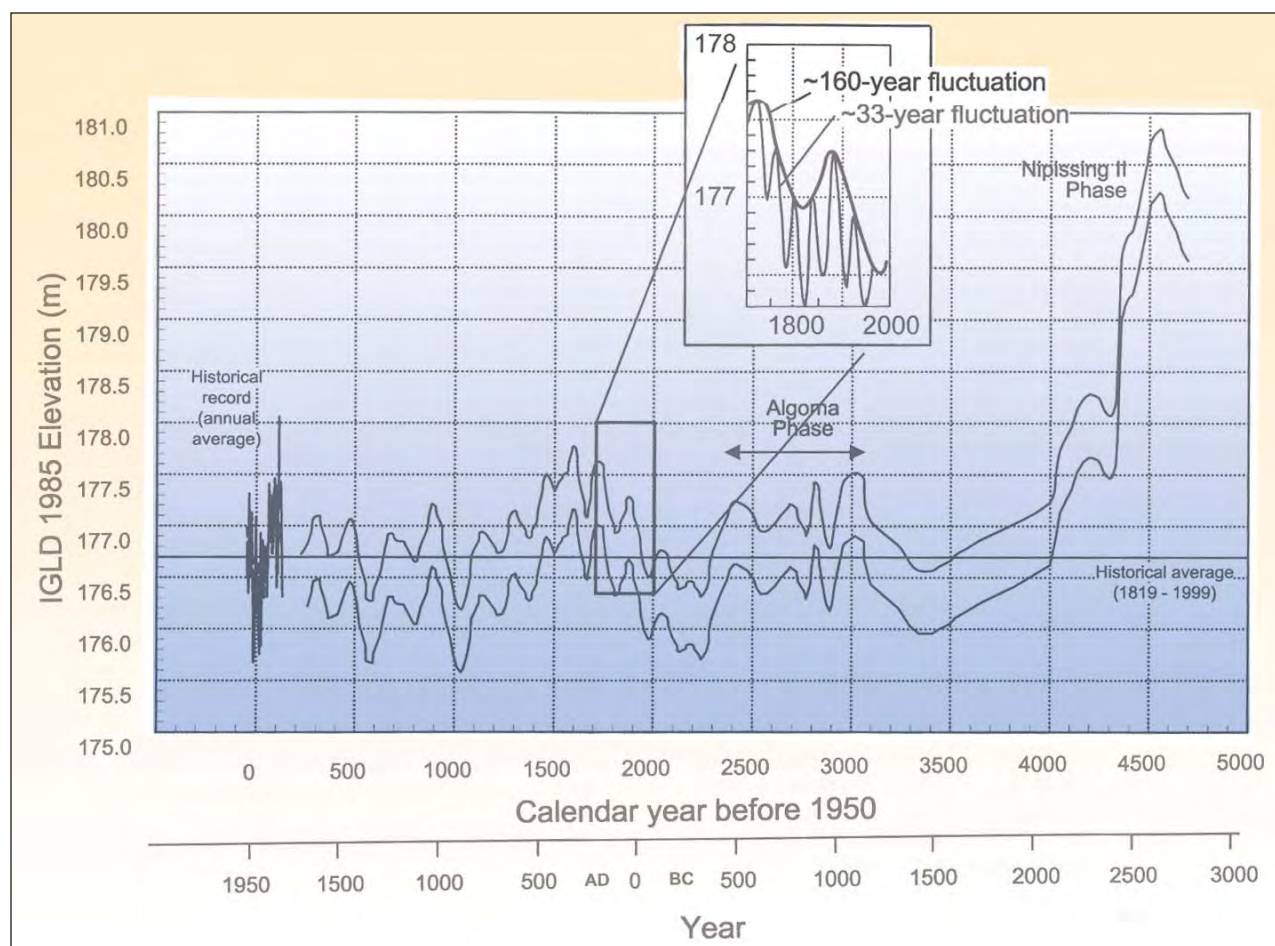
Three types of water level fluctuations occur on the Great Lakes: short-term; seasonal; and long-term:

- *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.
- *Seasonal fluctuations* of the Great Lakes levels generally correspond to the basin's annual hydrological cycle. The cycle is characterized by higher NBS during the spring and early summer, and lower NBS during the remainder of the year. Each Great Lake loses water through evaporation from its surface. The relative importance of evaporation varies from one lake to another, depending primarily upon the area of the lake surface as compared to the area of the watershed draining to the lake. Summer evaporation over the lakes is much less important than in colder months. The presence of ice cover on the lakes will reduce water losses through evaporation. Conversely, the absence of ice cover on the lakes in the fall and winter will increase the volume of water lost from evaporation. 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 a number of years of above or below average precipitation or evaporation. Their magnitude and duration are irregular. Prior to 1918, there were insufficient water level data and gauge stations to determine the lake-wide average monthly mean lake levels accurately and consistently. Table 2-3 lists the long-term average and range of water level and outflow fluctuation for the upper Great Lakes for the period 1918-2008.

Prehistoric Water Levels

Recent research has provided interesting insights into prehistoric water level changes on Lake Michigan-Huron (Wilcox *et al.*, 2007). By analyzing coastal features, the formation of beach ridges and sedimentary deposits, researchers have reconstructed a hydrograph of lake-level change for Lake Michigan-Huron over the past 4,700 years (Figure 2-5).

Figure 2-5 Prehistoric Water Levels of Lake Michigan-Huron



Source: Baedke and Thompson (2000)

The results suggest that 4,700 years ago the level of Lake Michigan-Huron was about 4 m (13 ft) higher than the present level. There then was a period of more than 500 years of lake-level decline during which lake levels dropped to elevations similar to historic (about post-1860) averages. Three high-level phases – from 2,300 to 3,300, 1,100 to 2,000 and 0 to 800 years ago – followed these declines.

The same study suggested that prehistoric water level fluctuations have been closely linked to climatic variability, particularly climate-driven changes in water balance. This includes lake-level highstands commonly associated with cooler climatic conditions and lows associated with warm climate periods.

Recent Trends in Water Levels

Long-term water level fluctuations are the result of persistent low or high water supply conditions within the upper lakes basin, which in turn culminate in extremely low and high levels. As shown in Figure 2-6, record low water levels for the various lakes occurred during the late

1920s and 1930s and again in the mid-1960s. Note that the low water level period from 1998-2007 is similar to that of the period from 1928-1937.

Record high levels occurred in the early 1950s, in 1973, and in 1985-1986. Water level trends can also reverse quickly, as demonstrated in the drop from very high to very low values in a matter of about two years from 1986 to 1988 and again from 1997 to 1998 (Assel *et al.*, 2004). Large variations in precipitation, evaporation and runoff accompanied these changes. No patterns are discernable over the short term. The intervals between periods of high and low levels and the length of such periods can vary widely over a number of years.

As a result of increasing concerns about the implications of climate change, there have been numerous studies of climate change and climatic variability, and their effects on Great Lakes water levels. Many of the global climate modelling results point to a decrease in NBS, which would in turn reduce the upper Great Lakes outflows.

Table 2-3 Summary of Monthly Mean Water Levels and Outflows

| | Water Levels (IGLS 1985) | | Outflows | |
|----------------------------|--------------------------|--------|-------------------|--------------------|
| | metres | feet | m ³ /s | ft ³ /s |
| Lake Superior | | | | |
| Average | 183.41 | 601.74 | 2120 | 74,900 |
| Maximum | 183.91 | 603.38 | 3740 | 132,100 |
| Minimum | 182.72 | 599.48 | 1160 | 41,000 |
| Range | 1.19 | 3.90 | 2580 | 91,100 |
| Lake Michigan-Huron | | | | |
| Average | 176.44 | 578.87 | 5150 | 181,900 |
| Maximum | 177.50 | 582.35 | 6740 | 238,000 |
| Minimum | 175.58 | 576.05 | 3000 | 105,900 |
| Range | 1.92 | 6.30 | 3740 | 132,100 |
| Lake St. Clair | | | | |
| Average | 175.01 | 574.18 | 5300 | 187,200 |
| Maximum | 175.96 | 577.30 | 7080 | 250,000 |
| Minimum | 173.88 | 570.47 | 3170 | 111,900 |
| Range | 2.08 | 6.82 | 3910 | 138,100 |
| Lake Erie | | | | |
| Average | 174.14 | 571.33 | 5930 | 209,400 |
| Maximum | 175.04 | 574.28 | 7820 | 276,200 |
| Minimum | 173.18 | 568.18 | 3340 | 118,000 |
| Range | 1.86 | 6.10 | 4480 | 158,200 |

(1) Water levels for each lake are calculated using recorded monthly values from a network of gauges on the lake for the period 1918-2008. Daily and instantaneous water levels at a location on the lake can be significantly more extreme than the values shown.

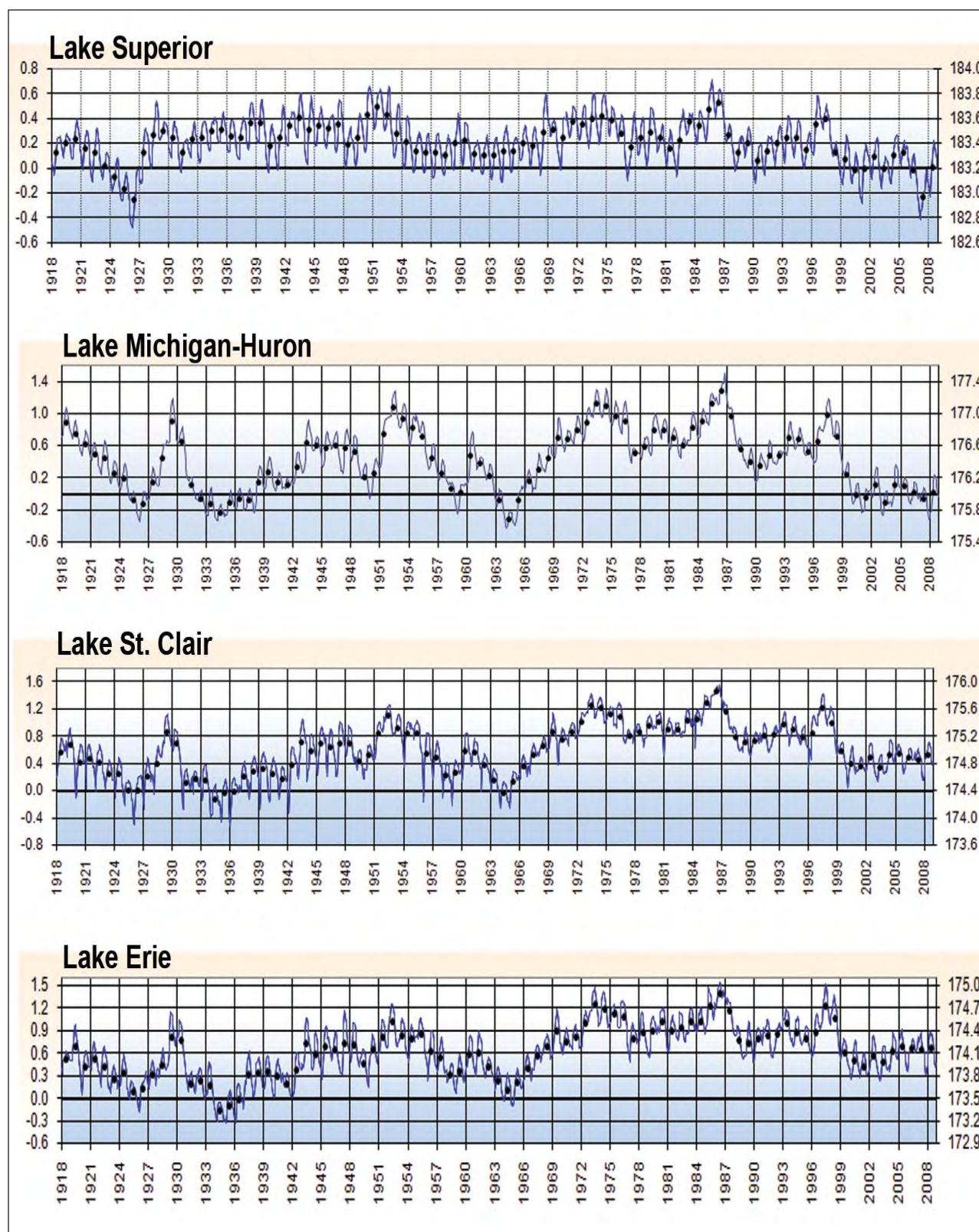
(Source: Environment Canada, Great Lakes – St. Lawrence Regulation Office)

Concerns about Low Lake Level Conditions

For the past decade, low lake level conditions have been a serious concern for commercial shippers, property owners, recreational boaters, Native Americans, First Nations and others across the upper Great Lakes basin. Persistently low water levels in the basin can:

- reduce a ship's capacity to transport the maximum cargo the vessel was built for, requiring more voyages and increasing operating costs, which are ultimately passed on to the consumer in the form of higher prices;
- increase the risk of a ship going aground and being damaged, which translates into increased costs and delays while the ship is being repaired;
- affect wetlands by damaging habitats and reducing the diversity in plants and animals supported by these habitats;
- lead to increased pumping and water treatment costs for municipalities along the lakes;
- affect shore-wells, a primary source of water outside of urban areas;
- expose shore protection infrastructure;
- expose the shoreline to muddy bottom lands, rocks, or shoreline sedimentation;
- limit access to lakefront property by owners and emergency boats; and
- impede accessibility to marinas, docks and boat ramps, thus restricting recreational boating and other tourism activities.

Figure 2-6 Upper Great Lakes Water Levels, 1918-2008



(Source: Upper Lakes Plan of Study Revision Team, 2005)

Note: Water surface elevations at 0.0 are at chart datum on IGLD (1985). The black dots represent annual mean values.

2.3.2 Climate Patterns and Climate Change

Climate Patterns

The climate of the Great Lakes basin varies considerably due to the basin's north-south extent and the effects of the lakes on near-shore temperatures and precipitation. For example, the mean January temperature on land ranges from -19 °C (-2 °F) in the north to -2 °C (28 °F) in the south, while the mean July temperature ranges from 18 °C (64 °F) in the north to 23 °C (74 °F) in the south (Nicholas, 2003).

Precipitation is distributed relatively uniformly throughout the year, but does vary from west to east across the Great Lakes basin, ranging from a mean annual precipitation of 710 mm (28 in) north of Lake Superior to 1,320 mm (52 in) east of Lake Ontario. Mean annual snowfall is much more variable because of temperature differences from north to south and the snow-belt areas near the east side of each lake. Annual snowfall ranges from about 51 cm (20 in) in the southern areas of the basin, to 355 cm (140 in) in snow-belt areas downwind of Lakes Superior and Ontario (Nicholas, 2003).

Wind is also an important component of the Great Lakes climate. In fall and winter, very strong winds from weather systems moving across the region are common. In near-shore areas, very strong winds can result from the temperature differences between the lakes and the air moving over the water.

Climate Change

In its most recent assessment, the Intergovernmental Panel on Climate Change (IPCC) concluded that scientific evidence based on well-established theory and observations from long-term monitoring networks indicates that climate change is occurring, though the effects differ regionally (Brekke *et al.*, 2009). The IPCC also noted that climate trends since about 1970 have been driven predominantly by greenhouse gas concentrations in the atmosphere and that this will continue to be the case in future decades.

The effects of climate change on the levels of the upper Great Lakes are uncertain. NBS to the upper Great Lakes has had historical variations on many timescales. Periods of higher and lower water supplies can be expected in the future due to the natural variation in climate, and are affected by anthropogenic increases of greenhouse gases in the atmosphere (Hall and Stuntz, 2007).

The IPCC reaffirmed its conclusion that society needs to consider the many sources of uncertainty and drivers of climate change. These drivers include demographic change, energy use and deforestation rates, changes in the way people use water, declining amounts of groundwater in some regions, and demands for water to meet ecological goals.

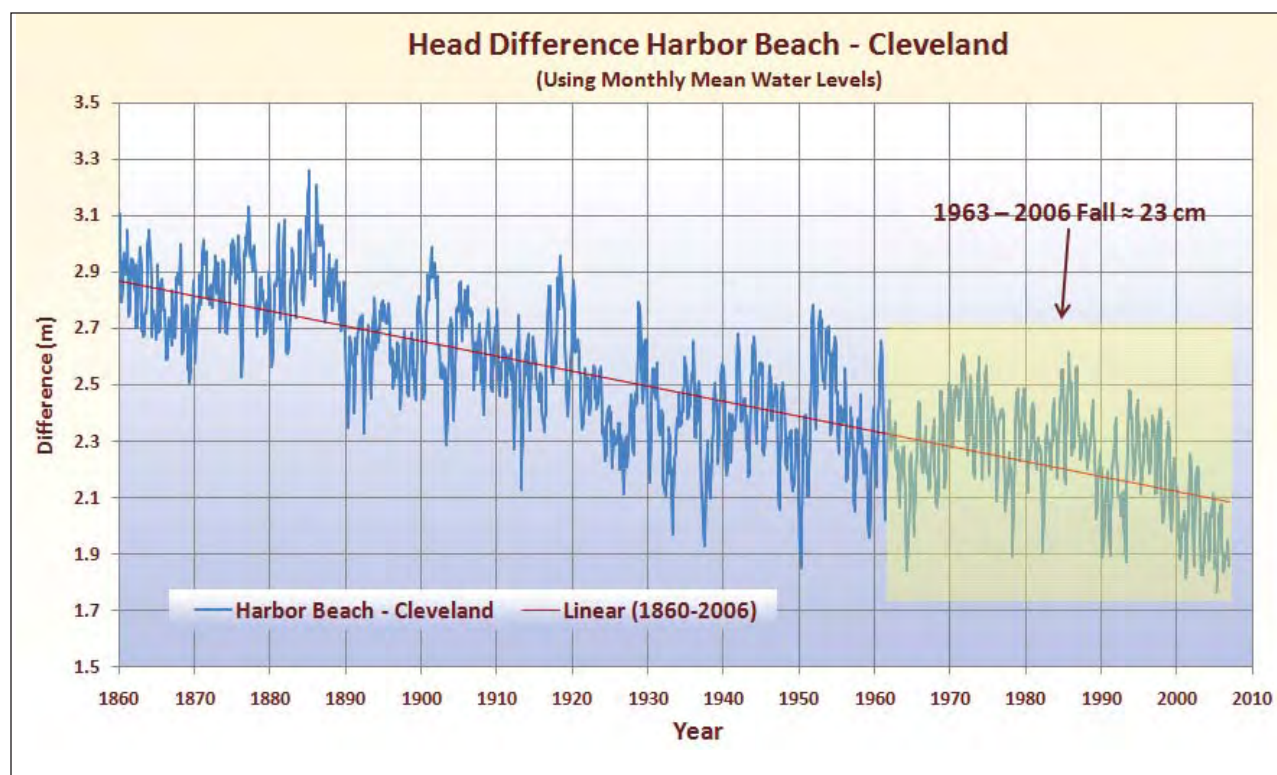
The IPCC also emphasized that long-term monitoring networks are critical for detecting and quantifying climate change through the collection and analysis of data on precipitation, evaporation or surface water temperatures, snowpack, soil moisture, groundwater and streamflow. Understanding the effects of climate change on these factors makes for more effective broadly-based adaptation or mitigative actions in addressing climate change. This monitoring work, along with continuing efforts in predictive modelling, is needed to narrow the range of uncertainty for planning and management of water resources in the future.

2.3.3 Changes in Head Difference Relationship between Lake Michigan-Huron and Lake Erie: Key Contributing Factors

The key considerations relating to variations in upper Great Lakes water levels are whether the head difference relationship between Lake Michigan-Huron and Lake Erie has changed over time, and if so, whether this change is a result of natural processes, or human activities, or some combination of the two.

The head difference between Lake Michigan-Huron and Lake Erie is the result of gravitational forces that drives the flow of water from the former to the latter. As shown in Figure 2-7, records of annual mean water levels (recorded at Harbor Beach, MI (about 100 km [62 miles] north of the lake's outlet) and Cleveland, OH on Lake Erie) show that the head difference between the two water bodies was about 2.9 m (9.5 ft) between 1860 and 1880 (though it should be noted that pre-1900 data may not be reliable because of data collection techniques and the use of different standards). The difference decreased sharply over the course of several years around 1890, and subsequently exhibited a declining (but irregular) trend over the next century through to the present. By 2008, the head difference was about 1.9 m (6.2 ft). As Figure 2-7 illustrates, the head difference declined by an estimated 23 cm (9 in) between 1963 and 2006, the Study's primary period of focus.

Figure 2-7 Head Difference between Lake Michigan-Huron and Lake Erie



(Note that there is a distinction between the actual head difference in individual years, which can vary from one year to the next, and the trend line shown in Figure 2-7, which represents the best linear fit to the changes in the measured data over the time period.)

A combination of factors likely has contributed to the change in the head difference between Lake Michigan-Huron and Lake Erie over time:

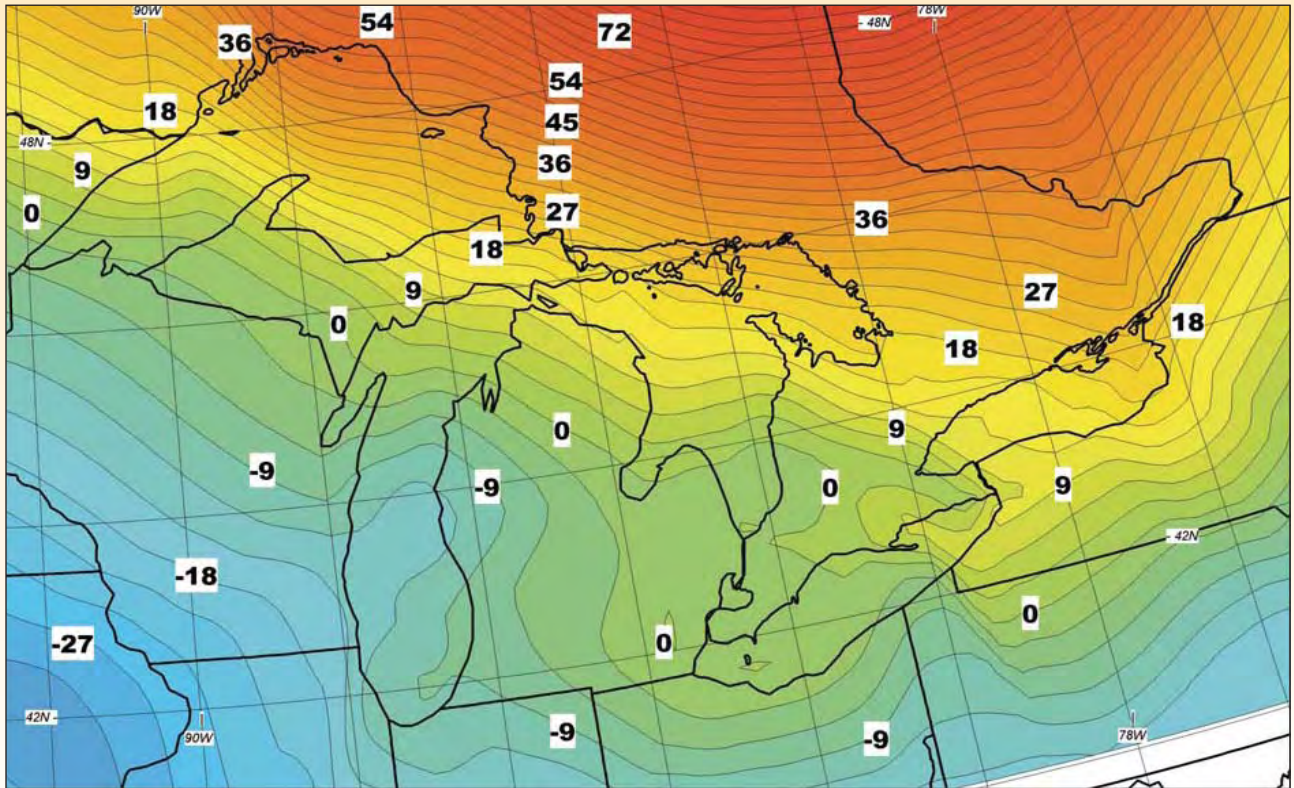
- changes in water supplies to the Lake Erie basin and to the upstream basins as a result of *climatic variability* or *shifting climate and weather patterns* (as noted in 2.3.2)
- the effect of GIA on the head difference between the two lakes and its implications on recorded water level data on these two lakes (as described below); and
- changes in the *conveyance* of the St. Clair River due to natural forces and human activities such as dredging (as described in 2.4).

Effects of Glacial Isostatic Adjustment

During the last period of continental glaciation, which ended in North America only about 10,000 years ago, the tremendous weight of the glacier that covered most of the Great Lakes region depressed the earth's crust underneath it. 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 and melted, the crust, relieved of the weight, began to recover. The glacier was thicker and remained longer over the areas that became the northern and eastern portions of the Great Lakes basin. As a result, the land in these regions is rising relative to the earth's core. At the same time, areas in the southern and western portions are subsiding, as the former forebulge collapses.

This process continues today, though at different rates across the Great Lakes basin, affecting water depths along the shoreline around each lake (Figure 2-8). In general, GIA has the effect of tilting the Lake Michigan-Huron basin generally towards the southerly direction. This shift causes water levels on the northern and eastern shores of the lakes to appear to recede or decline over time, and water levels on the southern and western shores to appear

Figure 2-8 Glacial Isostatic Adjustment in the Great Lakes Region
(Relative vertical rise or fall (-) in cm/century)



Source: Mainville and Craymer (2005), from http://www.geod.nrcan.gc.ca/publications/papers/pdf/great_lakes.pdf

to rise over time. It also affects the available head, or water depth, at the outlet of Lake Michigan-Huron, with related effects on the flow in the St. Clair River, and hence water storage in Lake Michigan-Huron over time. GIA also affects how Lake Erie's outlet shifts relative to the outlet of Lake Michigan-Huron. This may lead to a backwater effect, which can alter the water level regime at the confluence where the Detroit River enters Lake Erie, thereby affecting the conveyance of the St. Clair River.

Baird Report Hypotheses

As noted in Chapter 1, a 2005 report prepared for Georgian Bay Forever (formerly the GBA Foundation), investigated the decline in head difference between Lake Michigan-Huron and Lake Erie (Baird, 2005). The report identified three possible causes for the "ongoing and significant drop" in the head difference:

"The possible causes included: glacial rebound; a shift in the relative net basin supplies (NBS) making the E (Erie) basin wetter than and [sic] MH (Michigan-Huron) basin; and erosion of the St. Clair River bed. Based on the review, glacial rebound was found to be negligible

compared to the total drop, the NBS shift was found to be unsubstantiated, and the primary cause of the drop in MH lake levels is due to river bed erosion, particularly across a relatively short section, between the Fort Gratiot and the Mouth of the Black River water level gauges, at the upstream end of the river."

The report concluded that the possible causes of the observed river bed erosion fall into three primary groups:

"... 1) changes to the upstream supply of sand and gravel through shore protection and harbor breakwater construction on the US and Canadian shores of Lake Huron leading up to the St. Clair outlet; 2) changes to the flow patterns at the outlet owing to the configuration of the outer navigation channel; and 3) removal of a protective gravel lag either through sand mining in the 1920's or through increased flow speeds related to point (2) above."

2.4 ST. CLAIR RIVER FLOW REGIME AND CONVEYANCE

2.4.1 Flow Regime

A flow regime in a river is defined by a relatively consistent set of conditions that influence the flow of water through the river. Permanent changes or shifts in certain conditions can result in permanent changes in the flow regime. On the Great Lakes connecting channels, these conditions are generally considered to be related to:

- the geometry of the river channel; the geologic make-up of the river channel, which can influence natural erosion;
- long-term shifts in climatic or weather patterns, which affect the headwater and backwater effects of the upstream and downstream lakes; and
- the seasonally reoccurring flow retardation induced by ice cover and aquatic plant growth.

River channel geometry can change naturally through erosion and deposition, and by human activities such as dredging, construction of dams, dikes and piers and even shipwrecks.

Channel geometry in the St. Clair River has been changed by human activities many times since the mid-1800s, primarily by dredging for navigation and by sand and gravel mining¹. Each time a major episode of dredging or mining was concluded, a change in flow regime was observed. The flow regime was considered to be stable until the next major dredging episode occurred. Until recently, the geology of the river and historic climatic conditions were considered to be unchanging.

The assumption of stable flow regimes, defined by stable channel geometry, has been the basis of most continuous (monthly) estimates of river discharges. These estimates are derived from rating equations and models based on limited discharge measurements and the recorded water level profile in the river.

Although measurable changes to the flow regime have occurred over the last 150 years, the St. Clair River continues to have relatively stable outflows thanks to its geographical location downstream of massive lakes with their immense storage capacities. Historically, the river's monthly mean outflows during the open-water season have varied within 20 to 30 percent of the average discharge of 5,150 m³/s (181,900 ft³/s) (based on the period of record

from 1918-2008). Ice can significantly impede flow however, and monthly mean outflows as low as 3,000 m³/s (106,000 ft³/s) have been recorded.

2.4.2 Conveyance

In hydraulic terms, conveyance is a measure of the discharge capacity (or the water-carrying capacity) of a river or channel. The flow in the St. Clair River system is "sub-critical" meaning that gravity is the primary driving force and that no single river cross-section in this system completely controls the rate at which water flows between Lake Michigan-Huron and Lake St. Clair.

In steady-state flow where the flow characteristics such as water levels, depths, and velocities along the channel do not change over time, there is a perfect balance between the forces that drive the water and the flow resistance generated by the river's geomorphology. Steady-state flow conditions are very infrequent in nature, however, because of continuously changing lake level and meteorological conditions. As a result, investigators generally need to use unsteady-state computer models to analyze water levels and flows, because these models more realistically simulate the dynamic conditions in a river system.

At a particular river section or reach, the rate of water flow can be estimated by an empirical hydraulic formula for open-channel flow that relates the flow with the available cross-sectional area and its geometry, gradients or slopes of the river bed and water surface profile, and roughness of the river banks and bed. A change to any of these parameters can lead to changes to the rates of flow. For example, a decrease in conveyance can occur when an obstruction is placed in the river or because of added flow resistance resulting from shoreline or river bed changes (*e.g.*, the construction of a new structure jutting into the water or an increase in aquatic vegetation). The reduction in flow causes some water to be stored in Lake Michigan-Huron, raising its level and resulting in a higher head, which overcomes the added flow resistance. The ultimate result could be a permanent rise in the long-term average Lake Michigan-Huron level. Conversely, the river's conveyance can be increased when flow resistance is reduced, such as following channel deepening and enlargement.

Mathematical expressions, called *stage-discharge relationships* or *rating equations*, can be developed to define the relationships between the river flow and water levels of Lake Michigan-Huron and Lake Erie. These relationships are developed using water level and flow data collected over the years through a variety of methods. The relationships are periodically updated as warranted to reflect changes in conveyance resulting from physical changes in the river.

¹ Sand and gravel mining started in 1908 but was stopped in 1925 in the U.S. and 1926 in Canada.

Physical changes in the St. Clair River system neither increase nor decrease the long-term net water supplies to the upper Great Lakes. However, by altering the relationships between water levels and flows in the river, they can change the long-term water level regime of the river and the lake upstream. These changes also can alter the timing of the movement of water supplies from Lake Michigan-Huron to Lake Erie, though this effect is insignificant in most cases, unless an occasional ice jam occurs.

2.4.3 Factors Affecting Conveyance

The St. Clair River system has been subject to – and in some cases continues to be subjected to – a range of physical changes, both natural and human-caused, that can contribute to changes in conveyance.

Human Activities

Dredging

Dredging has altered the natural state of the St. Clair and Detroit Rivers more than any other human activity.

In its natural state, the St. Clair River had depths of 6 m (20 ft) or more throughout most of its length, excluding some isolated shoals. The St. Clair River Delta (also known as the St. Clair River Flats), at the downstream outlet into Lake St. Clair, has many winding channels that had minimum natural depths of only 1.2 to 1.8 m (4 to 6 ft). The Detroit River had varying depths, but was generally deep in the upper portion with many islands and channels in the lower portion (CCGLHHD, 1988).

Dredging of the St. Clair River began in the late 1850s and has continued for the last 150 years, amounting to a total of more than 25.2 million m³ (33 million yd³) of material (Giovannettone, 2009). Most of this dredging was undertaken to enhance the rapid increase in commercial navigation, while about 2.3 million m³ (3 million yd³) were removed in the early 1900s by commercial sand and gravel mining operations. These dredging projects were authorized by the United States Congress, following consultation between Canada and the United States and approval of both countries.

Early dredging focused on the St. Clair Flats area, where the waters were shallowest, and in a small area at the head of the St. Clair River. Dredging operations spread to other parts of the river, providing a minimum depth of 6.1 m (20 ft) until 1930.

The largest dredging activity ever undertaken in the river occurred between 1933 and 1936, when 8.4 million m³ (11 million yd³) were excavated to deepen the channel to 7.6 m (25 ft). This volume accounts for *one third* of the total volume of dredging that has taken place in the St. Clair River over the last 150 years. In fact, the volume of material removed from the St. Clair River from all the

new and maintenance dredging that has occurred since 1936 amounts to only about 70% of the volume removed during that brief 1933-1936 period.

The last major dredging in the St. Clair River was undertaken between 1960 and 1962, when the navigation channel was deepened again to 8.2 m (27 ft) throughout the entire river. The total volume of dredging during this period was about 1.5 million m³ (2 million yd³) of material. This volume was only 19% of the total volume dredged during the 1933-1936 dredging event, and accounts for only about 27% of the total volume dredged since 1936.

Figure 2-9 illustrates the volume of dredging in the St. Clair River since 1918, and indicates the relative magnitude of the 7.6 and 8.2 m (25 and 27 ft) dredging projects undertaken in 1933-1936 and 1960-1962, respectively.

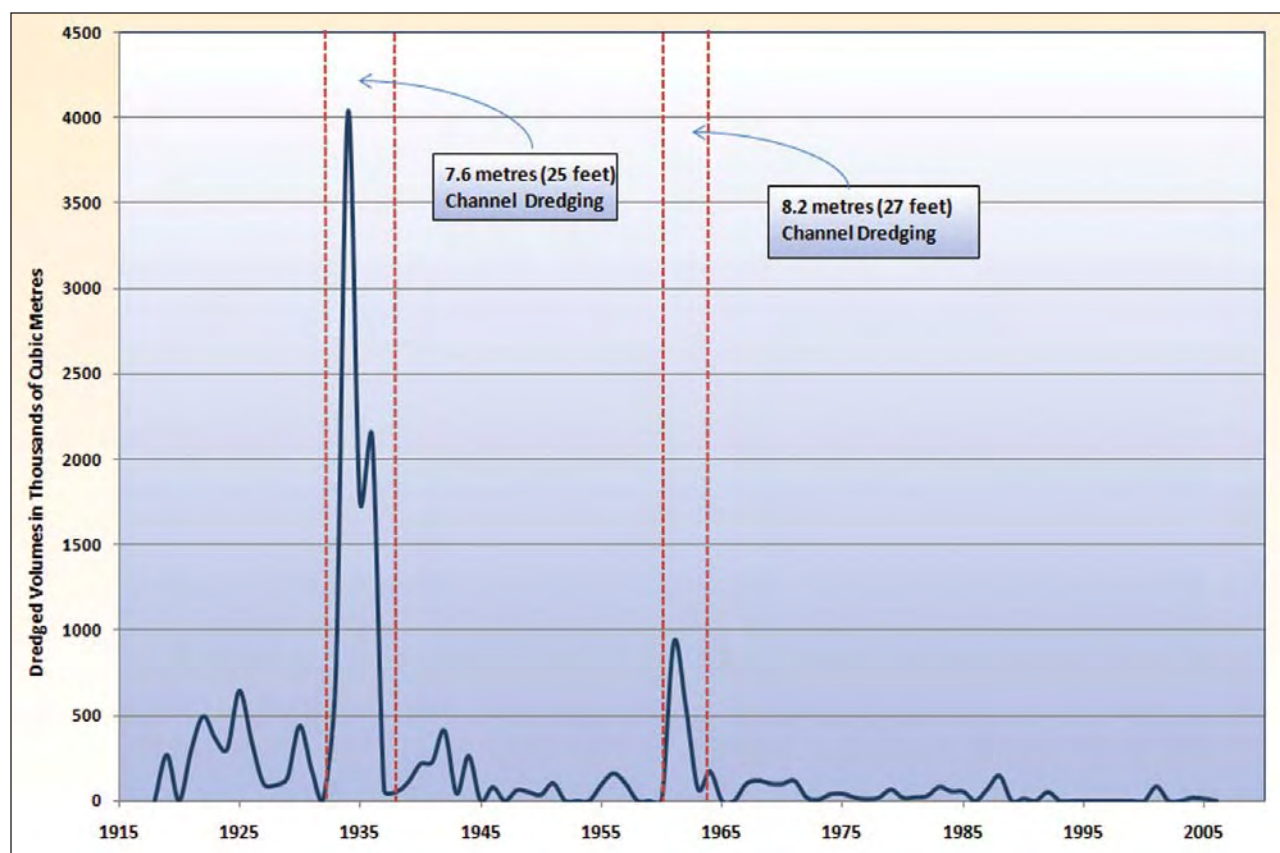
Since 1962, all dredging in the St. Clair River has been related to maintenance dredging, which entails restoring the channel bottom to its authorized navigation channel depths by the removal of sediment and obstructions. Total maintenance dredging between 1964 and 2005 in the St. Clair River is about 1.8 million m³ (2.4 million yd³). A large percentage of this maintenance dredging has been limited to locations near the mouth of the Black River, the St. Clair Middle Ground, and Russell Island.

The total dredging volume in the Detroit River since the late 19th century is about double the volume dredged in the St. Clair River during the same period. As in the St. Clair River, dredging undertaken on the Detroit River since 1962 has been related entirely to channel maintenance.

Given that the outflows of Lake Michigan-Huron are not regulated, dredging of the river system will increase the river's conveyance and thus lower Lake Michigan-Huron. As a result, discussion of compensating structures often accompanied major dredging projects in the past. Various studies were done for these projects to compute the effects of dredging projects on lake levels and identify compensating works. Many studies focused on the change over time in fall between Lake Michigan-Huron and Erie.

Most of the material dredged for navigation purposes was deposited in various locations within the St. Clair and Detroit Rivers so as to not impede navigation for either the 7.6 m (25-foot) project or the 8.2 m (27-foot) project. This practice has resulted in some compensation of the increased conveyance of the river system. Although Congressional authorizations proposed compensating structures (in the form of a series of underwater sills placed in the St. Clair River) as an integral part of the dredging work, and studies were conducted on submerged weirs or sills, control structures, dams and breakwaters, full compensation to maintain the pre-dredging water level and flow conditions was never undertaken for the St. Clair River (Baird, 2009).

Figure 2-9 Dredging Volumes in the St. Clair River



On the Detroit River, compensating dikes have been constructed in the lower reaches to partially offset the lowering of water levels due to previously authorized navigation improvements. As early as 1909, some cofferdams constructed in the river to facilitate dredging operations were left in place afterward. Much of the lower Detroit River bed is rock. To reduce transportation and disposal costs, the material was placed alongside the new channels to form dikes. The dikes provide some hydraulic compensating effects. Dikes continued to be constructed throughout the dredging of the Livingstone Channels and at Stony Island in the 1920s and 1930s, and in the Amherstburg Channel in the late 1950s. At the start of the 8.2 m (27-foot) project, it was noted that some over-compensation existed on the Detroit River as a result of previous work. The remaining compensation for the Detroit River dredging of the 8.2 m (27-foot) project was obtained by the construction of two dikes, created from the deposition of dredged material.

In the early 1960s, Canada and the United States agreed to examine water level issues related to dredging. While the two countries were determining the magnitude of lake level declines caused by channel changes (estimated at the time to be about 13 cm [5.1 in]), the Great Lakes region moved from record low water levels in mid-1960s to record highs

in the mid-1970s. As a result, there was no pressing interest to place submerged sills in the St. Clair River that would have raised water levels even higher. The compensating structures, originally authorized in 1930, were de-authorized in 1977. The 1973-1974 record high levels on Lake Michigan-Huron were surpassed in 1985-1986, and lake levels remained above average, for the most part, until 1999.

Shoreline Changes

The upper St. Clair River shore zones are generally urbanized, with cities, towns, and industries along much of its length. The balance of the shoreline is agricultural land.

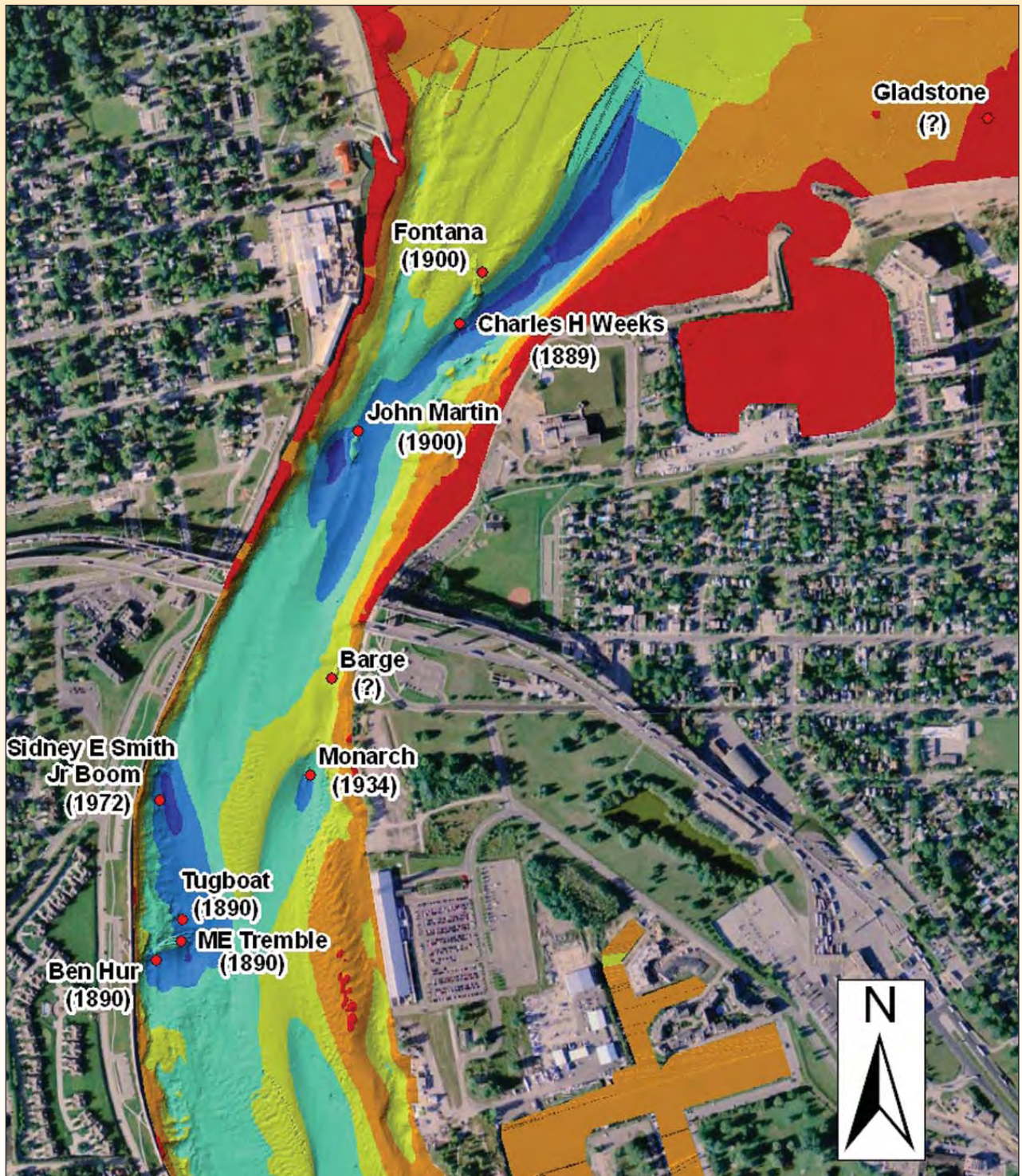
Over the years, various shoreline protection works have been installed to prevent river bank erosion or to protect urban and industrial developments along parts of the system, particularly along the upper portions of the St. Clair and Detroit Rivers. One major shoreline hardening was the construction of the Peerless Seawall immediately downstream from the International Blue Water Bridge on the U.S. side. This project, completed in the early 1980s, is located in a deeper part of the channel. Such projects can affect bed topography through, for example, the construction of pilings.

Obstructions in the River

Retardation of water flow can occur when obstructions such as bridge piers or sunken vessels are placed in a river. One example was the sinking of the steamers *Fontana* and *John Martin* in 1900 in the narrows at the head of the St. Clair River. Figure 2-10 indicates the location of these and eight other major shipwrecks in the river.

Unlike flow retardation due to ice and weed growth, these obstructions remain in place year-round and thus have long-term effects on the water level regime of the river and possibly the lakes both upstream and downstream.

Figure 2-10 Shipwrecks in the St. Clair River



Natural Changes

Sedimentation and erosion

Sedimentation and erosion or the movement of bed materials (clay, silt, sand, gravel and cobbles) is a natural and on-going process. However, it can be affected by human activities that take place either in the river or upstream.

Aquatic vegetation growth, ice cover and ice jams

Although aquatic vegetation growth, ice cover and ice jamming in the St. Clair River are not permanent physical changes, they are recurring seasonal changes that can have varying effects on the river's conveyance. These effects can be significant at the local level.

Aquatic weeds in the St. Clair River during the growing season generate resistance to the river's flow, thus reducing its conveyance. This effect typically causes a small rise in the water levels of Lake Michigan-Huron, which is subsequently offset by a higher outflow in late summer and fall when weed growth is no longer a limiting factor.

Around the mid-1980s, much of the Great Lakes experienced effects from the widespread growth of invasive species, such as zebra mussels (which have subsequently been generally displaced by the more dominant quagga mussel). Mussels filter or clean the water, thereby allowing light to penetrate deeper, resulting in vegetation growing faster in some lakes and connecting channels. Such vegetation growth can reduce a river's conveyance, as reflected in some data collected in these lakes and channels after the mid-1980s.

In a typical winter, the flows in the St. Clair River often are impeded by ice formation at the outlet of Lake Michigan-Huron and within the St. Clair River, Lake St. Clair and the Detroit River. This flow retardation leads to some water being temporarily retained on Lake Michigan-Huron, raising water levels higher at the time of the spring breakup. Given the size of Lake Michigan-Huron, the increases in water levels in most cases are not significant. The increase in the Lake Michigan-Huron levels resulting from this water storage causes higher outflows following the breakup, and this seasonal effect is gradually dissipated. Severe ice jams can occur in the St. Clair River and lead to large local changes in the water levels of the river, such as occurred in April 1984. An ice jam of this size could potentially result in scouring of the bed. For the St. Clair River, a common problem is the large amount of ice that typically forms on Lake Huron, particularly at the lake's outlet.

The Detroit River generally is not subjected to a large degree of flow retardation due to ice cover on Lake St. Clair. The lake ice typically remains intact through the winter and prevents ice from entering the Detroit River in large enough quantities to cause ice jams.

2.5 KEY POINTS

- ▶ The St. Clair River system is part of the upper Great Lakes basin. Due to the large volumes of water stored in the lakes, the Great Lakes are naturally self-regulating, with lake levels remaining within a certain range over long periods of time.
- ▶ Beyond the limited capability to regulate Lake Superior at the St. Marys River, there are few opportunities for governments to influence upper Great Lakes water levels, particularly in the short- to medium-term timeframe.
- ▶ Long-term fluctuations in water levels in the upper Great Lakes – and specifically the head difference between Lake Michigan-Huron and Lake Erie – likely have been affected by a combination of factors:
 - changes in water supplies to the Lake Erie basin and to the upstream basins as a result of *climatic variability* or *shifting climate and weather patterns*;
 - the effects of GIA; and
 - changes in the conveyance of the St. Clair River due to natural forces and human activities.
- ▶ In the 1960s, Canada and the United States agreed to construct compensating works in the St. Clair River in response to water level concerns related to dredging of the channel. However, the works were never built, because the Great Lakes region moved from record low water levels in mid-1960s to record highs in the mid-1970s.
- ▶ Based on the revised Plan of Study and extensive scientific and public input, the Study focused on conveyance, NBS and GIA as being the most significant factors when addressing the water balance of the upper Great Lakes. A number of factors, notably groundwater and consumptive uses, were considered to be of lesser importance for addressing the St. Clair River issue.

CHAPTER 3

STUDY ANALYTICAL FRAMEWORK

Chapter 3 describes the analytical framework used to guide the Study in examining physical processes and the possible ongoing changes in the St. Clair River and their impacts on the water levels of Lake Michigan-Huron. The framework consisted of three distinct but interrelated perspectives: *sediment*, *hydraulic* and *hydroclimatic*. Over the course of the Study, the effects of *glacial isostatic adjustment* (GIA) on the water levels of the upper Great Lakes basin emerged as an important issue that needed greater recognition.

The Chapter reviews the specific science questions, data requirements, and modelling strategy for each of the Study's focus areas. Finally, the Chapter reviews the Study's approach to addressing scientific uncertainty in the analysis and integration of results.

3.1 STUDY APPROACH

3.1.1 Overview

The fluctuation of water levels and flows in the upper Great Lakes is a dynamic and complex process. The St. Clair River is an integral part of this process. For example, an increase in the St. Clair River conveyance of five percent, or 250 m³ (8,830 ft³) a second at a mean annual flow of 5,150 m³ (181,900 ft³) a second, could lower the water levels on Lake Michigan-Huron by as much as 10 to 12 cm (3.9 to 4.7 in) over a period of a few years before the levels on these lakes reached their new equilibrium. A lowering by such amount, in turn, would have implications for the interests and the environment in the upper Great Lakes.

As outlined in Chapter 2, conveyance changes in the St. Clair River may be the result of human-caused or natural factors or a combination of both. Human-caused factors can include dredging and channel realignment, shoreline protection works, vessel traffic and flow obstructions such as sunken vessels. Natural factors can include sediment erosion and deposition, changes in water supply, changes in aquatic vegetation growth and ice formation and ice jams in the river.

Beyond the question of the St. Clair River's conveyance, other natural and human factors can affect the upper Great Lakes water levels. These include changes in the components of the upper Great Lakes net basin supply (NBS) (precipitation, evaporation and runoff), decadal variations in ice cover which affects evaporation rates, Lake Superior outflow regulation, water diversions and consumptive uses, and GIA.

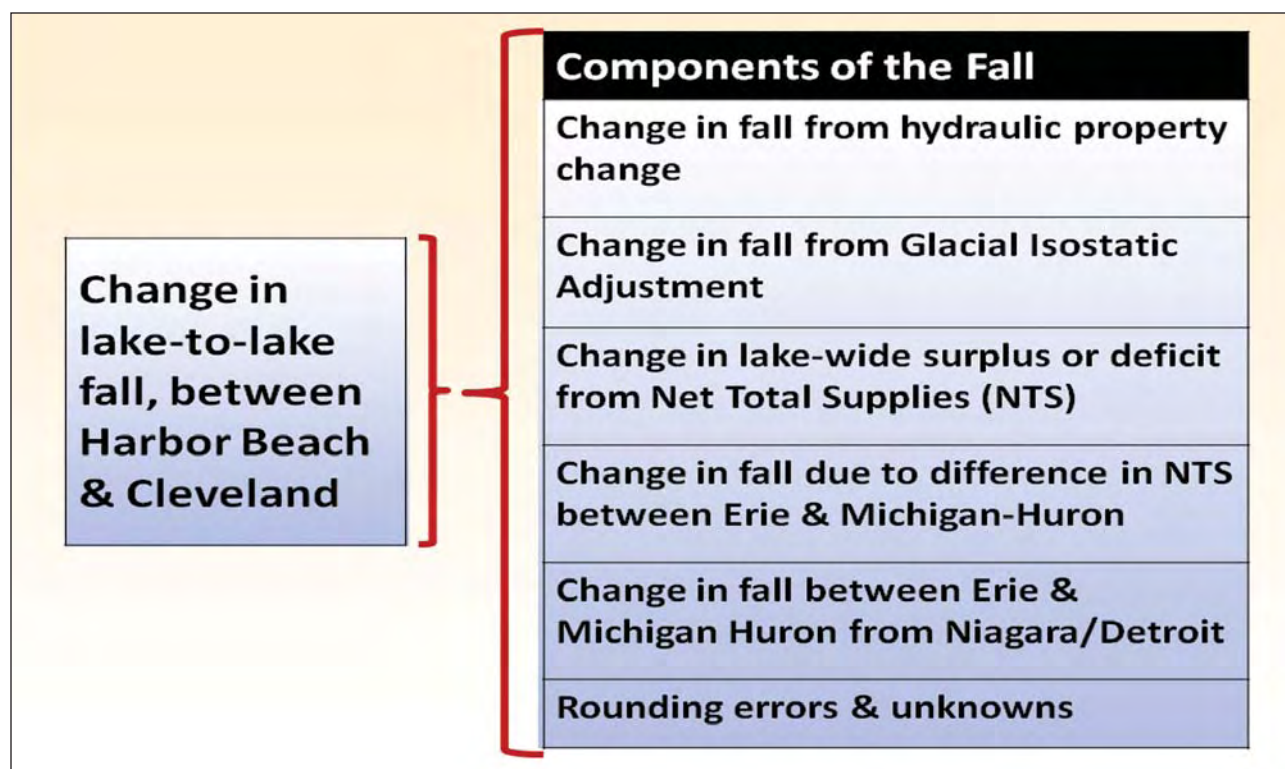
The central challenge of the St. Clair River part of the Study was to determine whether in fact the conveyance of the river has changed and, if so, what factors may have caused the change. In addition, it was recognized early on that uncertainty associated with all the data collected, instrumentation used and the various models employed to calculate conveyance and NBS would be a key part of the Study. Hence, an important role of this report would be to convey clearly scientific uncertainty in light of the findings and conclusions.

3.1.2 Study Strategy

Defining the Problem to be Solved

The International Joint Commission's Directive to the Study Board required an examination of the physical processes and possible ongoing changes in the St. Clair River and the effects of such changes on levels of Lake Michigan-Huron. Addressing these two closely linked issues required a comprehensive understanding of hydraulic, hydrological and geomorphological processes.

Figure 3-1 Study Approach: What factors are responsible for the change in lake-to-lake fall?



The water levels in Lake Michigan-Huron depend not only on the connecting channel flows and NBS, but also to varying degrees on the respective conveyance changes in the St. Clair, Detroit and Niagara rivers and on the water level in Lake Erie.

What is implicit in the state of Lake Michigan-Huron water levels is not only the steep decline in levels since 1997, but also the narrowing of the water level difference between Lake Michigan-Huron and Lake Erie (also known as the head difference). Since 1962, the decline in the head difference has been 23 cm (9 in). To make a meaningful interpretation of the change in the head difference since the dredging in 1962, the Study used the entire water level data series from 1860 to 2006.

Figure 3-1 illustrates the Study's approach. It identifies the fundamental question that the Study was designed to answer: *what factors are responsible for the change in lake-to-lake fall (the head difference)?* The change in lake-to-lake fall is likely a result of a combination of factors:

- changes in the conveyance or hydraulic properties of the St. Clair River;
- changes due to GIA;

- changes due to hydroclimatic factors, including changes in the lake-wide surplus or deficit from net total supplies (NTS)¹, differences in the NTS between the Lake Michigan-Huron and Lake Erie basins, and changes in the conveyance of the Detroit River and the Niagara River (this last factor was assumed to be small, given the scale of uncertainties associated with the other factors, and covered by hydroclimatic factors).

The Study also recognized that, from a scientific perspective, rounding errors and unknowns are an additional contributing factor. However, given the scale of uncertainties associated with the analyses of the three key factors, the influence of rounding errors and unknowns is likely negligible.

Interrelated Perspectives

At the outset, the Study Board considered all the natural and human factors as to their importance and relevance to St. Clair River conveyance and, in turn, the implications on the water balance of the upper Great Lakes. Following this initial assessment, the Study Board decided to focus on those factors essential to addressing the question of possible changes in the St. Clair River and resulting effects on water levels of Lake Michigan-Huron, and not to undertake in-depth analysis of relatively minor contributing factors, such as groundwater and consumptive uses (see Chapter 2 for more information on these latter two factors.)

¹ Net total supply (NTS) is the sum of the NBS to each Great Lake and the inflow from the Great Lake located upstream of it.

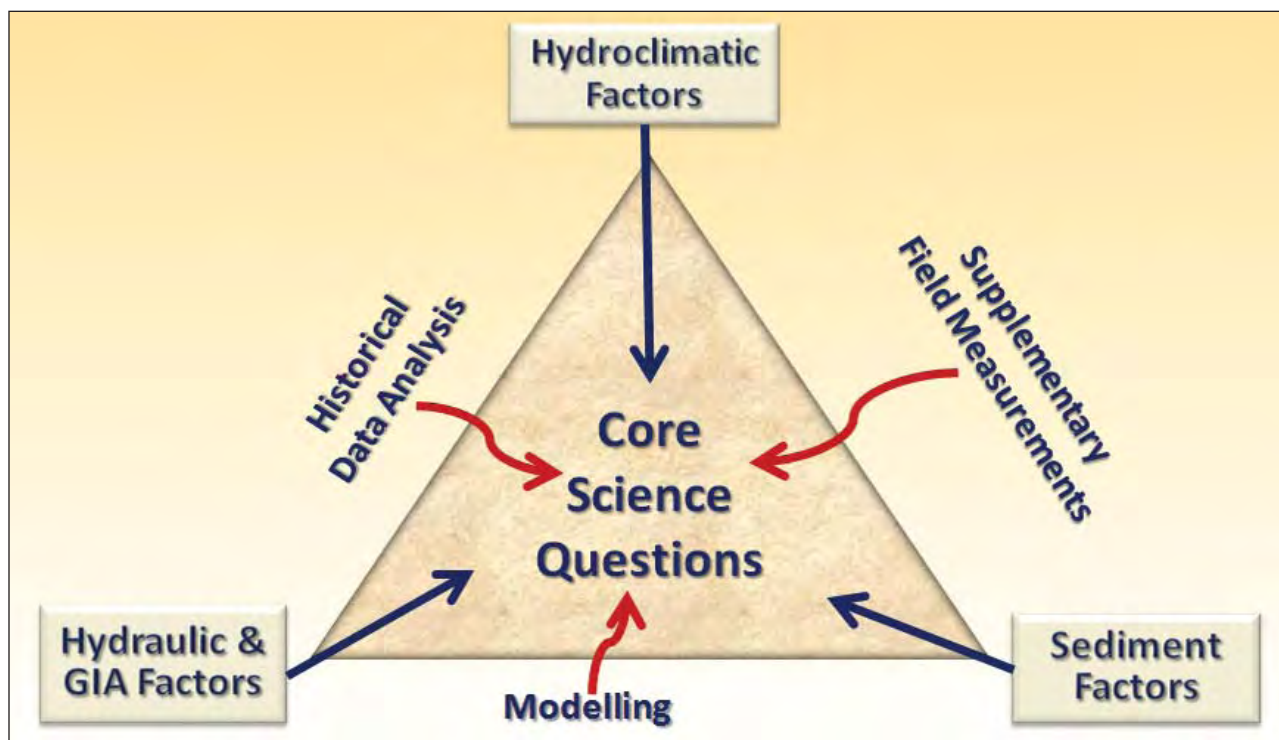
Considering the number of factors related to St. Clair River conveyance and upper Great Lakes water balance, the Study Board decided to address St. Clair River conveyance issues from several distinct but interrelated perspectives (see Figure 3-2):

- **sediment (morphology)**, which examined the sediment processes in the St. Clair River to determine whether the river bed is eroding or stable (*Chapter 4*);
- **hydraulic**, which focused on understanding the relationships between levels and flows for the St. Clair River, how changes in the river bed (*e.g.*, changes to its geometry, scouring, deposition and roughness) have affected conveyance, and its effects on upper Great Lakes water balance (*Chapter 5*); over the course of the Study, data analysis of the effects of GIA on the water levels of the upper Great Lakes basin suggested that the question of GIA and its implications for St. Clair River conveyance and water balance calculations needed to be addressed separately, though the issue remains closely linked to both the hydraulic and hydroclimatic analyses (*Chapter 6*);
- **hydroclimatic**, which examined the components in the water balance – precipitation, evaporation, runoff and other factors – to determine how they affect water levels and flows and what portion of the change in head differences between Lake Michigan-Huron and Lake Erie can be explained through changes in NBS (*Chapter 7*).

For each of the perspectives, the Study formulated a series of science questions and designed applied research projects to generate information needed to answer the questions. Some of the applied research projects were designed to address more than one science question, so that the Study could address a particular question from a number of perspectives. The applied research projects, in turn, were the basis for the preparation of the 34 major scientific/technical reports that formed the scientific foundation of the Study's final report. This number includes two supplemental reports commissioned by the Study to address specific engineering and institutional questions relevant to the Study's mandate.²

Another aspect of the Study's strategy was to deal with each perspective through multiple methods. These methods included mathematical models, analytical tools, data mining and analysis, measurements, visual inspection and laboratory analysis. Again, the Study adopted an approach of useful redundancy. Several hydraulic models were used to determine if the solutions converged. This, in turn, would bound the uncertainty related to results from individual models. The main perspectives of the Study are addressed through the set of science questions articulated by the Study and described in this Chapter.

Figure 3-2 Analytical and Modelling Strategy for the International Upper Great Lakes Study



2 The 34 reports are available through the Study's website: www.iugls.org

The integration of analyses and findings was a critical task in the Study. Looking at the issue of the St. Clair River conveyance from different perspectives and integrating the findings allowed the Study's investigators to better understand the interrelationships of the many natural and human-caused factors at work in the river. Integrating the findings of multiple studies also increased the confidence in the Study's conclusions.

Data and Modelling Challenges

At the start of the Study, it was clear that a comprehensive and reliable assessment of the question of the conveyance of the St. Clair River was possible only by first addressing a number of critical issues related to available historical data and lack of data. The Study grouped these data and modelling challenges under four categories: water quantity; bathymetric; sediment (morphology); and hydroclimatic. The key challenges identified under each area are listed below.

Water Quantity

- There is a lack of comprehensive, continuous discharge data on the interconnecting channels. In the past, measurements were taken periodically to develop/update a discharge rating curve that was used (together with models) to determine the discharge.
- Data accuracy and comparability are impeded by the application of different standards over time for collecting water quantity data and by the different degrees of accuracy of the measurement instruments that were used.
- It is difficult to determine trends because there are long periods of time, sometimes a decade or more, for which no direct measurements of discharge were collected. Measurement biases were unknowingly introduced when different measurement technologies were introduced without any systematic assessment of the effect on the data time series.
- When new discharge rating curves were adopted, flows after the administrative date of adoption reflected the new rating, but prior data may not have been adjusted or data adjustment may not have been possible because of a lack of information.
- Artificial discontinuities were introduced in the data time series when interagency coordination procedures of the flow data changed over time.
- There are only limited reliable water level data at key Lake Michigan-Huron and Lake Erie water level gauges.

Bathymetric

- Cross-sectional surveys have not been conducted at regular intervals. This gap constitutes the single most important deficiency in hydraulic analyses. Prior to 2000, there was a bathymetric survey in 1971 but there are concerns about the accuracy of these data. Cross-sectional surveys were also undertaken in 1954, but field sheets for only the upper two-thirds of the St. Clair River (north of 42°46'N) have been located.
- Bathymetric data collected in 1971 and 2000 were determined using single beam technology, where depth soundings were measured along transects spaced upwards of 100 m (328 ft) apart, with individual soundings along these transects spaced between 10 and 15 m (32.8 and 49.2 ft) apart, depending on the year. Data collected after 2000, including data collected for the entire river in 2007, were measured using multi-beam technology, which measures data for the entire river over a grid with a spacing of 1.5 m (4.9 ft) that can be re-sampled to a grid of 60 cm (23.6 in). Many of the hydraulic models used in the Study required interpolation of the bathymetric data, and differences in data density cause variations in the error associated with these interpolations.
- In addition to differences in data density and resulting interpolation error, errors can occur due to inaccurate recording of the boat location while bathymetric data are being collected. Both the survey and interpolation error introduced in each survey needed to be assessed to determine if the changes in channel geometry are significant.
- Bathymetric data originally collected for a different purpose (*e.g.*, creating navigation charts) were adapted for the Study's purposes (*e.g.*, measuring changes in bed geometry and defining hydraulic model cross-sections). The methods used in the original collection and management of the bathymetric data may be suitable for some uses, but not for others.

Sediment

- There are very limited historical data on the characteristics of the river bed material and on the sediment flux along the river. Apart from inferences from historical reports, there were very limited data collection programs in the 1960s and 1980s. These provide only partial "snapshots" of sediment conditions and sediment load and a side-scan survey of the river bed material in the late 1990s. These limitations made it challenging to determine whether the sediment regime has changed over time.
- Recording of dredging data was not consistent and key supporting information was not properly documented.

Hydroclimatic

- Until this Study, there have been few direct instrumentation measurements undertaken of outflow in the connecting channels or of evaporation in open waters of the upper Great Lakes.
- Comparing data over time periods is difficult, because of a number of changes over the years in methods used to compute component supplies.
- Efforts to represent precipitation over the open water surface areas of the upper lakes, as well as runoff computations in the contributing watersheds, are hampered by the limited (and declining) number of meteorological stations collecting precipitation data in the Great Lakes basin, particularly in the Superior basin and Georgian Bay region. The shortfall is particularly critical on the Canadian side of the border.
- Similarly, efforts to estimate surface runoff are hampered by the fact that a large percentage of basin areas in the upper Great Lakes is not covered by hydrometric gauges. The reliability of estimates of residual NBS, available for some of the lakes as early as 1860, is uncertain given the uncertainty in connecting channel flows and the lake-wide mean elevations. The accuracy of these estimates has been further weakened by the lack of corrections made for thermal expansion and by imprecise estimates of diversions, consumptive uses and groundwater contributions to residual NBS.
- Component NBS estimates are available from 1948 to 2006, but the quality of the overlake precipitation and watershed runoff estimates has changed over time with the quantity and regional representativeness of the gauging network. The lake evaporation is modelled instead of measured, depending mostly upon land gauging stations and a small number of lake meteorological gauging stations for input.
- Comparison of the residual and component NBS estimates reveals discontinuities and trends in the differences, but it is difficult to identify and attribute the causes for the differences given all these issues.

The remainder of this Chapter provides more details on how the Study addressed these data and modelling issues and the specific projects that were undertaken in each of the areas.

3.2 ST. CLAIR RIVER SEDIMENT REGIME

Chapter 4 presents the analysis and findings of the Study's work on the St. Clair River sediment regime. This section presents an overview of the science questions, data requirements and modelling strategy associated with this focus of the Study.

3.2.1 Sediment-Related Science Questions

The framework for the sediment perspective of the St. Clair River study was founded on the following primary and secondary science questions:

Has the morphology of the St. Clair River been altered since the 1962 dredging? Specifically,

- ▶ Is the St. Clair River bed stable or eroding?
- ▶ If the bed of the St. Clair River is eroding, what initiated the erosion and when?

3.2.2 Sediment Data Requirements

To address the science questions related to the St. Clair sediment regime, the Study required information on river channel topography and bed-forms, composition and particle-size distribution of the river bed and surficial material, underlying geology and geological history of the river and surrounding area. Assessment of river dynamics required measurement and modelling of flow velocity and flow structure, bed shear stress and bed and suspended sediment load and bathymetric changes over time. These data can then be combined to describe and map areas of potential and actual erosion and deposition, changes to bed composition over time and potential effects of sunken vessels and navigation dredging.

To address these data needs, the Study undertook extensive efforts to identify historical data and information and to acquire new data. New data included high resolution bathymetric surveys, acoustic surveys of the river bed and sub-bottom geology, Acoustic Doppler Current Profiler (ADCP) velocity profiles of the flow, and video surveys of the river bed material and of the lake approaches to the head of the river. Investigators videotaped more than 50 km (31 mi) of the St. Clair River bed to assess bed materials and understand river bed morphology. The videotapes also allowed investigators to determine whether the river bed is stable or eroding, and so, the likelihood of erosion continuing into the future. Concurrent with these efforts, the Study examined bathymetric data collected over

the years (1954, 1971, 2000, 2002, 2005, 2006 and 2007) to identify areas of major changes in the river bed. This information was also used to develop and operate sediment and hydraulic models to understand sediment processes in the St. Clair River and identify zones of active erosion and deposition.

Several of the analytical and visualization projects were used to assist in the interpretation of not only the modelling results but also to map the bed material, making qualitative assessments of the erodibility of the material and quantifying flow patterns. For example, a two-pronged approach of ADCP-based velocity maps, using back-scatter information, allowed scientists to calculate the shear stress particularly close to the river bottom. This project helped the calibration of the HydroSed2D model and supported the estimation of the potential for erosion across transects where velocities are measured. Another element of this project helped establish the strength of the vertical velocity, a key parameter in determining sediment entrainment potential.

Investigators also reviewed information on direct human-caused changes that have occurred in the St. Clair and Detroit Rivers. The review generated a chronological listing of the past dredging and compensating works and channel re-alignment since the mid-1850s.

Finally, the Study commissioned additional applied research to review the potential of ship effects, particularly turbulence caused by a vessel's "propeller wash", to contribute to the movement of bed material.

3.2.3 Sediment Modelling Strategy

The modelling strategy addressed St. Clair River conveyance issues from two perspectives – understanding the hydraulic processes from rigid boundary conditions, and the morphologic processes from a mobile bed setting. In rigid boundary modelling, the cross-sectional boundaries were assumed rigid within a reach. Investigators also conducted modelling assuming mobile bed conditions. Figure 3-3 is a flow chart showing the approach to establishing the modelling strategy and the sequence of steps in assessing the sediment processes and effects on conveyance (Moin, 2008).

To understand the sediment regime, a two-dimensional (2-D) sediment model was employed. The 2-D sediment transport model HydroSED2D was used to derive the sediment routines to identify zones of active erosion and deposition. To test the applicability of 3-D (hydraulic or sediment) modelling, a limited scale testing of a 3-D sediment model was developed using the Open-FOAM program. The results were compared with those from the 2-D model.

3.2.4 Sediment Reports

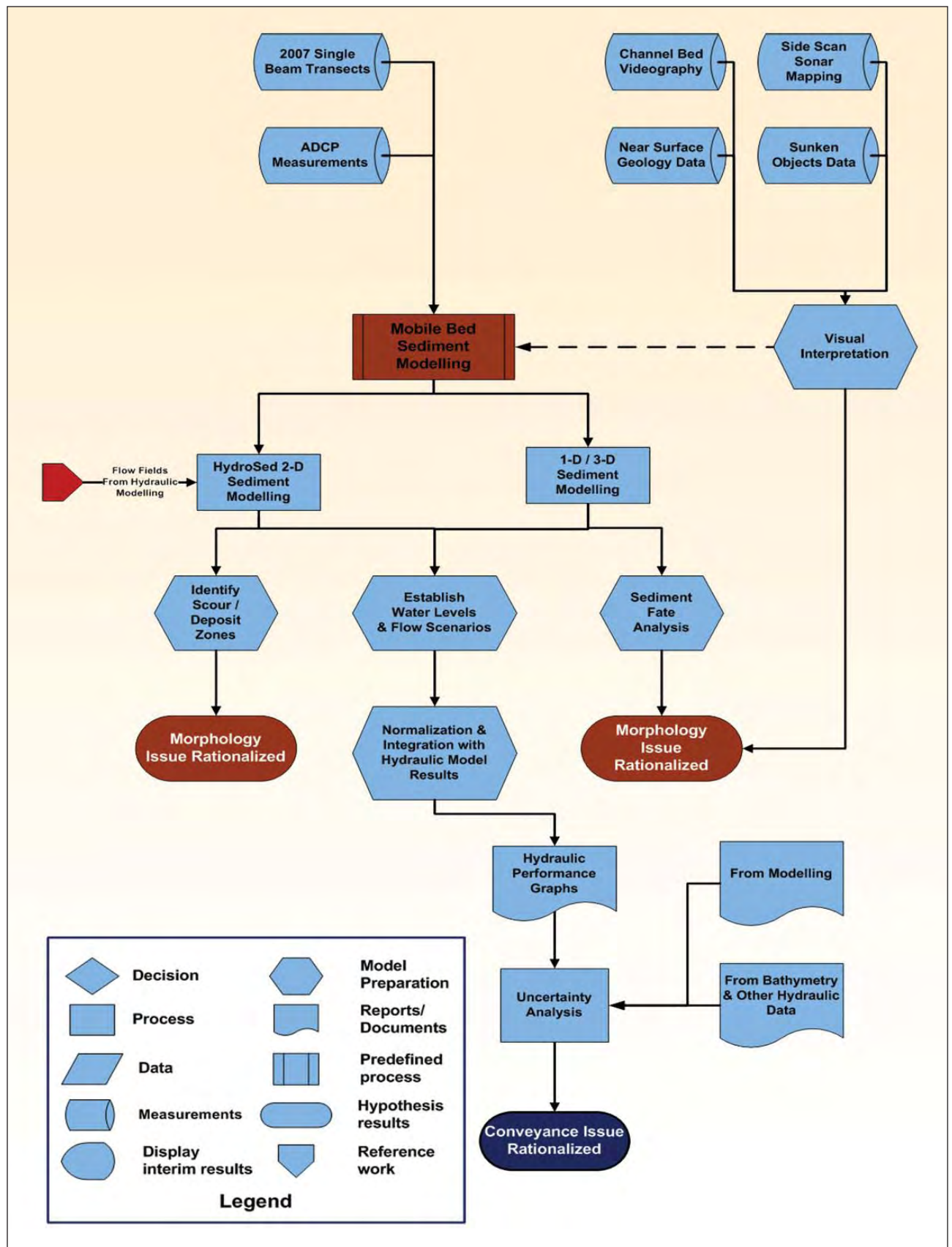
In summary, Table 3-1 lists the nine scientific/technical reports completed by the Study to address the sediment-related science questions, taking into account the data requirements and modelling strategy. All of the reports were subject to extensive internal reviews by the appropriate technical work groups, the Task Team and the Study Board. In addition, one of the reports was reviewed by external peer reviewers.

Table 3-1 Scientific/Technical Reports: Sediment Regime

| Report No. | Report Title | Author(s) |
|------------|--|---|
| 1 | Sediment Transport Regime of St. Clair River | Dr. B. G. Krishnappan |
| 2 | Quaternary Geologic Framework of the St. Clair River between Michigan and Ontario, Canada | Dr. D. Foster & J. F. Denny |
| 3 | St. Clair River Project: Critical Shear Stress Analysis of Clay Sediment Sample (Glacial Till) | Dr. M. H. Garcia & J. M. Meir |
| 4 | Combined Multi-beam Echo Sounder and Acoustic Doppler Profiler Mapping of the Upper St. Clair River: Morphology, Grain Size, Bedload Transport Paths and Flow Dynamics | Dr. J. L. Best, J. Czuba, K. Oberg & Dr. D. Parsons |
| 5 | History of Dredging and Compensation: St. Clair and Detroit Rivers (<i>Synthesis report: Review of Dredging in the St. Clair and Detroit Rivers</i>) | R. Moulton & S. Thieme (Dr. J. Giovannettone) |
| 6* | Modelling of Hydrodynamics and Sediment Transport in St. Clair River | Dr. G. Parker & Dr. X. Liu |
| 7 | Synthesis of Information on Quaternary Geology in the Vicinity of the St. Clair River | Dr. T. F. Morris |
| 8 | Impact of St. Clair River Erosion on the Water Levels of Lake Michigan-Huron from 1962-2005 | Dr. F. H. Quinn |
| 9 | Impact of Navigation on Bed Mobility of the St. Clair River | Dr. J. Waters |

Note: * - Externally peer reviewed report

Figure 3-3 Resolution of Morphology Issues with Sediment Studies Strategy



3.3 ST. CLAIR RIVER HYDRAULIC REGIME

Chapter 5 presents the analysis and findings of the Study's work on the St. Clair River hydraulic regime. This section presents an overview of the science questions, data requirements and modelling strategy associated with this focus of the Study.

As discussed in 3.3.4, the effect of GIA on water levels in the upper Great Lakes basin was identified as an important issue over the course of the Study, linked to both the hydraulic and hydroclimatic regimes. Therefore, the Study Board decided to profile the analysis and findings of GIA effects in a separate chapter in the final report, Chapter 6.

3.3.1 Hydraulic-Related Science Questions

The framework for the hydraulic perspective of the St. Clair River study was founded on the following primary and secondary science questions:

What is causing the declining head difference between Lake Michigan-Huron and Lake Erie? Specifically,

- ▶ Has the conveyance of the St. Clair River changed since 1962?
- ▶ If the conveyance has changed, what were the causes?

3.3.2 Hydraulic Data Requirements

An understanding of the hydraulics of the St. Clair River requires a good knowledge of the morphology of the river. In addition, applications of analytical techniques and modelling to simulate levels and flows for a range of scenarios were necessary. To support the analytical and modelling work, the Study collected new detailed bathymetry data to describe the geometry of the St. Clair bed. This investigation measured flow velocities in the river using a boat-mounted ADCP and installed a permanent side-looking Acoustic Velocity Meter (AVM) on the St. Clair and Detroit Rivers.

Bathymetric data for 1971, 2000 and 2007 were used to calibrate the hydraulic models and simulate water levels and flows. Partial river bathymetric surveys conducted in 1954, 2002, 2005 and 2006 were utilized for a limited number of scenarios.

The Study examined whether the present set of equations used to estimate flows in the St. Clair and Detroit Rivers and the methods of interpreting them are valid. It also calculated how well historical flow data since 1962 represent actual flows, and evaluated whether there have been changes in the flow regime since 1962.

3.3.3 Hydraulic Modelling Strategy

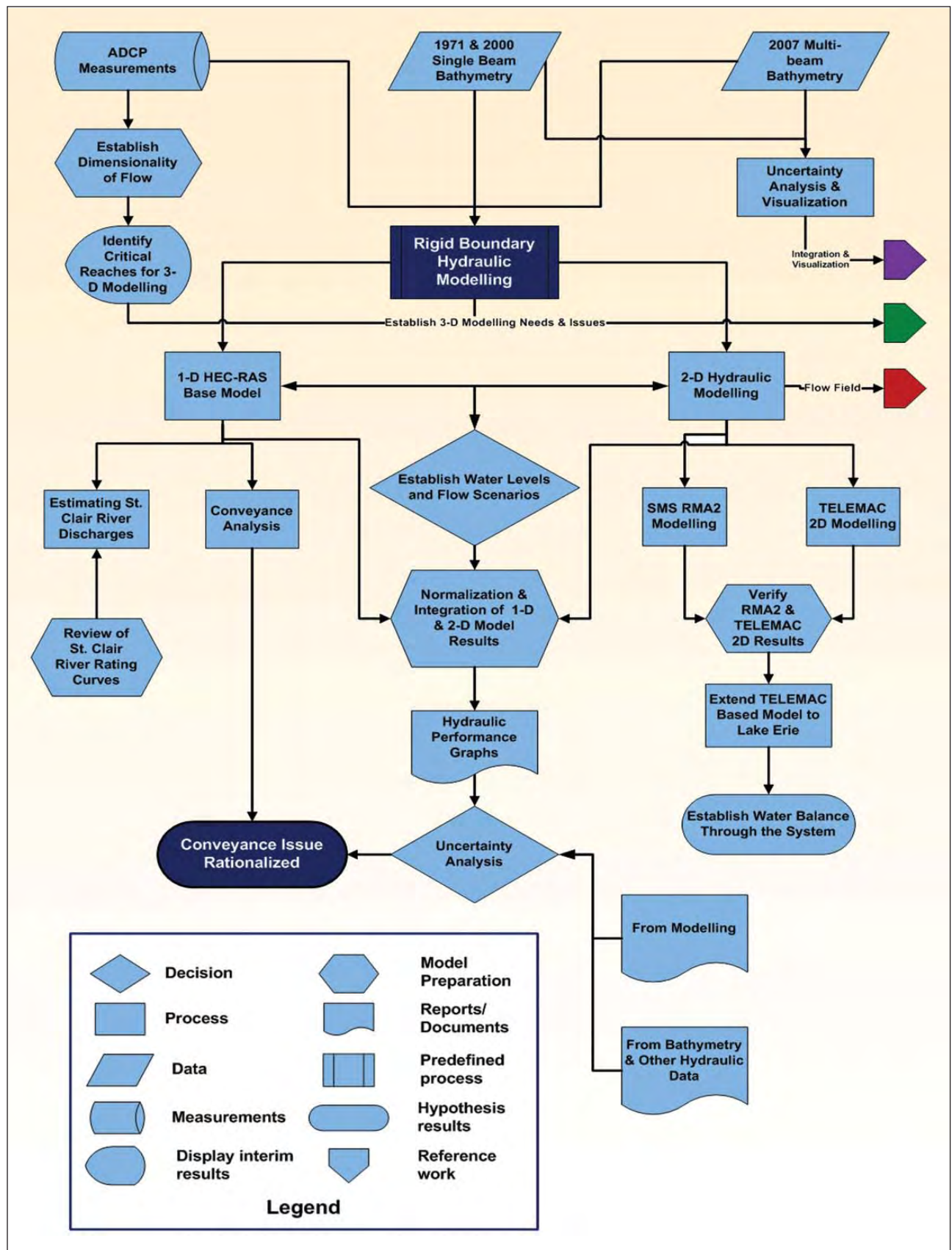
The issue of St. Clair River conveyance is a phenomenon related to the entire reach. The conveyance in the St. Clair River can be simulated adequately with a one-dimensional (1-D) hydraulic model. However, a 2-D model can help researchers better account for non-stream currents, ineffective/inactive flow areas, and eddy zones.

The modelling strategy called for using 3-D models only if there were significant vertical velocities in the reach, or if they were needed to resolve issues related to local scour and/or secondary currents in bends. The Study chose to take a graduated approach to determining the need for a more complex model on a case-by-case basis. The team determined that the deployment of 3-D models was not required to evaluate the hydraulic regime, given the marginal benefit of the incremental information generated by 3-D models, the lack of reliable historical data needed to operate them, the complexity associated with their calibration and operation, and the usefulness of the preliminary results using ADCP data.

Figure 3-4 is a flow chart for the hydraulic studies and modelling that was undertaken to address the St. Clair River conveyance question.

The Study used the 1-D hydraulic model from the Hydrologic Engineering Center-River Analysis System (HEC-RAS), a standard analysis tool used world-wide for developing water surface profiles for flood risk mapping projects. For the Study, the model was used in the unsteady-state mode. A base model with 2007 bathymetry was developed to serve as a baseline condition to compare with other scenarios incorporating 1954, 1971, and 2000 data to assess the conveyance. The results helped identify where conveyance values are highly sensitive to changes in channel area, and assess possible conveyance changes since 1962. The HEC-RAS model was used as the foundation for a subsequent ice simulation model, HyDAS. The HyDAS model was used to produce hourly estimates of conveyance factors to evaluate the influence of ice on possible changes in conveyance.

Figure 3-4 Strategy for Hydraulic Study and Modelling



The 2007 bathymetry-based 1-D HEC-RAS model was employed to test a 'null hypothesis' of changed conveyance in the St. Clair River – *i.e.*, that conveyance has not changed over the period from 1962-2007. The project was deployed to approach the science questions from a different perspective. Using the calibrated 2007 model, the 'null hypothesis' was tested by adjusting model parameters that served as surrogate representations of conveyance changes.

A parallel modelling task was the application of a 2-D model previously developed for the St. Clair-Detroit River system by the United States Geological Survey (USGS) and United States Army Corps of Engineers (USACE) (Holtschlag and Koschik, 2002). This model is an application of the Resource Management Associates' 2-D, depth-averaged, finite-element model, RMA2. Holtschlag and Koschik extensively calibrated and validated the model against observed water levels, velocities and flow distributions. Investigators focused on the St. Clair River by shortening the model to terminate it at Lake St. Clair and increasing the model mesh density. Next, investigators used bathymetric data from 1971, 2000, and 2007 to assess the effects of changes on the conveyance of the St. Clair River. To enhance confidence in the results, they conducted both sensitivity and uncertainty analyses to determine how changes as well as uncertainty in the bathymetric data, roughness coefficients, boundary condition water levels and flows, among other parameters, affect simulated water levels and flows. Lastly, they used the results to generate stage-fall-discharge curves and hydraulic performance graphs (HPGs) to help assess whether the St. Clair River conveyance has changed over time.

An additional model used in the hydraulic analysis was the 2-D hydraulic model TELEMAC-2D, developed by the Laboratoire National d'Hydraulique et Environnement d'Electricité de France. Similar to the RMA2, this model simulates 2-D, depth-averaged velocities on a finite-element grid. Similar analyses to those completed with RMA2 were conducted with TELEMAC-2D. The results from this model served as an independent check of the RMA2 model results. Secondly, this model was expanded to include the Detroit River to assess the effect of water level changes in Lake Erie and its backwater effects on Lake Michigan-Huron. The results from this model were also used by investigators in the sediment studies and thus served to supplement and support the findings for that portion of the research.

The effects of ice may be significant, leading to short-term effects on the levels and flows of the St. Clair River. The Study therefore estimated the potential and actual long-term ice effects in the connecting channels using the most recent apparent flow retardation estimates. The Study also utilized a 1-D unsteady HEC-RAS model adapted for ice simulation to evaluate the historical influence of ice cover in the St. Clair River on conveyance. The objectives were to: evaluate past effects of ice on river conveyance; determine the potential significance of any possible climate-induced changes to the flow retardation values; and determine whether any obvious trends were evident in recent historical retardation estimates. The Study also commissioned further work to specifically investigate and model the effects of the record 1984 ice jam in the St. Clair River and to determine whether that event could have impacted the conveyance of the river.

The results of the analytical and modelling tasks related to sediment and hydraulic studies were compared with those of the hydroclimatic perspective of the Study.

3.3.4 Glacial Isostatic Adjustment

Chapter 6 presents the analysis and findings of the Study's work on the effects of GIA on the head difference between Lake Michigan-Huron and Lake Erie, and on the implications of GIA for St. Clair River conveyance and water balance calculations.

At the scoping stage of the Study, GIA was not expected to be a significant factor in the overall analysis. Previous reports (*e.g.*, Baird, 2005) had dismissed GIA as an important contributing factor to water levels in the upper Great Lakes and changes in the conveyance of the St. Clair River. Study investigators originally planned to analyze and present GIA effects under the hydraulic regime analysis, though it was recognized that GIA also had implications for the analysis of hydroclimatic issues.

However, over the course of the data analysis, Study investigators determined that the effects of GIA are likely more important than previously believed, in part because of the methodological limitations of past studies. Moreover, investigators recognized that GIA effects, which are ongoing throughout the Great Lakes basin, will need to be better understood and incorporated in future studies of Great Lakes water levels, particularly as the implications of climate change are brought into the analysis.

As a result, the Study Board decided to profile the analysis and findings of GIA effects in a separate chapter in the final report.

GIA Data Requirements and Studies

The primary GIA analysis focused on using the correct water level data to represent the change in head difference between Lake Michigan-Huron and Lake Erie over time, recognizing and accounting for the effects of GIA and adjustments to the International Great Lakes Datum (IGLD) on recorded water level data.

Previous studies of GIA effects had used the differences between water levels recorded at Harbor Beach, MI on Lake Michigan-Huron (about 100 km [62 mi] north of the lake's outlet) and at Cleveland, OH on Lake Erie to represent the head difference between Lake Michigan-Huron and Erie over time. However, GIA affects the land-to-water relationship around each lake and can have an effect on the water levels recorded at individual water level gauging stations. These effects, in turn, can affect the apparent head difference between the two lakes calculated using different pairs of gauges. To account for the effect of GIA and the use of IGLD on historical water level data, the fall relationship between Lake Michigan-Huron and Lake Erie must be based on the differences between water levels recorded at (or as close as possible to) their outlets.

Therefore, the Study undertook a review of the effect of GIA on recorded water levels to determine if the reduction in head differences based on water levels recorded at Harbor Beach, MI and Cleveland, OH properly reflects the changed head difference between Lake Michigan-Huron and Lake Erie. The issues that needed to be resolved as part of this effort included:

- the selection and/or estimation of the water levels used to represent the levels of Lake Michigan-Huron and Lake Erie at their outlets over time;
- the water level data averaging period used (e.g., monthly, annual, or summertime average); and
- the length of data record to be used for the various aspects of the analysis.

Study investigators also needed to address the sensitivity of results to the level of rounding applied to apparent relative vertical movement rates, water level estimates and their differences.

The review of GIA identified several additional factors related to the relative movement between Lake Michigan-Huron and Lake Erie that could affect the fall between the lakes over time. First, investigators needed to estimate the possible impact of a “backwater effect” on the apparent change in fall between Lake Michigan-Huron and Lake Erie due to the relative movement, if any, between the outlets of these lakes. They also provided advice to the Study's hydraulic modelling technical work group regarding the

sensitivity of hydraulic models to possible changes in bed slope in the St. Clair and Detroit Rivers due to relative movement between the head of the St. Clair River and the mouth of the Detroit River.

Finally, due to differential GIA, portions of each of the Great Lakes are either rebounding or subsiding relative to their outlets. As a result, each of the lakes is potentially storing or decanting a certain amount of water over time due to the differential tilting of their lake basins. Therefore, the Study undertook an analysis to determine whether the effect of GIA on water balance and NBS calculations was significant and needed to be addressed as part of the analysis.

3.3.5 Hydraulic and GIA Reports

In summary, Table 3-2 lists the 17 scientific/technical reports completed by the Study to address the hydraulic-related science questions and the issue of GIA, taking into account the data requirements and modelling strategy. All of the reports were subject to extensive internal reviews by the appropriate technical work groups, the Task Team and the Study Board. In addition, four of the reports were reviewed by external peer reviewers.

3.4 UPPER GREAT LAKES BASIN HYDROCLIMATIC CONDITIONS AND TRENDS

Chapter 7 presents the analysis and findings of the Study's work on the hydroclimatic regime of the upper Great Lakes basin and the St. Clair River. This section presents an overview of the science questions, data requirements and modelling strategy associated with this focus of the Study.

3.4.1 Hydroclimatic-Related Science Question

The framework for the hydroclimatic perspective of the St. Clair River study was founded on the following primary science question:

How has climate affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?

This information was specifically used to address the question of changing water levels in Lake Michigan-Huron and Lake Erie and in particular to address the issue of the apparent head difference reduction over time.

Table 3-2 Scientific/Technical Reports: Hydraulic Regime and GIA

| Report No. | Report Title | Author(s) |
|------------|---|--|
| 1 | Lake Huron Water Level Gauge Analysis | Dr. F. H. Quinn & C. Southam |
| 2 | Estimation of Pre-1960 Water Levels At Parry Sound on Georgian Bay | Dr. F. H. Quinn & C. Southam |
| 3 | Determining the Impact of Glacial Isostatic Adjustment on the Estimated Reduction in Lake Michigan-Huron – Lake Erie Head Difference Over Time Based on Recorded Water Levels at Harbor Beach and Cleveland | C. Southam |
| 4 | Review of Apparent Vertical Movement Rates in the Great Lakes Region | J. Bruxer & C. Southam |
| 5 | Analysis of Great Lakes Volume Changes Resulting from Glacial Isostatic Adjustment | J. Bruxer & C. Southam |
| 6* | Review of Discharge Measurements and Rating Equations on the St. Clair and Detroit Rivers since 1962 | Dr. A. Schmidt, N. J. Choi & S. Banjavic |
| 7 | Preparation of the 1-D St. Clair River HEC-RAS Model in Order to Study Changes in River Conveyance and Morphology | Dr. J. Giovannettone |
| 8* | Detection of Conveyance Changes in the St. Clair River Using Historical Water Level and Flow Data with Inverse One-Dimensional Hydrodynamic Modelling | D. Holtschlag & C. J. Hoard |
| 9 | Investigation of Changes in Conveyance of the St. Clair River Over Time Using a State-Space Model | Dr. S. F. Daly |
| 10* | St. Clair River Hydrodynamic Modelling Using RMA2: Phase 1 Report | J. Bruxer & A. Thompson |
| 11 | Preparation of a Hydrodynamic Model of St. Clair River with Telemac-2D, to Study the Impacts of Potential Changes to the Waterways | T. Faure |
| 12 | Hydrodynamic Model of St. Clair River with Telemac-2D: Phase 2 Report | T. Faure |
| 13* | Statistical and Spatial Analysis of Bathymetric Data for the St. Clair River 1971-2007 | D. Bennion |
| 14 | Development of New Stage-Fall-Discharge Equations for the St. Clair and Detroit Rivers | D. Fay & H. Kerslake |
| 15 | 1-D HEC-RAS Model and Sensitivity Analysis for St. Clair River from 1971 – 2007 | D. Stevenson |
| 16 | Qualitative analysis of the St. Clair River Ice Jam of 1984 | Dr. S. Beltaos |
| 17 | St. Clair River Ice Jam Modelling | Dr. H. T. Shen & Dr. T. Kolarski |

Note: * - Externally peer reviewed report

3.4.2 Hydroclimatic Data Requirements

The approach to the hydroclimatic focus of the Study consisted of three steps:

1. Define and reduce the uncertainties in NBS;
2. Explore new methodologies to develop improved estimates of NBS; and
3. Identify the hydroclimatic factors and trends affecting lake levels.

Sophisticated statistical methods and hydrometeorological models were used throughout the three steps to investigate the inter-relationships among NBS, river conveyance and water level regimes. Each individual task contributed to at least one of the steps, but many contributed to two or all three. Data requirements were extensive, ranging beyond

the component and residual NBS to the underlying explanatory data of hydrometeorological observations and land surface characteristics. Completion of the first two steps was a prerequisite to removing artifacts of the data and understanding any uncertainty that could obscure the hydroclimatic factors affecting lake levels.

The first step in conducting the hydroclimatic study was the assessment of contemporary estimates of the water balance. The factors used to determine Great Lakes NBS data using the component method and residual method were discussed in Chapter 2. Each of these factors needed to be assessed to generate the best estimates of NBS for analytical and modelling work. An essential task completed by the Study was the comparative analysis of the residual method and the component method to understand better where and why differences in the data occur.

To ensure the most recent data were used, the data for the two models were updated through 2006. The comparative analysis also provided insights to the uncertainty in the NBS data due to problems with lake storage data, overlake precipitation estimates, watershed runoff and lake evaporation.

In the second step, the Study used independent models and other studies to assess and pinpoint potential deficiencies in the current approaches to estimating residual and component NBS and to further refine the water balance estimates. Tasks included:

- hindcasting overlake/overland precipitation using an operational numerical weather and data assimilation system to compare with the existing data and new radar estimates;
- hindcasting lake evaporation with data assimilation of remotely-sensed lake surface temperatures and ice cover to compare with the existing data; this project was supplemented by direct measurement of evaporation using modern technology at a site on Lake Superior;
- hindcasting basin runoff using a coupled land surface-atmosphere numerical model to compare with existing data and a new geospatial-statistical method;
- examining the relationships among lake ice cover regimes, surface water temperature and evaporation flux; and
- assessing the trends and significance of connecting channel ice formation and weed growth to lake levels.

The direct measurement of lake evaporation was one of the research projects to consider both the uncertainty in the computation of NBS (step 1) and new methodologies for improved estimates of NBS (step 2). Investigators conducted direct measurements of lake evaporation using instrumentation that relied on the eddy covariance method, a proven modern technology based on analyzing the degree of covariance between high-frequency measurements of vertical wind shear and water vapor density. While the technology has been used successfully on other large lakes, this was its first application to the upper Great Lakes.

For the third step, identifying the hydroclimatic factors and trends affecting lake levels, investigators conducted comprehensive trend, change-point and teleconnections analyses of the lake levels, NBS, and explanatory variables (including precipitation, evaporation, runoff, air and water temperature, and connecting channel flows). A water supply routing model also was used to perform a deterministic sensitivity analysis of the effect of NBS on lake levels and an uncertainty analysis of the effect of climate regimes on lake levels.

Based on the findings of these studies, the Study identified the hydroclimatic causative factors relating to the change in upper Great Lakes NBS, as well as factors related to the change in head difference between Lake Michigan-Huron and Lake Erie. Several improved methods for modelling and monitoring the water supplies to the lakes also were developed and tested.

3.4.3 Hydroclimatic Modelling Strategy

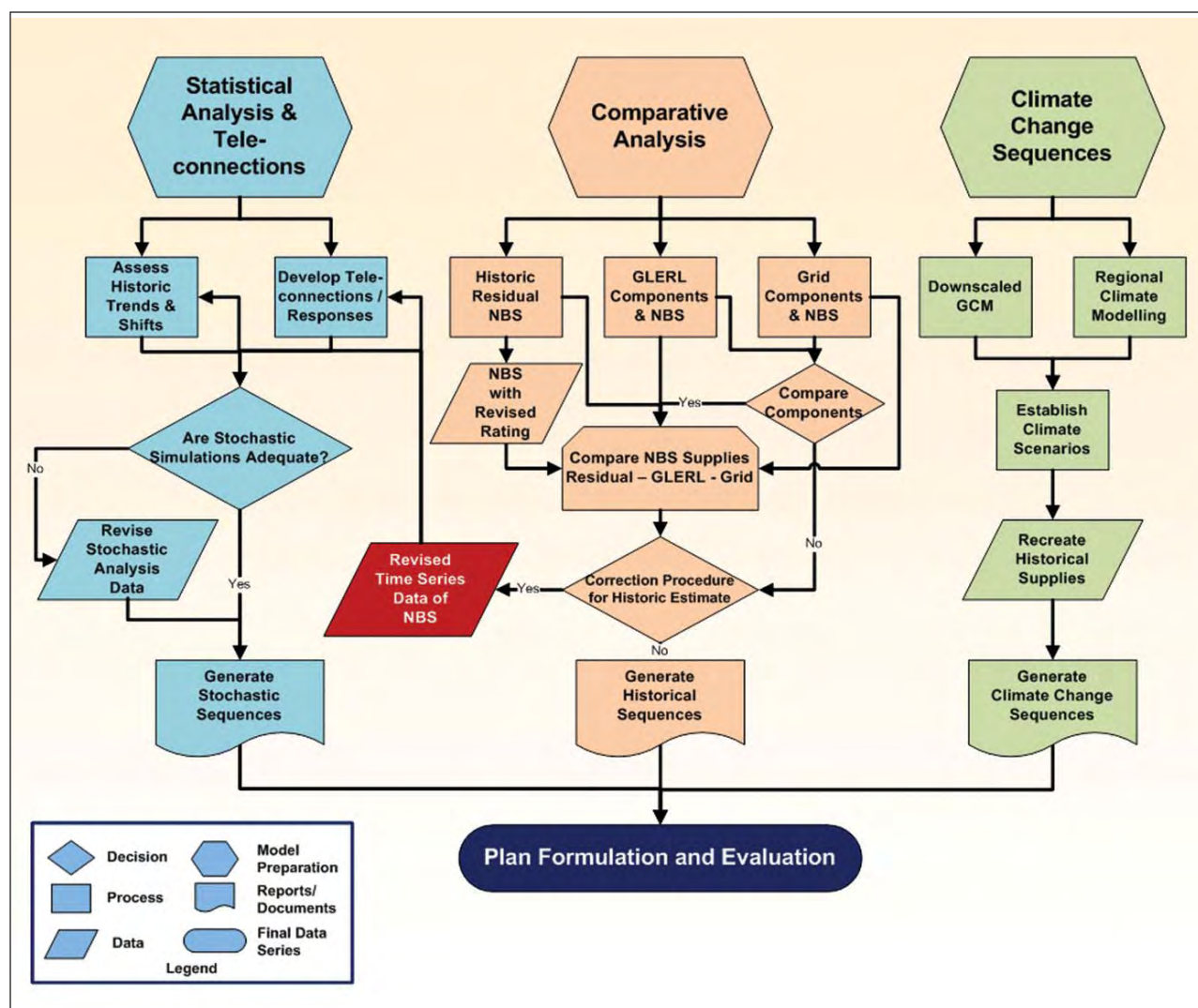
The strategy called for establishing a comprehensive and reliable climatic, hydrological and hydraulic data base, adopting and (where required) improving existing models (Lee and Pietroniro, 2008).

Figure 3-5 is a flow chart showing the strategy for conducting the hydroclimatic analytical and modelling studies. The strategy was designed to address both the St. Clair River and the Lake Superior regulation parts of the Study.

The Study employed several hydroclimatic models and computational techniques. Some of these were developed in past studies of Great Lakes levels and flows and were updated and modified for the Study. Where appropriate, the Study relied on the data and information generated by other models and computational techniques developed and operated by other agencies and research institutions. The models used in the Study are listed below:

- Coordinated Upper Great Lakes Regulation and Routing Model (CGLRRM), developed under the auspices of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data;
- Canadian Regional Climate Model (CRCM), coupled with the Canadian Land Surface Scheme (CLASS) developed by Environment Canada;
- Large Basin Runoff Model and Large Basin Thermal Model, developed by the Great Lakes Environmental Research Laboratory (GLERL) of the National Oceanic and Atmospheric Administration (NOAA);
- US National Center for Environmental Prediction Climate Data Analysis System (NCEP CDAS); and
- Environment Canada's Numerical Weather and Data Assimilation System (ECNWDAS).

Figure 3-5 Strategy for Hydroclimatic Study and Modelling



Computational techniques used in the Study included:

- National Center for Environmental Prediction Multi-sensor Precipitation Estimates (NCEP MPE) (radar observed precipitation);
- INRS-ETE geospatial-statistical runoff approach;
- Area Weighted Gauge runoff approach by GLERL;
- Thiessen Weighed Gauge overlake/overland precipitation approach by GLERL;
- Spence and Blanken Eddy Covariance System algorithm;

- Bayesian Change Point Detection Method; and
- Mann-Kendall and modified Mann-Kendall trend test with independence, short-term persistence and long-term persistence hypotheses.

One of the initial tasks in the Study was to update the CGLRRM. The updated model was an improved tool for the hydraulic and hydrological assessments of the effects of natural and human-caused factors on the levels, flows and conveyance of the St. Clair River, and for the assessment of climate change effects.

The CRCM, GLERL models, and the US and Canadian Analysis/Assimilation Systems were used to generate alternative estimates of NBS and NBS components (overlake precipitation, watershed runoff and lake evaporation) for the comparative analyses and the uncertainty assessments.

Similarly, most of the computational techniques were used to develop spatial estimates of the components from direct observations. The direct measurement of Lake Superior evaporation using the eddy covariance method also was important for verifying, calibrating and improving parameterization of the lake evaporation algorithms within the ECNWDAS model. The statistical techniques (Bayesian Change Point and Mann-Kendall) were used to assess shifts and trends in the hydroclimatic data.

3.4.4 Hydroclimatic Reports

In summary, Table 3-3 lists the six scientific/technical reports completed by the Study to address the hydroclimatic-related science questions, taking into account the data requirements and modelling strategy. All of the reports were subject to extensive internal reviews by the appropriate technical work groups, the Task Team and the Study Board. In addition, three of the reports were reviewed by external peer reviewers.

3.5 SUPPLEMENTAL REPORTS

Over the course of the analysis, the Study Board identified the need to address several specific engineering and institutional questions relevant to the Study's objectives and mandate. As a result, the Study Board commissioned two supplemental reports (see Table 3-4).

3.6 SCIENTIFIC UNCERTAINTY ANALYSIS

3.6.1 Nature of the Problem

The Study characterized the scientific uncertainty through the following categories:

- *natural or intrinsic uncertainty* is associated with the “inherent” randomness of natural processes, manifesting itself as variability over time and space;
- *model uncertainty* reflects the inability of a model to represent accurately a system's true physical behavior, due to a poorly or incompletely specified model, or instabilities and non-linearities in the phenomena modelled;

Table 3-3 Scientific/Technical Reports: Hydroclimatic Regime

| Report No. | Report Title | Author(s) |
|------------|---|---|
| 1 | Assessment of Potential/Actual Long-Term Ice Impacts in the Connecting Channels Using Apparent Retardation Analyses | R. Caldwell |
| 2 | Lake Superior Beginning-Of-Month Levels Analysis | Dr. F. Quinn |
| 3* | Net Basin Supply Comparison Analysis | Dr. F. Quinn |
| 4* | Analysis of Changes in the Great Lakes Net Basin Supply (NBS) Components and Explanatory Variables | Dr. T.B.M.J. Ouarda, Dr. E. Ehsanzadeh, Dr. H. M. Saley, Dr. N. Khaliq, Dr. O. Seidou, Dr. C. Charron, Dr. A. Pietroniro and D. Lee |
| 5 | Effects of Net Basin Supply on the Changes in Lake Michigan-Huron and Lake Erie Water Level Relationships (Residual Method) | D. Lee & T. Dahl |
| 6* | Rationalizing the Decline in Lake Michigan-Huron levels using the Coordinated Great Lakes Routing Model | Dr. B. Tolson |

Note: * - Externally peer reviewed report

Table 3-4 Scientific/Technical Reports: Supplemental

| Report No. | Report Title | Author(s) |
|------------|--|-------------------------|
| 1 | Preliminary Study of Structural Compensation Options for the St. Clair River | W.F. Baird & Associates |
| 2 | Preliminary Appraisal of the Institutional Feasibility of Potential Compensating Works in St Clair River | R. Pentland |

- *parameter uncertainty* results from an inability to assess accurately parameter values from the test or calibration data due to a limited number of observations or statistical imprecision; and
- *data uncertainties* associated with measurement errors, instrumentation errors, inconsistency and non-homogeneity of data, data handling and inadequate representativeness of data over time and space.

The above uncertainty characteristics manifest themselves in all areas of the Study's analysis and modelling. The Study considered a strategic approach to handling uncertainty by identifying the sources in various components of the hydrological cycle and in hydraulic modelling (Moin, 2008; Neff and Nicholas, 2004).

3.6.2 Approach to Addressing Uncertainties

The Study convened five workshops with modellers and experts in the subject of scientific uncertainty to develop an approach to scientific uncertainty analysis. Additionally, the Study benefited from the feedback of the Independent Peer Review Group, particularly in focusing on the key aspects of the various models and analytical methods employed to evaluate the possible causes of the decline in head difference between Lake Michigan-Huron and Lake Erie.

The Study developed a process in which the key Study perspectives were subject to a thorough uncertainty analysis treatment. In some projects, notably in the sediment studies area, uncertainty was estimated in a qualitative sense. The strategy for addressing the various aspects of uncertainty is illustrated in Figure 3-6.

The strategy consisted of tasks designed to generate the following results:

- produce better estimates of NBS and diversion dataset for purposes of determining levels and flows under various scenarios;
- produce better estimates of flows in the upper Great Lakes connecting channels for St. Clair River modelling purposes;
- produce a rectified historical upper Great Lakes water storage dataset, taking into account the effects of GIA;
- determine whether St. Clair River channel dimensions (bathymetry) are changing, based on soundings taken over time;
- determine whether channel conveyance has increased, based on modelling flows with different historical channel configurations using 1-D and 2-D models;

- determine the relative certainty that NBS has changed over time and whether, or to what extent, the changes in supplies can explain the decline in head difference between Lake Michigan-Huron and Lake Erie; and
- determine the susceptibility of the channel to erosion, by examining historical channel cross-sections and borings, conducting new videotape analysis and sampling suspended load and bed load.

Another key task to addressing the issue of uncertainty was the development of a deterministic mid-lakes routing model. To determine the uncertainty inherent in such a model, the component uncertainties first are quantified. The combined effect of the component uncertainties is then determined.

A number of tasks that included scientific uncertainty quantification fed into the mid-lakes deterministic model (e.g., the project computing hydrological components of precipitation, evaporation and runoff, where each of the components is subject to Monte Carlo-based uncertainty analysis). The overall Study framework objective for the mid-lakes routing model is depicted in Figure 3-7.

As part of the Hydraulic/Sediment strategy, hydraulic modelling applying the RMA2 model was selected for uncertainty analysis in conveyance calculations. The Study examined the propagation of bathymetry uncertainty through the hydraulic model on Lake Michigan-Huron water levels. It was assumed that the RMA2 model would serve as the surrogate for all other hydrodynamic modelling, including the sediment model, HydroSED2D. Following the independent peer review evaluation, the Study undertook additional sensitivity analysis and uncertainty analysis with the HEC-RAS model.

To display uncertainty, several visual interpretations traditionally have been used. One such interpretation is a qualitative statement that quantifies the computed uncertainty. For the results of the St. Clair River Study, the Study Board adopted the protocols implemented by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007). In that report, IPCC scientists and policymakers expressed their relative degrees of confidence to deal with the scientific uncertainties inherent in the various sources of information upon which their conclusions were based. The Study Board used a modified version of this confidence scale that factored in the uncertainty of the information.

Figure 3-6 Uncertainty Framework in International Upper Great Lakes Study

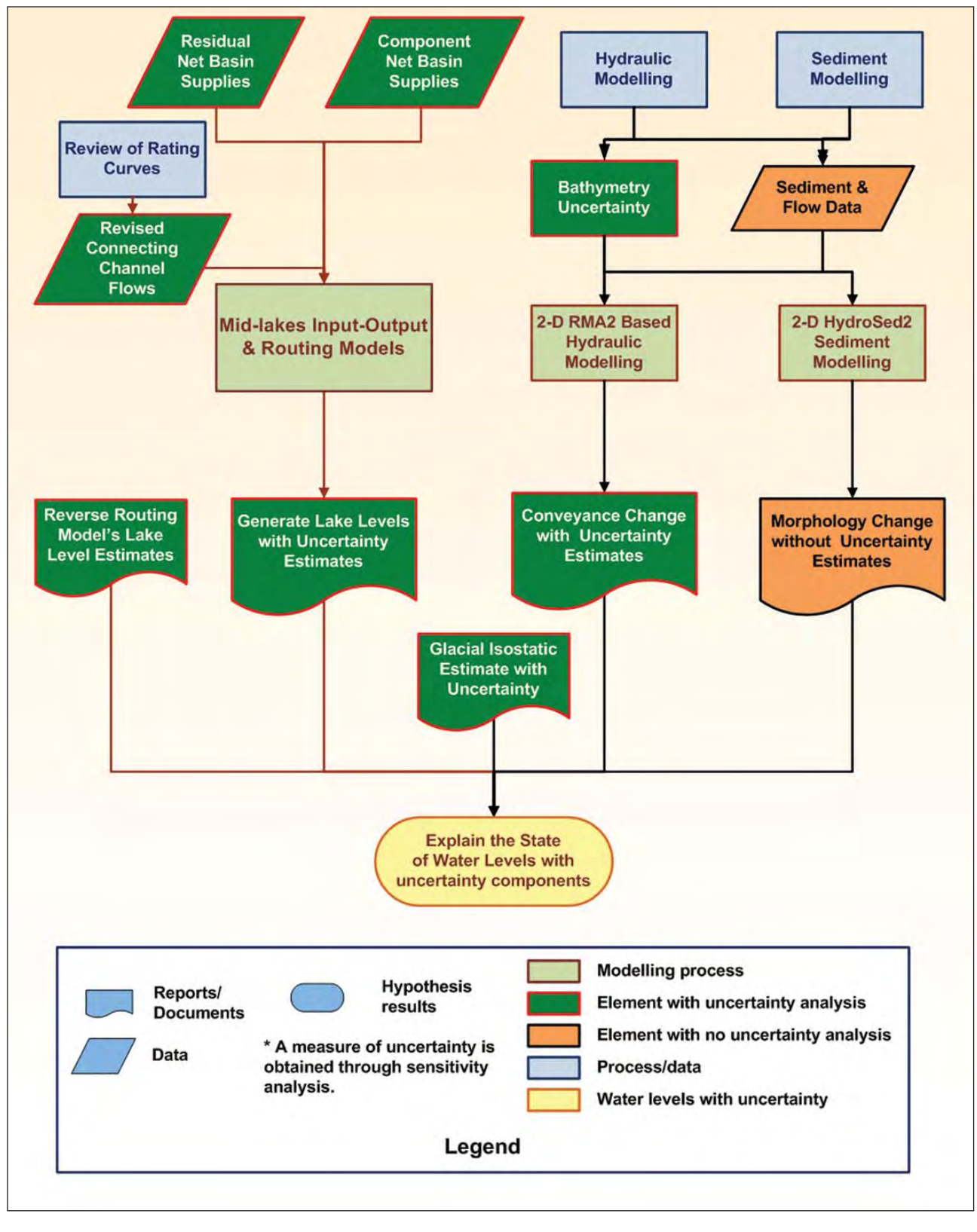
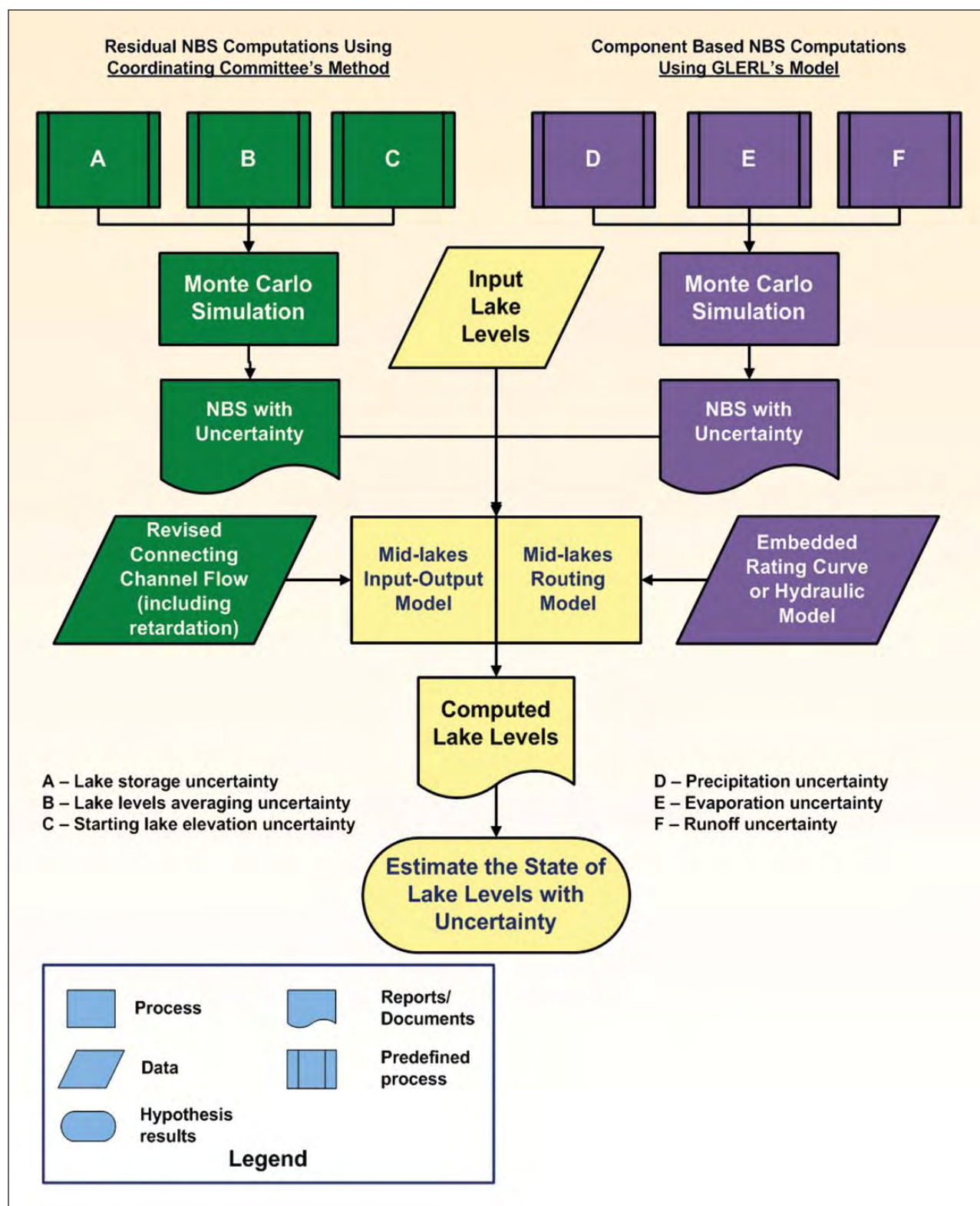


Figure 3-7 Uncertainty Framework for the Mid-lakes Input-Output & Routing Models



3.7 INTEGRATION OF RESULTS

The Study's applied research projects were designed to enable investigators to examine the various issues from all three perspectives, while providing a degree of analytical overlap and redundancy to reduce uncertainty in the results and enhance confidence in the findings and conclusions.

The use of a multi-pronged analytical approach, coupled with the design of the tasks and research projects, enabled the Study's investigators to conduct the Study in a logical and effective manner, focusing on the key science questions. Proper sequencing of the tasks and research projects was critical. By first examining the sediment and morphology of the St. Clair River, investigators were able to understand more thoroughly the dynamics of the river, and what current velocities were required to move the material in each segment of the river.

The results of the sediment study then were taken to the next step – hydraulic studies – where the conveyance of the St. Clair River was examined through technical analyses and sediment and hydraulic modelling. The results of the analysis of the effects of GIA were included in the data analysis and modelling of the St. Clair River hydraulic regime, and in the water balance calculations necessary for the analysis of the hydroclimatic regime.

The hydroclimatic study of the water balance of the upper Great Lakes was also a necessary input into the overall hydraulic analysis of conveyance, as uncertainties in precipitation and evaporation affect the interpretation of head differences measured since the early 1900s.

Finally, the results were synthesized to provide a comprehensive picture of conveyance changes and their causes.

3.8 KEY POINTS

- ▶ The Study was designed to answer the fundamental question: *what factors are responsible for the change in lake-to-lake fall (the head difference) between Lake Michigan-Huron and Lake Erie?* The change in lake-to-lake fall can be the result of a range of natural and human-caused changes in the St. Clair River and the upper Great Lakes basin. To answer the questions relating to the magnitude and causality of St. Clair River conveyance changes, including whether there is on-going erosion, the Study needed to examine all the factors possibly affecting the upper lakes water balance.
- ▶ The analytical framework consisted of strategies to address the St. Clair River from several perspectives: sediment (morphology); hydraulic, including GIA; and hydroclimatic. This approach has enabled the Study to better understand the inter-relationships of the natural and human-caused factors and their relative importance to the questions of St. Clair River conveyance and upper Great Lakes water balance. The converging analytical and modelling results from the various perspectives enhanced confidence in the conclusions reached by the Study.
- ▶ The strategies for the perspectives started with the science questions designed to generate the critical information for decision making. These science questions drove the generation of tasks and applied research projects. The Study deliberately chose to have a measure of overlap and redundancy in some of these projects, so as to increase confidence in the Study's results and facilitate proper integration of results.
- ▶ Over the course of the Study, investigators determined that the effects of GIA on the head difference between Lake Michigan-Huron and Lake Erie, and on the implications of GIA for St. Clair River conveyance and water balance calculations are likely more important than previously believed. As a result, the Study Board decided to profile the analysis and findings of GIA effects in a separate chapter in the final report.
- ▶ The Study required data analysis and modelling efforts with a much higher level of precision and accuracy than in past studies. One significant problem identified early on was a lack of reliable historical data and the uncertainty associated with some early historical water level, flow, bathymetric, sediment and NBS data. To address this problem, the Study collected new field data using the most advanced technology, and conducted a critical review of past historical data prior to their use in analytical and modelling tasks.
- ▶ To enhance the credibility of, and confidence in, the findings, the Study concurrently employed different analytical models and compared their results. For example, numerous iterations of hydraulic model runs using different models were made to identify potentially conveyance-sensitive and erosion-prone reaches of the St. Clair River. These iterations helped determine subsequent modelling work using 2-D models, taking into consideration the availability of data, time, and relevancy of the modelling results. The most recently developed and advanced models were used in the Study following further peer review.

- ▶ The Study included a comprehensive consideration of scientific uncertainty analysis. As with most scientific studies, there are uncertainties in the results due to uncertainty in the data, analytical techniques, modelling and associated assumptions. Given the high level of precision and accuracy in the results that were required of the Study, the analytical framework incorporated an important component describing the various techniques and tools used to address the issue of scientific uncertainty. Care was taken in the use of historical data, and in the development and collection of new data. Multiple runs of different models were undertaken with the objective of enhancing confidence in the results.
- ▶ The Study generated new and revised data that have helped investigators update existing sediment, hydraulic and hydroclimatic models and develop new ones.
- ▶ Each step in the Study's analytical framework was independently peer-reviewed. Peer reviewers confirmed the validity of the overall approach, and made a number of specific suggestions for strengthening the framework, which the Study subsequently adopted.

CHAPTER 4

ST. CLAIR RIVER SEDIMENT REGIME

Chapter 4 presents a synthesis of work undertaken to document and understand the sediment regime of the St. Clair River. The work involved projects examining the geomorphic history of the river, the type of material on and beneath the river bed, the river bed topography and morphology, changes to river bed topography since the 1962 deepening of the navigation channel, and the present-day patterns and rates of bed erosion, deposition and sediment transport along the river in relation to the known hydraulic conditions in the river.

4.1 INTRODUCTION

4.1.1 Science Questions

The key science question addressed by the Study related to the St. Clair River sediment regime is:

Has the morphology of the St. Clair River been altered since the 1962 dredging? Specifically,

- ▶ Is the St. Clair River bed stable or eroding?
- ▶ If the bed of the St. Clair River is eroding, what initiated it, and when?

To answer these questions effectively, it was necessary to design a series of projects to:

- provide the geological context;
- map the bed material and bed morphology in the river;
- measure and model flow, bed shear stress and sediment transport; and
- document historical changes in bed elevation to determine possible areas and rates of bed elevation change over time.

This information was then combined into an assessment of the erodibility and sediment transport rate in the river, using field measurements and computational models.

4.1.2 Background on the Glacial History and Geology of St. Clair River

The bedrock in the region of the St. Clair River is upper Devonian Antrim Shale (Kettle Point Formation in Ontario) or Mississippian Bedford Shale (Hough, 1958; Randall, 1987). Glacial drift was deposited on top of this bedrock with the advance and retreat of the Huron Lobe of the Laurentide Ice Sheet. Beginning 23,000 years ago, the ice sheet advanced and retreated several times, depositing glacial till, glaciolacustrine, and glaciofluvial sediment. Throughout glacial and postglacial history, the St. Clair River channel has been an intermittent primary outlet for drainage of the Lake Michigan-Huron basin. Larsen (1994) summarizes the Holocene history of the Port Huron outlet. The channel has been used continuously as an outlet since the Nipissing I high stand phase of the Great Lakes between 5,000 and 4,000 years ago. Lake Michigan-Huron water levels progressively lowered with the incision of the St. Clair River into glacial material between 5,000 and 2,100 years ago, but the outlet and river elevation stabilized about 2,100 years ago (Morris, 2008).

Some previous work at various sites along the river using well records and seismic profiles shows that much of the river bed is underlain directly by glacial deposits, with shale bedrock beneath these deposits. The glacial sediments are mainly stiff clay till containing isolated boulders, gravel particles, and some gravel and sand lenses. The till is also inter-bedded with glaciolacustrine sand and silt layers and lenses. The glacial deposits are of various ages relating to glacial phases between about 23,000 and 13,000 years ago.

The major exception to the dominance of the deposits by clay till is a thick sand and gravel deposit underlying much of the upper river (the first 2 to 3 km [1.2 to 1.9 mi] downstream from Lake Michigan-Huron). This sand and gravel appears in borings for the Blue Water Bridge footings in the 1990s (Morris, 2008; Foster and Denny, 2009) and is interpreted as a pro-glacial sub-aqueous delta (Morris, 2008) deposited close to the ice front.

4.2 SUB-BOTTOM GEOLOGY

4.2.1 Surveys

Although the general nature of the geology of the region is known, there are no detailed analyses and accounts of the Quaternary and modern stratigraphy. In addition, the bedrock elevation and topography beneath the river have not been mapped. As part of the Study, field surveys in 2008 were designed to provide these details, especially for the upper river, where earlier concerns had been expressed about river bed erosion (Baird, 2005).

Acoustic sub-bottom surveys were done for the entire upper river (Lake Huron to Black River), and in two short swaths of the middle and lower river, to characterize materials and strata beneath the river (Foster and Denny, 2009). The surveys provided information on the origin of the river bed materials, the alluvial or non-alluvial character of the river as a whole, and the sub-bottom material. Interpretation of this information was aided by the review of existing information on the glacial history and geology of the area, and by previous investigations of the below-channel geology done for bridge and tunnel construction (Morris, 2008; Foster and Denny, 2009).

Sub-bottom acoustic profiles, along with bathymetric data were acquired using two instruments (Chirp 3200 and “Boomer”). In combination, these instruments provided a detailed picture of sub-bottom acoustic stratigraphy within a few metres of the river bed. The instruments also provided lower-resolution information down as far as the top of the bedrock. These data were assembled into a complete three-dimensional (3-D) dataset of the main strata beneath the river (Foster and Denny, 2009). Vertical resolution for the Chirp data was approximately 30 cm (11.8 in), while the Boomer provided resolution of about 1 m (3.3 ft) vertically, though with much deeper penetration beneath the bed.

The major unconformities apparent in the acoustic data were interpreted based on correlations with all available ground-truth data and converted into thickness on a 20 m (66 ft) grid using the simultaneously-surveyed bathymetry gridded at 5 m (16.4 ft). The swath bathymetric data were acquired with SEA Ltd. SWATHplus interferometric sonar operating at a 234-kHz frequency. The SWATHplus transducer was mounted at the bow of the survey boat. Ship motion (heave, pitch, roll and yaw) were recorded with the Octopus F180 Attitude and Positioning system. Position was measured with a differential global positioning system (GPS). RTK-GPS corrections were applied to the navigation data during post-processing in order to provide sub-meter horizontal and vertical accuracies of the soundings. Bathymetric data were acquired over variable swath widths ranging from 10 to 100 m (32.8 to 328 ft), in water depths from 1 to 25 m (3.3 to 82 ft). Bathymetric data were corrected to IGLD 1985 and processed to produce 1 and 0.5 m (3.3 and 1.6 ft) grids. Acoustic backscatter data were obtained from the raw SWATHplus data and then used to generate a geo-referenced acoustic backscatter mosaic at a pixel resolution of 0.5 m (1.6 ft).

4.2.2 Survey Results

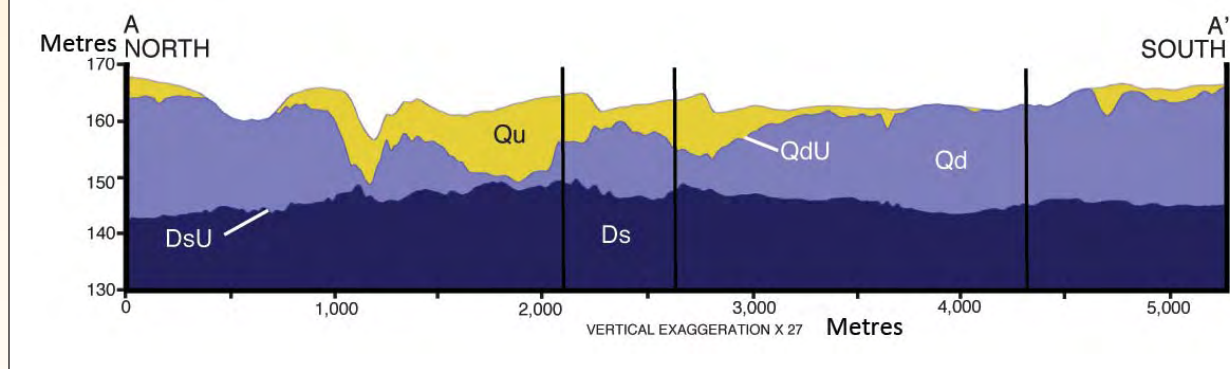
In the upper river, the sub-bottom geology consists of three main strata. The lowest is Devonian bedrock (mainly shale) (Figures 4-1a and b and 4-2a), the top of which is mostly flat with elevations between 139 and 154 m (456 and 505 ft) (IGLD 1985). The highest elevations are along the Canadian shore in the upper river. This bedrock surface is 10 to 30 m (32.8 to 98.4 ft) below the present river bed. The top of bedrock is an erosional unconformity (Figures 4-1a and b and 4-2a and b), above which are much younger Quaternary glacial deposits composed mainly of clay till, with gravel and boulders scattered within it, and interbedded with layers or lenses of glaciolacustrine sand and silt (Figure 4-1a and b). This till layer is overlain by Quaternary glaciofluvial, glaciolacustrine and fluvial deposits (Figure 4-1 and 4-2c). The total thickness beneath the river bed of these Quaternary deposits is 8 to 30 m (26.2 to 98.4 ft), and is thinnest beneath the deepest parts of the river. The till layer is relatively thin (and in places barely exists) beneath the upper river in the first 1 to 2 km (0.6 to 1.2 mi) of the river, where it appears to have been scoured by subglacial or proglacial meltwater to give an erosional unconformity (Q_{du}) and subsequently filled with a thick layer of glaciofluvial sand and gravel (Figures 4-2c and d).

Figure 4-1 Stratigraphy of the Upper St. Clair River

(a) Stratigraphic column along centre of upper St. Clair River

| Period | Epoch | Stratigraphic units | Seismic stratigraphic units and unconformities | |
|------------|-------------|---|--|---|
| QUATERNARY | HOLOCENE | Modern lacustrine Fluvial | Ql Qf | Transparent nearshore sand Transparent or prograding clinoforms |
| | PLEISTOCENE | Glaciolacustrine Proglacial subaquatic fans | Qu Qgl Qgf | Transparent - no internal structure Transparent or prograding clinoforms |
| | | St. Joseph Till Rannoch Till Tavistock Till | Qd | QdU - Strong, continuous reflection, channeled surface Amorphous or may contain many internal diffractions from boulders and coarse-grained lenses |
| | | Catfish Creek Till | | Continuous to discontinuous reflection |
| DEVONIAN | UPPER | Kettle Point Formation/Antrim Shale | Ds | DsU - High amplitude, continuous regional reflection |

(b) Longitudinal section along centre of upper St. Clair River

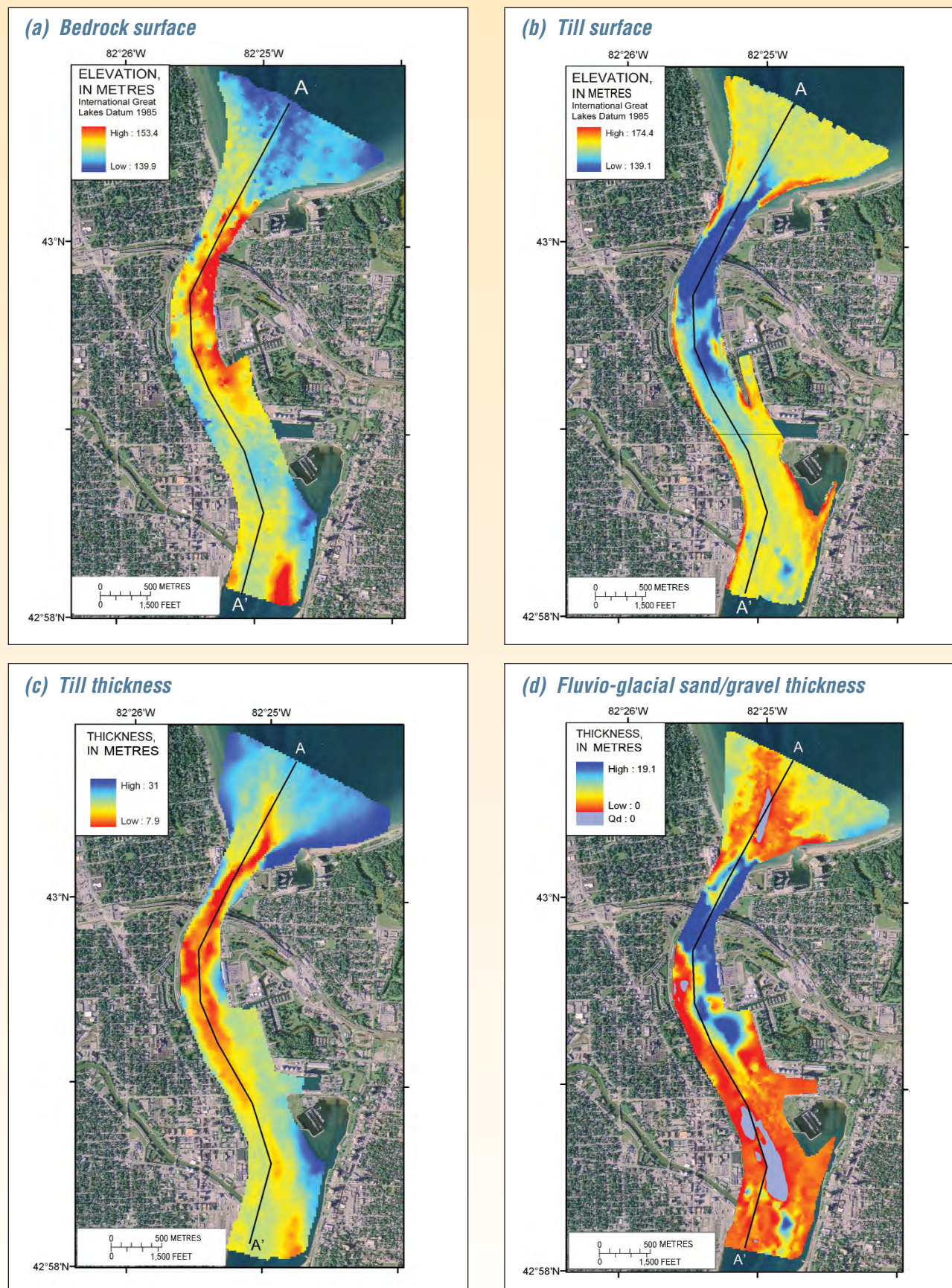


Note: For the upper St. Clair River area (Morris, 2008) with correlations to seismic stratigraphic units Devonian shale (Ds), Quaternary glacial drift (Qd), and Quaternary undifferentiated (Qu). Qu includes glaciofluvial, glaciolacustrine, fluvial and lacustrine deposits. Major unconformities are the top of Devonian shale (DsU) and the top of glacial drift (QdU). The line of the section in 4-1b is shown as a black line along the centre of the channel in Figure 4-2 and, similarly, on Figure 4-4.

Quaternary undifferentiated (Qu) contains well-defined sequences of downstream prograding clinoforms. This indicates that most of Qu was transported downstream by either glaciofluvial or fluvial processes, and the source of material is likely the glaciofluvial deposits beneath Lake Michigan-Huron or a coarse lag derived from the till or Quaternary glacial drift (Qd). The two tongue-like features located just downriver of the Blue Water Bridge have southward (downstream) dipping clinoforms within them. This suggests that these features are the result of the present flow of the river and likely formed during post-glacial time by transport and deposition from fluvial processes. See sections 4.5 and 4.8 for further discussion of these features.

Further downstream, this upper sand and gravel layer Qu pinches out so that the underlying Qd (till) layer is exposed at the river bed or is covered by a thin layer of sand and gravel (Figure 4-2d). The general characteristics of sub-bottom stratigraphy is also seen in U.S. Army Corps of Engineers (USACE) coring samples along the river obtained between 1958 and 1960, in which much of the river was found to have thin sandy gravel deposits overlying clay.

Figure 4-2 Elevation and Thickness of Geological Boundaries and Units in the Upper St. Clair River



Note: The purple area in Figure 4-2d has zero thickness and denotes where till is exposed

4.3 RIVER BED MATERIAL

4.3.1 Surveys

Surveys of the sub-bottom geology and bed material characteristics focused on the upper river (Lake Michigan-Huron to the confluence of the Black River). Previous analysis of existing, but uncalibrated bathymetric data had suggested that this was an area of ongoing net bed lowering (Baird, 2005). Previous investigation of bed material using side-scan sonar in 1999 for fish habitat surveys had shown that much of the river bed in this reach was covered with coarse gravel with some finer material along the channel sides. This finding was confirmed using underwater video (Manny and Kennedy, 2002). Attempts at grab sampling of the bed in the past in the upper river have been compromised by the coarse bottom material that made sampling impossible in most places (*e.g.*, Lakeshore Engineering Services, 2005, 2007). Much earlier accounts also report areas of sand and gravel overlying till in several areas of the river (*e.g.*, Bartlett, 1922).

As part of the Study, several investigations were undertaken to map the river bed material in 2007 and 2009, focusing on the upper reach and, in less detail, the middle and lower reach of the St. Clair River. Surveys used a combination of acoustic and direct observations from still images and underwater video, rather than attempting grab sampling or coring, which, based on past experience, were likely to be unsuccessful in areas of coarse gravel or cobble substrate. Grab samples were taken in areas of finer bed material in some locations.

Swath bathymetric data, acoustic backscatter data (taken from the swath bathymetry data) and side-scan sonar data were acquired in early June 2008 from 1 km (0.6 mi) out into Lake Michigan-Huron over the entire river width to 2 km (1.2 mi) downstream from the mouth of the Black River, and also along two 500 m (0.3 mi) lengths of channel at Marysville, MI and Port Lambton, ON. The acoustic backscatter data were processed to generate a geo-referenced backscatter mosaic at a pixel resolution of 0.5 m (1.6 ft) that could be overlaid on the bathymetric data. Sidescan-sonar data were acquired with dual-frequency sonar operating at 132 and 445 kHz (L3-Klein, 2009). The acoustic backscatter data provided information on the types of material and objects on the river bed. Interpretation of this acoustic mapping was aided by continuous bed video from longitudinal transects more than

11 km (6.8 mi) in length, about 450 still camera images of the bed and 15 grab samples of finer bed material (Foster and Denny, 2009). These data were used to produce an interpreted and verified map of the distribution of bed material types over the entire upper river.

In addition, as part of the Study, high resolution swath multi-beam bathymetry data were acquired in July 2008 using a RESON 200 kHz SeaBat 7125 multi-beam echo sounder over a slightly larger area than the other acoustic surveys. The survey provided information on river bed morphology and features. It also provided measurements of bed roughness from which particle diameter could be estimated (Best *et al.*, 2009) using “angular range analysis” of the acoustic data (Fonseca and Mayer, 2007). This survey consisted of:

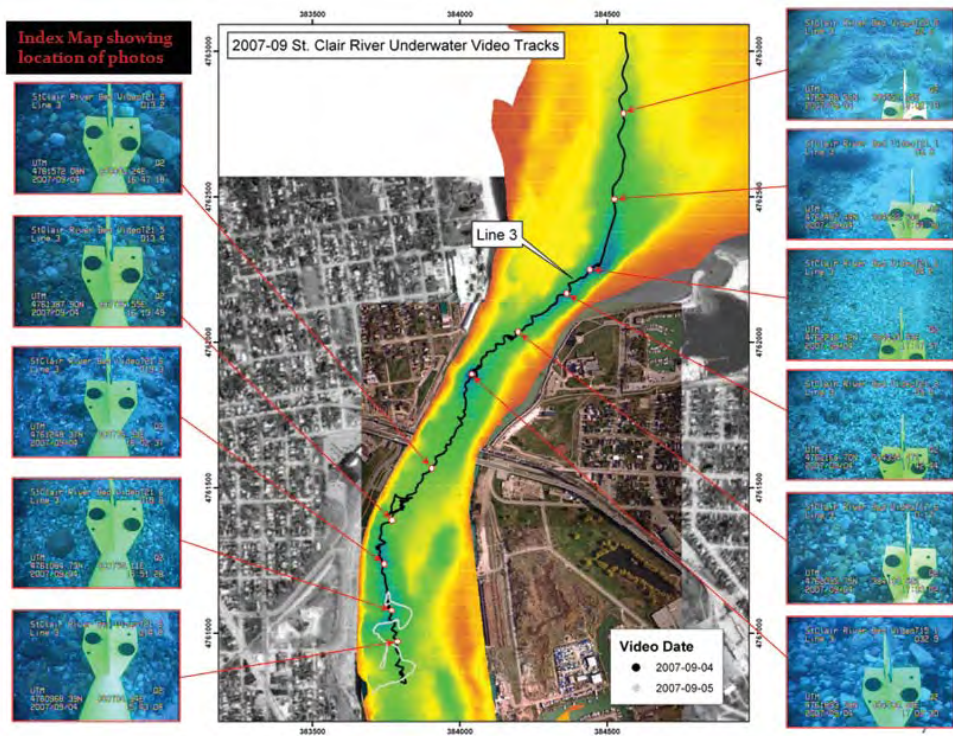
- analysis of the beam-by-beam time-series of acoustic backscatter data provided by the multi-beam sonar to correct the backscatter for river bed slope, beam pattern, time-varying and angle-varying gains, and the area of insonification;
- calculation of a series of parameters from stacking of consecutive time series over a spatial scale that approximates half of the swath width; and
- estimation of the acoustic impedance and bed roughness, based on these calculated parameters and the inversion of an acoustic backscatter model.

To assist with the roughness calibration and validation, the backscatter signals from the snippets were classified visually and verified using estimates of grain size and bed type from the bed video, images and analyses.

As part of the Study, underwater video of the river bed was acquired in 2007 and 2008 (Krishnappan, 2009), independent of the acoustic surveys (Figures 4-3a, b and c). This included transects across the channel at 2 km (1.2 mi) intervals along the entire river length and a longitudinal transect along the thalweg in the upper river. In addition, detailed video mapping of bed material on the tongue-like feature in the upper river was undertaken in 2008. Digital image analysis of selected video frames was used to provide measurements of grain size distributions at selected sites that were used in the analysis of critical shear stress for initiating bed erosion.

Figure 4-3 Video Tracks for Bed Material Surveys

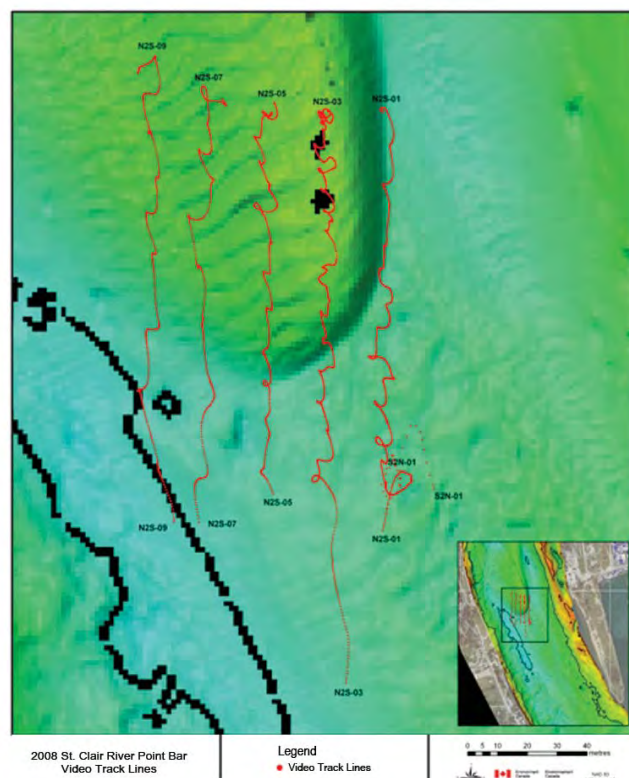
(a) Along thalweg of upper St. Clair River



(b) Transects along entire river



(c) Local survey of gravel tongue-like feature in upper river

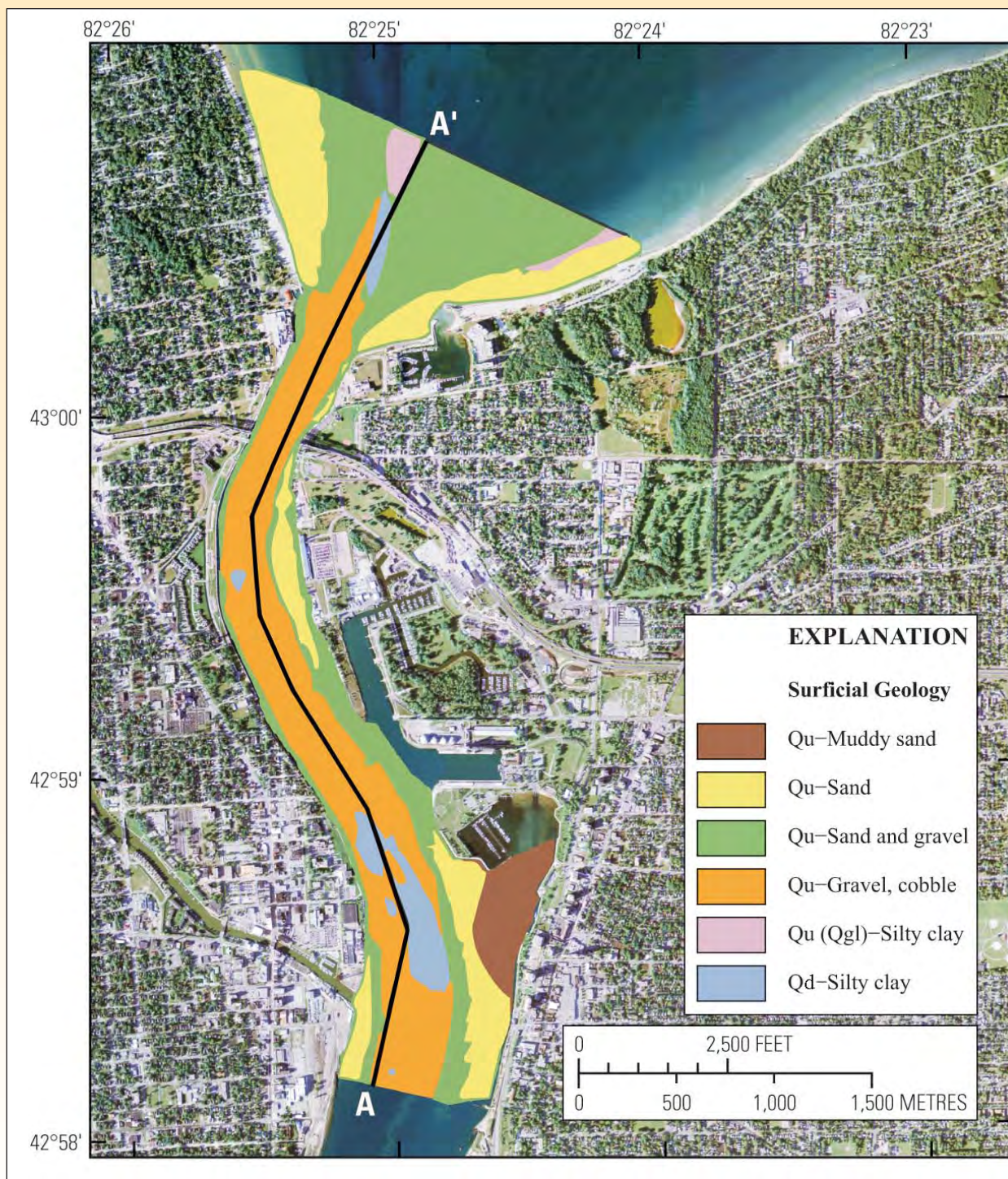


4.3.2 Survey Results

Based on these surveys, the bed material of the upper river has been mapped by classifying substrate into six categories (Figure 4-4). Most of the material is derived from the uppermost Qu unit, with the exception of some areas in which Qd (clay till) is exposed in the bed. Much of the river bed is covered with gravel and cobbles derived from

the underlying Qu deposit. A finger of this coarse material that covers the deeper parts of the channel extends about 500 m (0.3 mi) out into the lake. Image analysis of video frames from the longitudinal transect up the thalweg show that median particle size is highest in the reach under Blue Water Bridge (about 40 mm) (1.6 in) and is slightly finer (20 to 30 mm) (0.8 to 1.1 in) both upstream and downstream of this area. Maximum

Figure 4-4 Distribution of Major Types of Surficial Bed Material Along the Upper St. Clair River



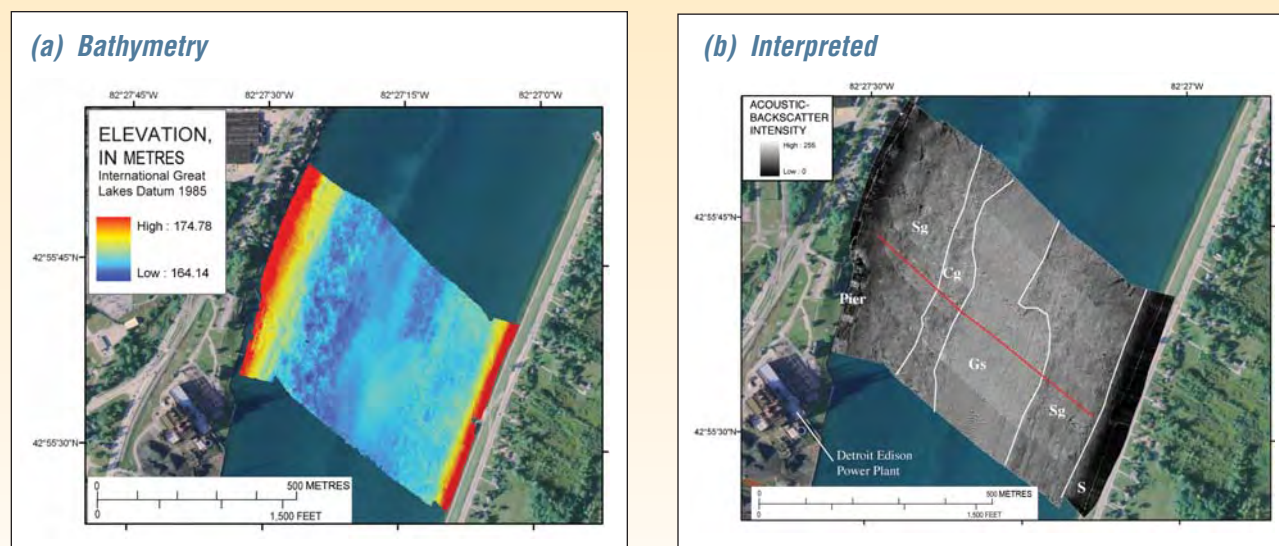
measured particle diameter exceeds 100 mm (3.9 in) and in places much larger boulders are visible in the video. Gravel also covers the surface of the prominent tongue-like feature on the bed in the upper river (apparent from the closely-spaced video tracks). Two separate image analyses of particle size on this feature provided estimates of the median grain diameter of 16 and 20 mm (0.6 and 0.8 in).

Finer gravel and sand occur closer to the banks of the river and on the bed of the outlet of Lake Michigan-Huron, while large areas of the lake bed outlet are encrusted with shells. The nearshore areas in the lake are covered with shallow <1 m (3.3 ft) sand deposits that are wider on the U.S. side. Close to the top of the river, shore-oblique sand waves with wavelength 10 to 15 m (32.8 to 49.2 ft) form as the current begins to transport the sand into the head of the river. There is very little sand deposition along the U.S. bank of the river, though extensive sand deposits occur on the Canadian side, where velocities are lower and where there is a large recirculation eddy (see sections 4.6 and 4.7 on flow and sediment transport). Glaciolacustrine clay is exposed in some areas of the lake bed. The cobble-gravel substrate becomes thinner and less continuous about 2,500 m (1.6 mi) downriver, giving way to an area of exposed till Qd at the southern end of the Study area, near the Black River, which was verified with several video drifts (Foster and Denny, 2009). Photographs of the till exposures show a rough topography with ridges, usually oriented parallel to the river current, and ledges of clay

till protruding from the river bottom (see section 4.5 on channel morphology). In some places, the till is covered with patches of rippled sand, gravel, cobbles, and boulders. Some of this material was likely derived from Qu, although there are clast voids within the till indicating that erosion of the clay material provides some of the coarse-grained lag deposit. Vegetation is also common on both till and sand/gravel substrate, particularly towards the channel margins.

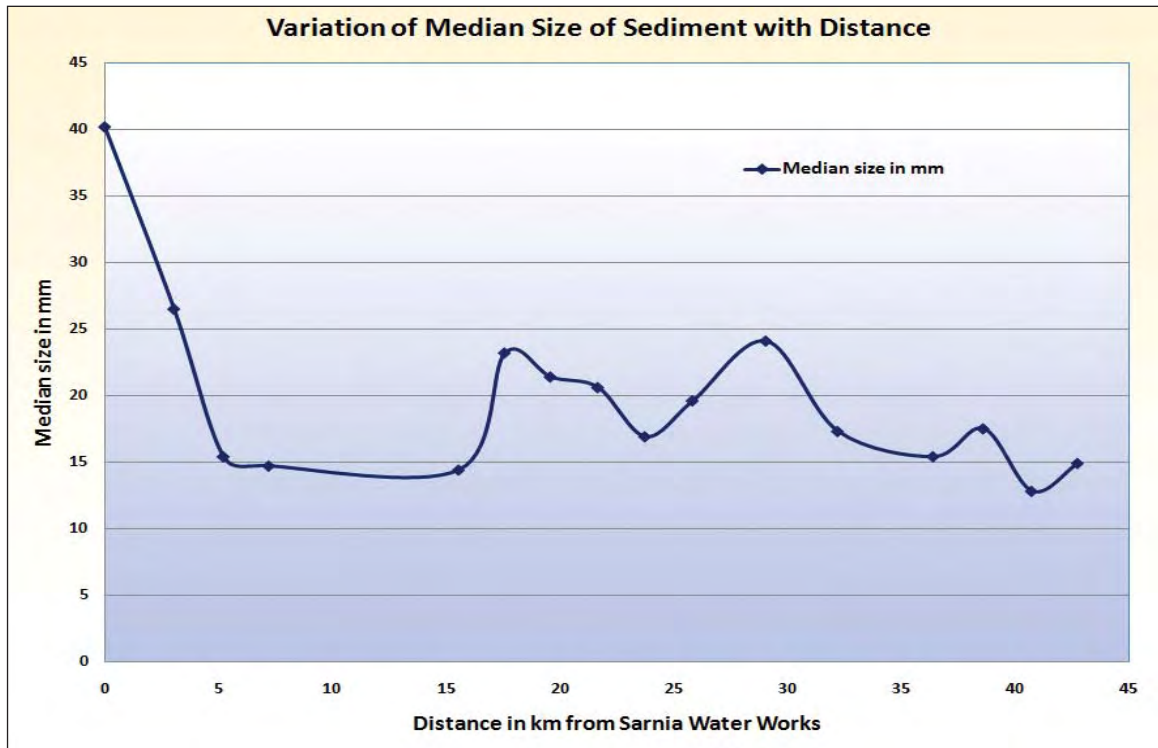
In the two swaths in the middle and lower reaches of the river, clay till, with gravel and scattered boulders, and glaciolacustrine clay form the river bed with variable (and, in places no) superficial sediment cover (Figure 4-5a and b). In the Port Lambton area, there is a sand and gravel deposit up to 3 m (9.8 ft) thick in the centre of the channel. Acoustic backscatter data show regular wave-like bedforms in the centre of the channel in places, presumably formed in sandy-gravel. Image analysis from video transects at 2 km (1.2 mi) intervals down the river as far as Port Lambton indicates that the centre of the channel remains gravelly along the length of the river with median particle size 12 to 25 mm (0.5 to 1 in) (Krishnappan, 2009) (Figure 4-6). Grab samples of bed material and visual inspection of video of bed material along these transects confirm that the centre of the channel is gravelly, while sediment along both channel margins is fine grained sand, silt and mud with large proportions of shell debris.

Figure 4-5 Bathymetry and Interpreted Bed Material of a Swath of the Lower St. Clair River (at Marysville, MI)



Interpretation: (S) area of low backscatter (dark) sand; (Sg) moderate backscatter area, sand and gravel; (Gs) high backscatter (light) area with dune bedforms (3-5 meters [9.8 to 16.4 ft] wavelengths), gravel with sand; (Cg) mottled area of high to low backscatter, clay till or glaciolacustrine silt with patches of gravel.

Figure 4-6 Longitudinal Variation of Median Grain Size of Bed Material in Thalweg of the St. Clair River



4.4 BATHYMETRIC AND MORPHOLOGIC CHANGE

4.4.1 Surveys

River bed morphology reflects the interaction among the river's flow, substrate and sediment transport. One means of assessing the occurrence of long-term erosion and deposition in the river, as well as rates of bed material transport, is to re-survey river bed topography at regular intervals. In the past, bed surveys in the St. Clair River were done primarily for navigation and dredging purposes and were based on regularly-spaced single cross-sections or survey lines. These past surveys provide information on change at those particular points or cross-sections, though spacing along the channel is often very wide. As a result, there was no information available on the changes in the river bed between the cross-sections or in places of irregular morphology. Nor was there information on rapid spatial changes in bed elevation, where interpolation between sections may be very unreliable. Since 2000, the river has been surveyed using multi-beam swath acoustic instruments that cover the entire river bed at very high

resolution. These recent surveys provide full coverage of the river morphology and changes over time. Horizontal positioning in these acoustic surveys was undertaken with high precision GPS data. In contrast, earlier surveys used triangulation from a shore station to the boat using a surveying instrument (i.e., Transit) to determine the angle from the base line and track the position of the boat. It was assumed the boat stayed on the pre-determined course perpendicular to the flow of the river.

Conventional cross-sections were surveyed on the St. Clair River in 1954 and 1971. There was then a long time gap before cross-sections were surveyed with a single beam acoustic instrument in 2000 and then with multi-beam instruments in 2002, 2005, 2006, 2007 and (for this Study) 2008. The entire river was surveyed in 1971, 2000 and 2007. The other surveys (2002, 2005, 2006 and 2008) were limited to the upper river (mainly upstream of the confluence of the Black River), because the upper river was hypothesized to be the area of particular concern about bed erosion (Baird, 2005).

The Study undertook extensive analysis of river bed bathymetric change to quantify and map areas of historic and present-day bed erosion and deposition. This required considerable work on assessing the comparability of surveys done using different technologies and at different horizontal and vertical resolutions. Data density and spatial distribution of the data points vary considerably among the surveys. The 1971 depths appear to have been rounded and 'binned' into depth ranges rather than preserving the original raw depths. The 2000 data were also rounded and binned but used different bin values from 1971. Both of these surveys were based mainly on widely-spaced (about 100 m [328 ft]) cross-sections, though some intermediate points were surveyed in 1971. The 2007 full river survey used an acoustic multi-beam swath instrument providing continuous coverage of the river bed. The 2007 data were mapped without any rounding or 'binning', and then were gridded. The total number of gridded points is about 100 times greater than in 2000 and about 1,000 times greater than the 1971 survey. The multi-beam surveys of the upper river (2002, 2005 and 2006) all had very similar areal coverage and point densities to that of the 2007 survey. The 2008 surveys done for this Study were at higher horizontal resolution than previous surveys. Nominal minimum vertical error in bed elevation in these surveys was 0.15 to 0.20 m (5.9 to 7.9 in). Errors for 2000 and 1971 are not known and, in analyzing bathymetric change, were assumed to be 0.3 m (11.8 in) (Bennion, 2008). For inter-comparison, all surveys were processed to reduce them to a common horizontal and vertical datum (Bennion, 2008).

In 2008, the Study undertook further analysis of survey error. Investigators surveyed an area of the river bed at high resolution (0.25 m [9.8 in] grids) twice within a few days using the same instrumentation and data processing. Thus, no bed erosion or deposition could have occurred between surveys, and any differences in bed elevation could only be attributed to actual survey uncertainty (Best *et al.*, 2009). Comparison of these two surveys showed measured bed changes (*i.e.*, actual survey error) with a maximum of plus or minus 0.25 m (9.8 in) and contiguous areas of positive or negative elevation change. This indicated that bathymetric change analysis, even under optimal conditions, is subject to significant uncertainty and may yield contiguous areas of apparent elevation change. The precision in this field test case suggested that the previous surveys may actually be less precise in the vertical than assumed in Bennion's analysis (Bennion, 2008).

Comparison of the widely-spaced cross-section data with continuous, gridded multi-beam data is problematic. It is inappropriate to interpolate sparse data into a continuous surface because of the large uncertainties and errors

involved. However, for the purpose of this Study an estimate was attempted so that errors could be computed and compared with those from the interpolated multi-beam surveys. All surveys prior to 2008 were interpolated to a common 1 m (3.3 ft) grid. Interpolation error for the multi-beam surveys was 0.2 to 0.3 m (7.9 to 11.8 in) vertical. For 1971 and 2000, these errors were 1.7 m and 0.7 m (5.6 and 2.3 ft). Overall uncertainty in bed elevation was at least an order of magnitude greater for the 1971 and 2000 surveys than for the subsequent multi-beam surveys.

The various surveys were compared using both elevation changes and interpolated volumes of erosion and deposition implied by bed elevation changes spread over contiguous areas of change. Vertical change was calculated for the multi-beam surveys using the interpolated surfaces and common points. The vertical changes for the 1971 and 2000 surveys were then compared to the multi-beam surveys by extracting coincident points from the multi-beam surfaces so as to eliminate the interpolation error. However, this restricted comparison to only those points and made it impossible to assess change anywhere else on the bed.

4.4.2 Survey Results

None of the measured volumetric change (erosion volume and deposition volume) was greater than the estimated error in cut-and-fill volume. This was the case even for the apparently large volumes of cut-and-fill between 1971 and 2000, and between 1971 and the multi-beam surveys. These large volumes may occur partly because of some apparent systematic negative bias in the 1971 survey. No clear pattern or trend of volumetric change (net total erosion or deposition) emerged from this analysis. Particular areas of the bed often switch from erosion to deposition between surveys.

Elevation comparisons for the multi-beam data show a few, isolated areas of significant and persistent changes in bed elevation since 2002 (Figure 4-7). There was an area of persistent deposition in the flow recirculation zone on the Canadian shore close to the Point Edward Casino. This area appeared to be building in the downstream direction and towards the east bank. The substrate mapping showed this to be an area of sand. Strips of bed elevation change (but not persistent erosion or deposition) occur close to both banks in the upper river, again in areas of fine-grained bed material. The tongue-like feature in the centre of the channel downstream of the first bend appeared to be active. In most comparisons, the downstream margin of this feature is advancing down the channel at a rate of up to 20 m (65.6 ft) a year, while the flatter, upstream surface shows net erosion. In addition, bathymetric comparisons indicate that the wave-like bedforms on the

surface of this feature (see below) are also migrating slowly downstream (Best *et al.*, 2009). Finally, there is an area of possible gradual erosion that coincides roughly with the area of exposed till in the centre of the channel immediately upstream of the mouth of the Black River. This area appears to have eroded by about 0.5 to 1 m (1.6 to 3.3 ft) between 2002 and 2007. However, the erosion does not always appear between individual years (2005, 2006, 2007, 2008), possibly because rates are below the detection error in the surveys over short periods. Changes in the upper river between 2007 and 2008 are consistent with these longer-term changes, except that erosion in the area of exposed till is not apparent in this comparison (Figure 4-8) (Best *et al.*, 2009). This 2007-2008 comparison also shows clear patterns of local elevation change associated with slowly-migrating transverse bedforms. Single-beam bathymetric cross-sections, with spacing of 2 km (1.2 mi), were also surveyed along the entire river in 2007 and 2008 (Krishnappan, 2009). Direct comparison of these cross-sections shows negligible change in all cases.

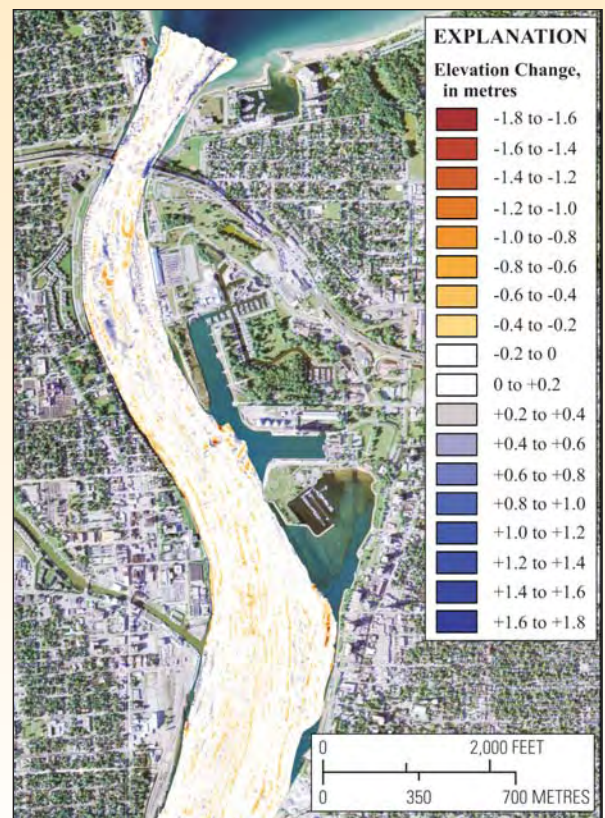
Analysis of the surveys since 2002 shows no widespread net erosion of the bed in the upper river or along the middle and lower reaches of the river. The large-scale erosion in the bend of the river below the Blue Water Bridge that

is apparent in comparing 1971 with subsequent surveys, is not apparent in any of the post-2000 surveys. Further detailed analysis was undertaken in an attempt to understand the changes since 1971, and to verify the large-scale bed erosion and deposition in the upper river between 1971 and 2000. Point-to-point comparisons between 1971 and 2000 and with the complete river multi-beam survey in 2007 and 2008 show that, in general, the river bed was higher in 1971 compared to 2007 along its entire length. Most of the points show apparent erosion along the entire river between 1971 and 2007, with the exception of an area of deposition on the east shore of the upper river. However, when 2000 is compared with the 2007 coincident points, much of the river (including the upper river) appears to show net deposition. It is difficult to find a physical explanation for this difference, particularly given the stability of the river bed and negligible bed load transport in the river (see below). Bennion (2008) suggests that it may reflect bias between the surveys given that the statistics of elevation distributions differ and because of the rounding and binning of the 1971 and 2000 survey data. This in part accounts for the large apparent elevation and volumetric changes between surveys in 1971 and 2000 and the later multi-beam surveys.

Figure 4-7 Detectable Net Bed Elevation Changes in the Upper St. Clair River from Multi-Beam Swath Surveys (2002-2007)



Figure 4-8 Detectable Bed Elevation Changes in the Upper St. Clair River (2007-2008)



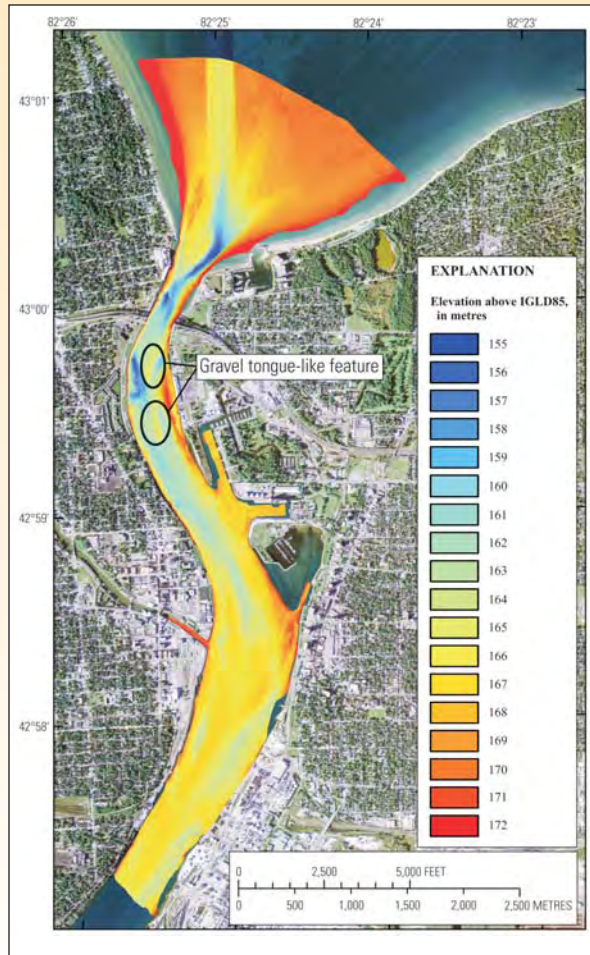
Comparisons of interpolated 1971 data with subsequent multi-beam data in the upper river suggest that substantial erosion could have occurred. In particular, the comparisons indicate substantial pools developed in the upper river in this time period, leading to apparent large net erosion volumes in the upper river (Baird, 2005; Bennion, 2008). The problem of interpolating between widely-spaced points in the 1971 data has been noted above. This apparent large-scale erosion is also problematic because there is no reason to suppose that bed material size has changed during this period (given the underlying geology and sediment delivery processes), and because this part of the channel currently is non-erodible by bed shear stresses generated by the river flow (see below). Furthermore, documented accounts of the sinking of the ship the *Sydney Smith* in 1972 suggest that a deep pool existed in this area at that time with a depth consistent with present day bathymetry. In addition, analysis of historical bathymetry suggests that there was a relatively deep pool in this area of the river in 1954 and even going back as far as 1900. This pool, up to 15.2 m (50 ft) deep, also appears on a published 1972 navigation chart. The 1971 survey is anomalous in not identifying this feature. In an area of complex river bed morphology, errors in surveyed and actual horizontal position of the survey points could cause considerable apparent differences in river morphology between two surveys. Comparisons of 1971 with nearby 1954 sections show that small upriver or downriver shifts in the real position of a cross-section could certainly account for substantial apparent changes in bed morphology. However, analysis of survey cross-sections between 2008 and 1971 shows substantial bed lowering in the first bend of the upper river, only part of which (maximum of 2 to 3 m) (6.6 to 9.8 ft) could possibly be attributed to misalignment of cross-sections (Best *et al.*, 2009). In addition, the 1971 survey was sufficiently dense that it could not have missed this deep pool had it been there. Details of the plans for construction of the sheet piling wall on the U.S. side immediately downstream of the Blue Water Bridge in the late 1970s show that the pilings were placed in the river beyond the pre-existing bank position. River bed profiles surveyed in 1979, prior to construction, showed depths in excess of 12 m (40 ft) in this area of the channel, which is comparable to current depths in that area. It is possible that bank realignment and installation of the vertical sheet piling along this shore, along with local clear water scour, may have caused some further adjustment of bed morphology in this area in subsequent years. However, this possibility is not readily analyzed except, perhaps, using physical model studies or numerical modelling of local scour.

Thus, there remains difficulty reconciling the actual bed morphology in 1971 relative to information before and after the 1971 survey. Bathymetric surveys since 2002 show only minor, local (<1 m [3.3 ft]) bed topography change in the upper river associated with particular features. The post-2002 surveys show no ongoing, widespread or significant bed erosion (or deposition) in the upper St. Clair River.

4.5 BED TOPOGRAPHY AND MORPHOLOGY

In 2008, two separate multi-beam surveys of river and lake bathymetry were carried out as part of the Study. The general features of the bed topography are the same as those of previous multi-beam surveys (Figures 4-9, 4-10). These surveys show the relatively high elevation lake floor funnelling down into a deep channel at the head of the river, along with the dredged shipping channel (running roughly north-south in the lake) converging at the same point. This deep central channel, with the lowest elevations in the upper river, runs along the centre of the river under the Blue Water Bridge and around the outside of the first bend, before elevations begin to gradually rise downstream towards the mouth of the Black River. The inside of the first bend has a prominent shoal (referred to in the discussion of bathymetric change) that is widest alongside the Point Edward Casino. The deep central channel features two deep pools, one immediately upstream of the Blue Water Bridge and the other at the outside (west side) of the first bend. In each case, there is a prominent tongue-like higher elevation bar in the channel downstream of the pool. The downstream bar is better defined and is the one that appears to have been advancing slowly downstream, based on mapping of bathymetric change (Figure 4-7). Downstream of the mouth of the Black River, with the exception of the island reaches, channel topography is much more regular and mostly-symmetrical in cross-section, with a roughly trapezoidal shape with a wide, fairly flat, channel bed and floor (Figure 4-5a).

Figure 4-9 River Bed Elevation Map for the Upper St. Clair River, July 2008



High resolution (0.25 m grid) (9.8 in) bathymetric survey in July 2008 (Best *et al.*, 2009) showed much greater detail of the bed morphology in the upper river than any previous survey. The survey revealed several areas of the river bed with apparently-active bedforms and other features. The most significant of these are wide fields of flow-transverse, wave-like bedforms with steep lee-sides facing downstream (Figures 4-11 and 4-12). These bedforms occur in several areas, notably: in the dredged navigation channel in Lake Michigan-Huron; superimposed on the sediment tongues; in the area of sand accumulation adjacent to the Point Edward Casino section on the east side of the river; in mid-channel downstream of the tongue-like features; and extensively across the bed both upstream and downstream of the Black River confluence. Wavelength and height of these features atop and near the downstream gravel tongue vary from 3 to 12 m (9.8 to 39.4 ft), and 0.053 to 0.65 m (2.1 to 25.6 in) respectively, and the height to wavelength ratio is 0.012 to 0.159. The bedforms are asymmetrical in cross-section (flow parallel) with shorter lee-side lengths and lee side slope angles average nine degrees. Their geometry is very similar to that of dunes measured in gravel-size sediment in a variety of other studies (*e.g.*, Carling, 1999). These transverse bedforms are also apparent in places along the navigation channel in the middle and lower reaches of the river (Foster and Denny, 2009). The transverse bedforms have morphology that shows downstream migration. However, close to the shore in the area near the Point Edward Casino, these sand dunes show upstream migration as a result of flow in the recirculation eddy in this area (Best *et al.*, 2009). These flow-transverse bedforms are also clearly visible, though at a lower resolution, on the bathymetric maps presented by Baird (2005) from the 2002 and 2005 bathymetric surveys.

Figure 4-10 Oblique Three-Dimensional (3-D) View of Bed Topography in the Upper St. Clair River

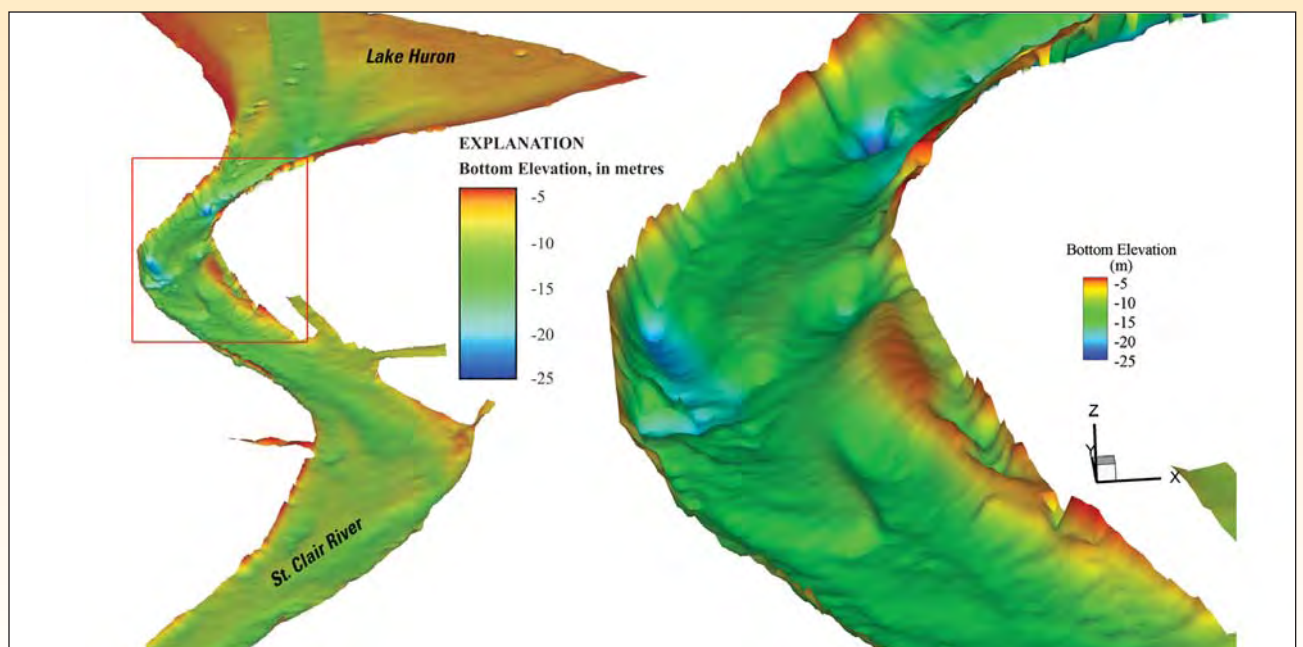


Figure 4-11 Gravel Tongue with Gravel Dunes on Top

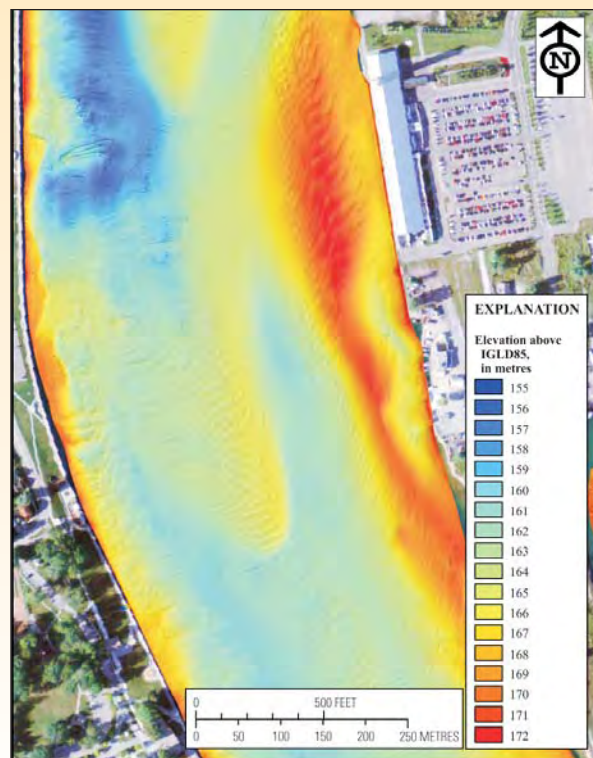


Figure 4-12 Transverse Bedform Field

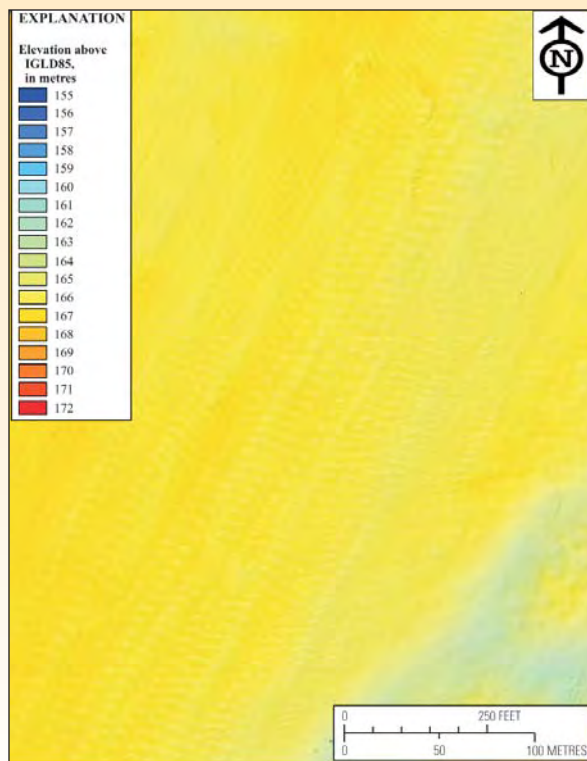


Figure 4-13 Ridges and Grooves in Cohesive Till and Transverse Bedforms

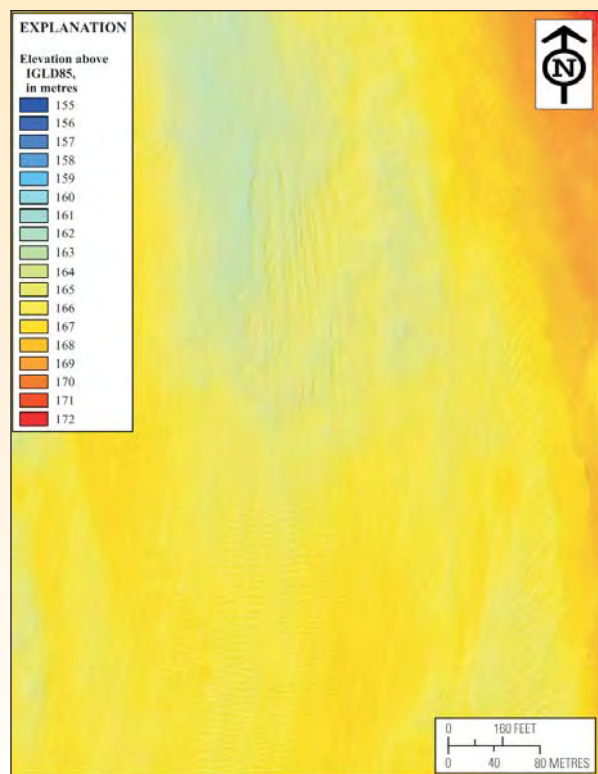
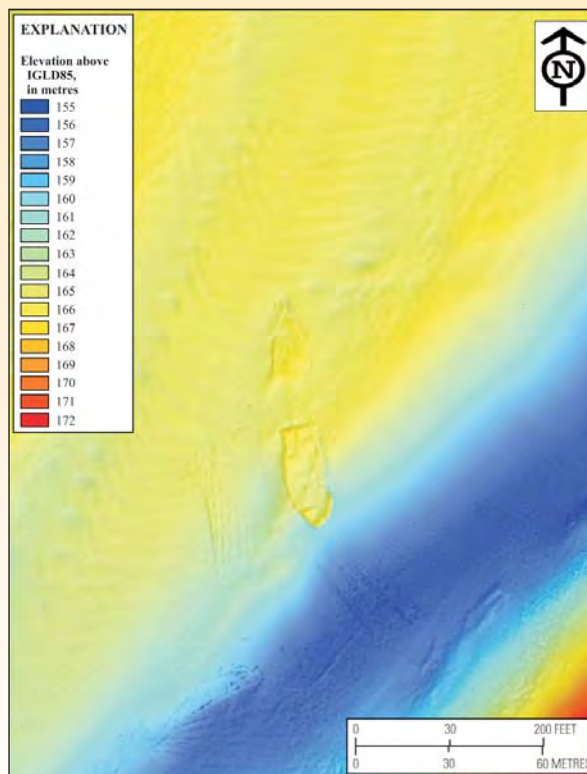


Figure 4-14 Detail of Bedforms around Wreck of the *Fontana*



Flow is top to bottom in all cases

Several areas of Lake Michigan-Huron and the St. Clair River show bedforms that have been cut into cohesive material that is either till or cohesive glaciolacustrine/ fluvial material. In the dredged channel in the lake immediately north of the river entrance, these bedforms appear as circular/ovoid scour features, some of which appear to have formed around some of the large concrete blocks tethering navigation buoys. In the river, there are areas of irregular topography at the sides of the channel, as well as areas of longitudinal grooves and furrows elongated parallel to the flow direction (Figure 4-13). The findings regarding the morphology of these features is consistent with past work describing erosion in bedrock and cohesive material, with the isolated scour features resembling flute marks (Richardson and Carling, 2005). Images of this groove and furrow morphology show that it is eroded into exposed till that has been sculpted into these flow-parallel forms (Foster and Denny, 2009). In the centre of the channel downstream of the tongue-like features, the gravel is a relatively thin and possibly patchy cover over glacial till. Patches of transverse bedforms appear interspersed with cohesive substrate showing erosional features. In the vicinity of the mouth of the Black River, there is a downstream transition from longitudinal grooves to transverse bedforms as river bed material changes from clay till to sandy-gravel and gravel-cobble (Figure 4-13).

Areas of both lower bed elevation and deposition are evident around the sides and downstream of several of the shipwrecks mapped during the survey. The wrecks of the Fontana (Figure 4-14) and the Martin have such scour associated with them. This illustrates both the highly-localized scour that has occurred over a number of years around these bluff bodies, as well as the presence of migrating transverse bedforms within these areas, in fine-grained sediment, typical of current-induced scour and sediment transport of fine-grained sediment. Several areas of the St. Clair River and Lake Michigan-Huron beds have a very disorganized bed character and appear to be complex, rough surfaces that lack any clear structure (e.g., on the west shore in the vicinity of the rail tunnel). Some of these areas may be regions

that are covered with stable aquatic vegetation that is growing on the river bed substrate, or accumulations of shell debris and in situ shell beds.

The variability and overall distribution of various types of bed morphology in the upper river is shown in Figures 4-15a and b. The classification of the bed morphological zones was conducted independently from the backscatter classification of substrate, but there is a clear correspondence between them (Figure 4-15c). The longitudinal grooves and other scour features coincide with the main areas of exposed clay till and with areas of thin sand/gravel veneer over till, and the main areas of flow transverse bedforms lie within the areas of sand, gravel and cobble material.

Figure 4-15 St. Clair River Bed Morphology

(a) Example of variation of St. Clair River bed morphology across the channel

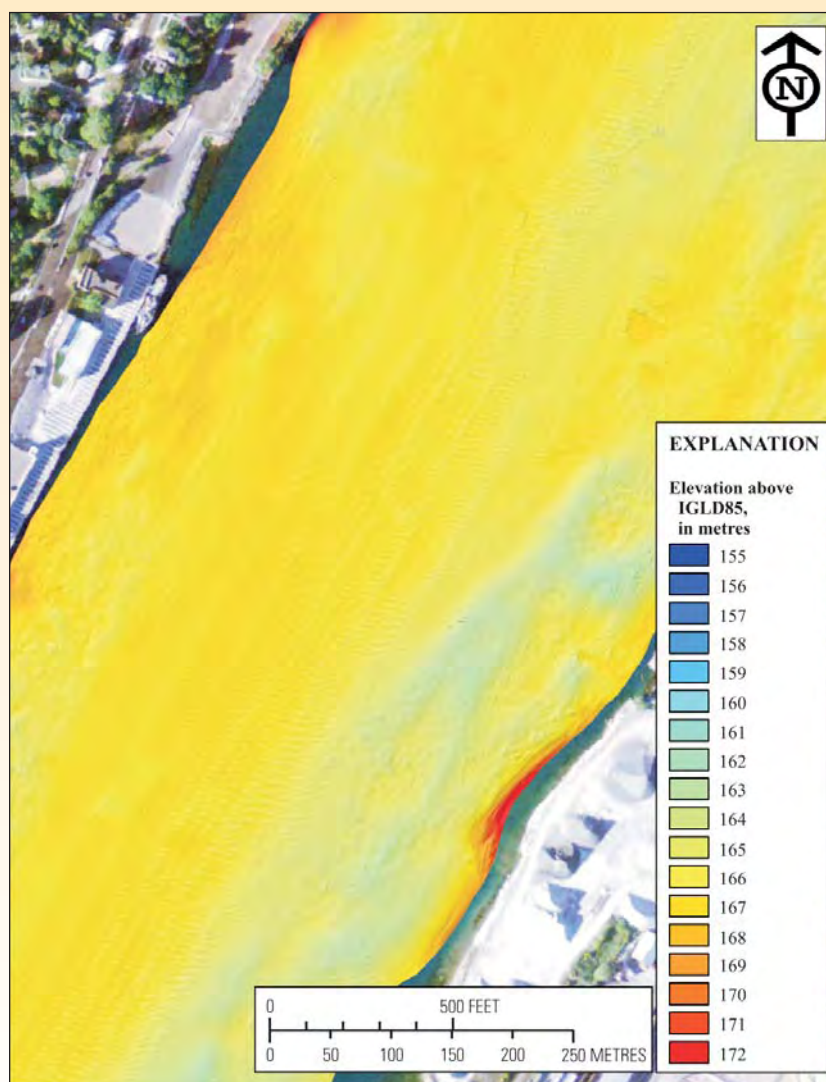
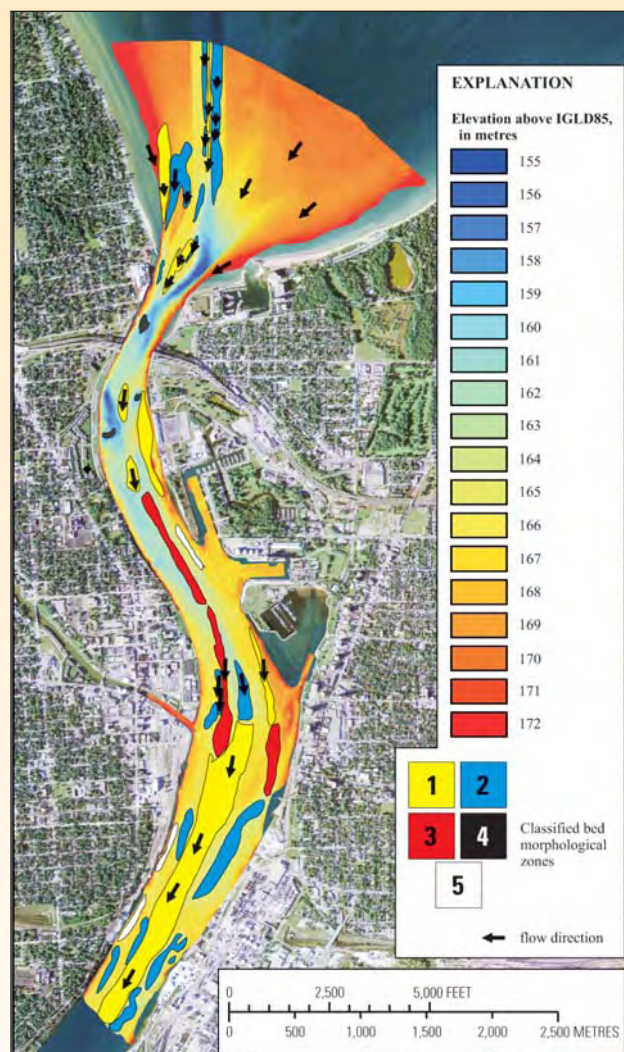
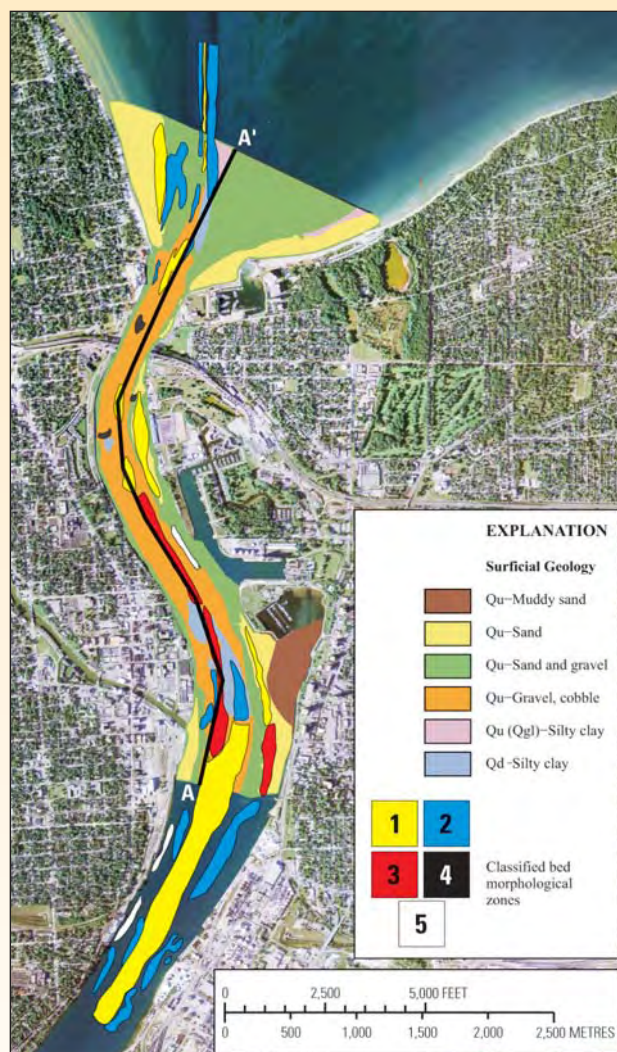


Figure 4-15 St. Clair River Bed Morphology

(b) Distribution of main types of morphology



(c) Overlay of morphological zones



Note on Figures 4-15b and c: Transverse forms in thalweg: 1 (Yellow): flow transverse bedforms; 2 (sky blue): bedforms within cohesive/consolidated material; 3 (red): bedforms within consolidated/cohesive material with a veneer of mobile sediment; 4 (black): scour associated with shipwrecks; 5 (white): vegetation.

Source: Identified with the bed substrate classification of Foster and Denny, 2009; Maps from Best *et al.*, 2009.

4.6. FLOW AND BED SHEAR STRESS

4.6.1 Measurements

Assessment of the erodibility of the bed and calculation of sediment transport rates requires knowledge of flow velocity, flow structure and bed shear stress. As part of the Study, the 2008 field surveys in the upper river included detailed measurements of the flow velocity using an acoustic Doppler current profile (ADCP) in 18 cross-sections from the lake, along the upper river to a point about 1 km (0.6 mi) downstream of the Black River (Best *et al.*, 2009). In addition, velocity profiles between the bed and water surface were measured in selected places using a conventional Price flow meter (Krishnappan, 2009).

As flow converges from the lake into the head of the river, flow accelerates, reaching maximum depth-averaged downstream velocity in the constriction at the Blue Water Bridge. Flow then decelerates as the channel widens and turns into the first bend. There is a large recirculation eddy

on the east bank in this bend. Close to the east bank, flow is directed upstream, consistent with sand bedform migration direction in this area. Channel expansion entering the second bend generates a second recirculation zone on the east bank in this area (Figure 4-16). Actual velocities vary over time with variations in discharge. Monthly surveys between November 2007 and June 2008 show mean velocity in three cross-sections in the upper river varying by as much as 0.4 m (1.3 ft) per second (approximately 25 to 30 percent of the mean velocity) in some locations (Krishnappan, 2009).

Calculation of the specific discharge (Figure 4-17) for each panel of the cross-sections (depth-averaged velocity multiplied by flow depth) shows that the flow is concentrated on

the east side of the channel, following the deep trough along the channel at the head of the river and then shifting over toward the west side of the channel before splitting into two flow streams just upstream of the Blue Water Bridge. These two streams persist through the first bend with highest specific discharge near the outside of the first bend, along the west bank. The specific discharge then adjusts as it enters the second bend becoming largest near the outside of the bend, along the east bank.

Secondary (transverse) flow components reflect overall flow channel constriction or expansion (lateral and vertical), curvature, and major topographic features of the bed. The flow at the outlet of Lake Michigan-Huron is mostly two-dimensional (2-D) with a significant secondary

Figure 4-16 Primary (Downstream) Velocity Field in the Upper St. Clair River

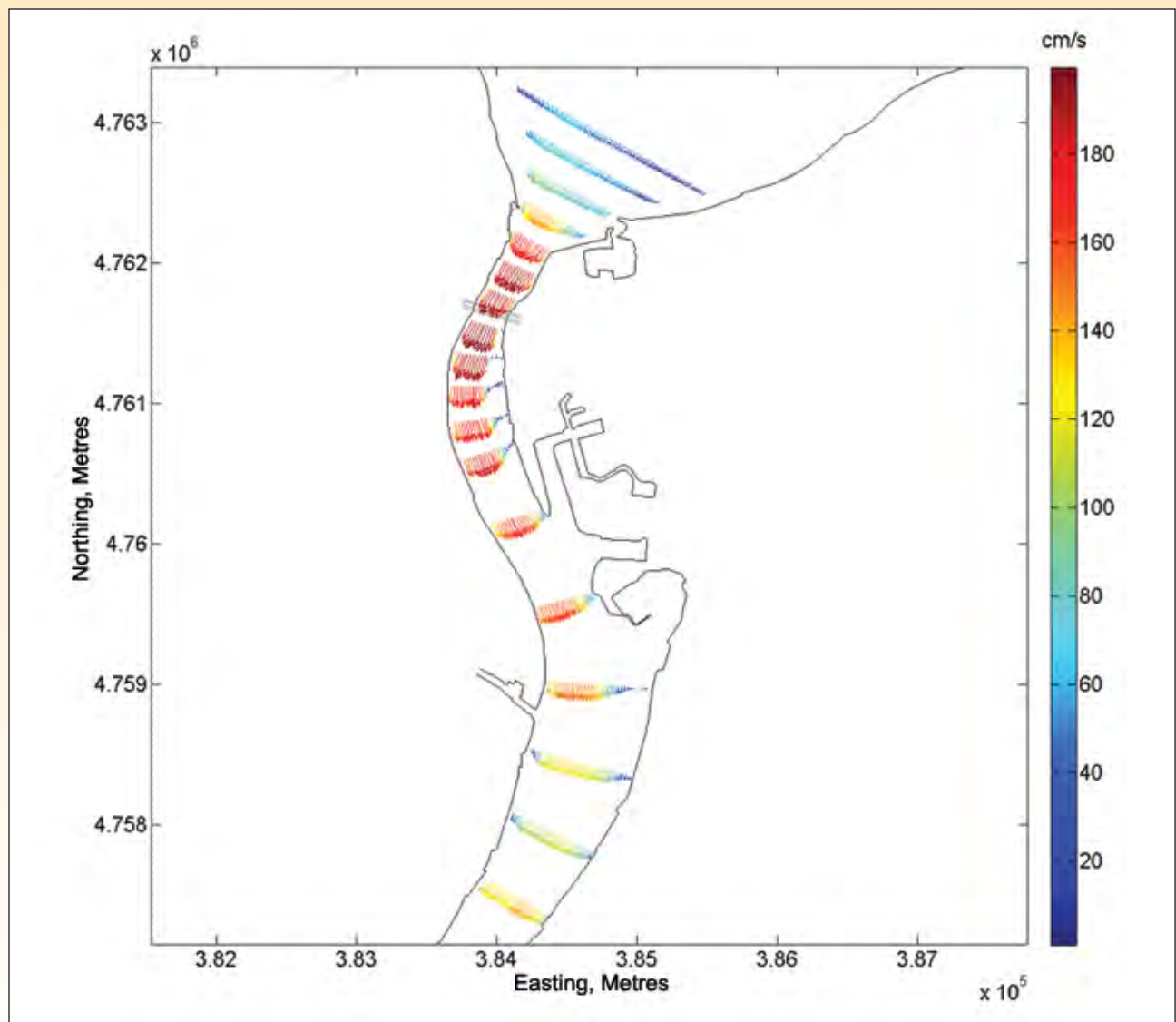
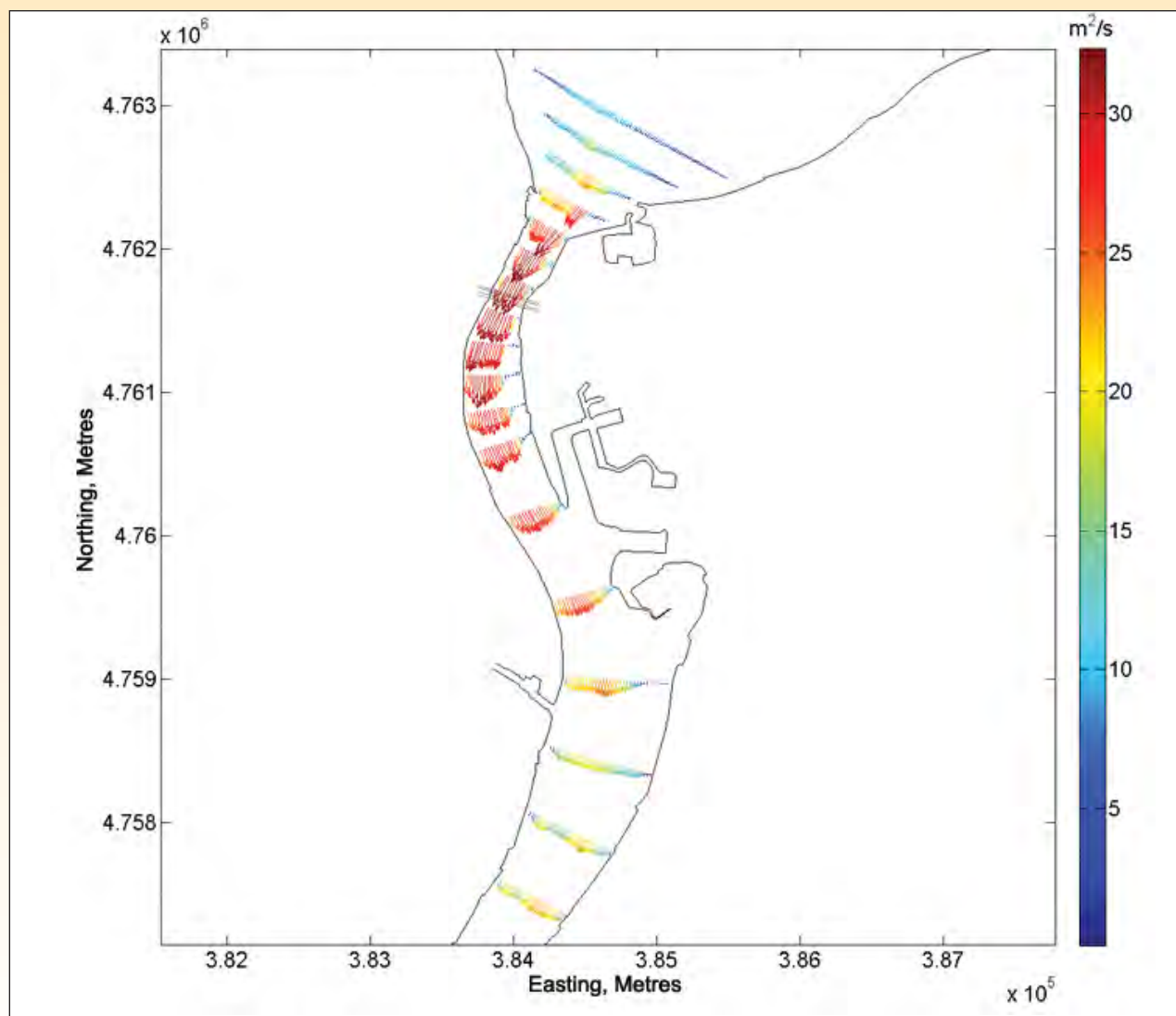


Figure 4-17 Specific Discharge Pattern in the Upper St. Clair River



(transverse) velocity component. The flow converges from Lake Michigan-Huron into the St. Clair River. After the flow passes under the Blue Water Bridge, the channel expands causing a recirculation zone to develop along the east bank. At the first bend, a clockwise rotating secondary flow cell develops in the right side of the cross-section. It drifts towards the centre of the channel downstream, following the thalweg, before gradually dissipating. As the channel straightens, the bed topography (*e.g.*, tongue-like features) forces some secondary flow before the flow enters the second bend, where a second recirculation eddy develops on the east side. A small recirculation zone forms at the confluence with the Black River. Even in areas of strong secondary currents, vertical velocity components are very weak (often less than 1 percent of primary velocity) and seldom impinge on the bed. Large objects on the bed can be seen

to affect the local flow structure. For example, the wreck of the *Fontana* strengthens the lateral and vertical flow vectors close to the wreck and creates a low velocity zone in its wake.

Estimates of bed shear stress in the upper river were calculated from the measured ADCP and velocity profiles measured with Price mechanical current meters. ADCP profiles used the vertically-averaged flow velocity, flow depth and assumed bed roughness length (5 cm or 2 in) across each transect (Best *et al.*, 2009). In the cross-sections in the lake and the head of the river, bed shear stress is on the order of only 1 to 2 Pa¹. This increases through sections 4, 5 and 6, reaching a local maximum of 8 to 13 Pa in section 6. These values are maintained through sections 7, 8 and 9 and then begin to decrease downstream, reaching values of 3 to 4 Pa at sections 16, 17 and 18.

¹ Pa is the abbreviation for Pascals, the common SI unit used to measure stress or pressure.

The velocity profiles measured with a Price current meter (Krishnappan, 2009) yield bed shear stresses similar to those computed from ADCP data. At the entrance to the river (Sarnia Water Works), shear stress maximum averaged about 8 Pa (though a few instantaneous values are higher than this). Further downstream, near the Sarnia Marina (the Duane section), shear stress drops to an average of 2 to 6 Pa. This reduces to an average of 2 to 3 Pa near Port Lambton.

As a point of reference and context, the median size of bed material in this section is approximately 30 mm (1.2 in). The shear stress that would be required to move this material is approximately 15 Pa (see section 4.7), a figure substantially larger than the bottom shear stress measured at the various cross-sections during average flow conditions. However, higher discharge flow volumes could generate higher velocities and bottom shear stresses capable of moving some of the coarse bed material.

4.6.2 Modelling Results

Bed shear stress was also calculated using a calibrated, 2-D depth-averaged hydrodynamic model, HydroSed2D (Liu and Parker, 2009) with sediment transport (Liu and García,

2008). The model is based on the shallow water equations. The hydrodynamic component of the code uses a quad-3-D grid structure, and has been used in many engineering applications, including scour due to levee breaching in the Yellow River, China. The capabilities of the hydrodynamic code were extended to handle sediment transport, both in suspension and as bed load, armouring of gravel beds, and morphological changes due to sediment erosion and deposition. HydroSed2D was developed for unstructured computational meshes, thus facilitating its application to complicated domains. The Godunov scheme is used to solve the governing equations. (See Liu, 2008 for more details).

A high quality mesh was generated and the HydroSed2D model was calibrated. The model then was used to investigate the possible causes of changes in conveyance, namely potential changes in bathymetry along the St. Clair River and around Lake Michigan-Huron's outlet alignment (Liu and Parker, 2009). Bathymetric data from year 1971 to 2008 were used. The output from the model is a continuous map of bottom shear stress, at the mesh resolution of the model, for the upper river and the entire length of the river, over a range of discharges. The model uses a resistance formulation (Manning-Strickler) based on particle-scale bed roughness (Liu and Parker, 2009).

Figure 4-18 Results from HydroSed2D Computational Model of Bed Shear Stress

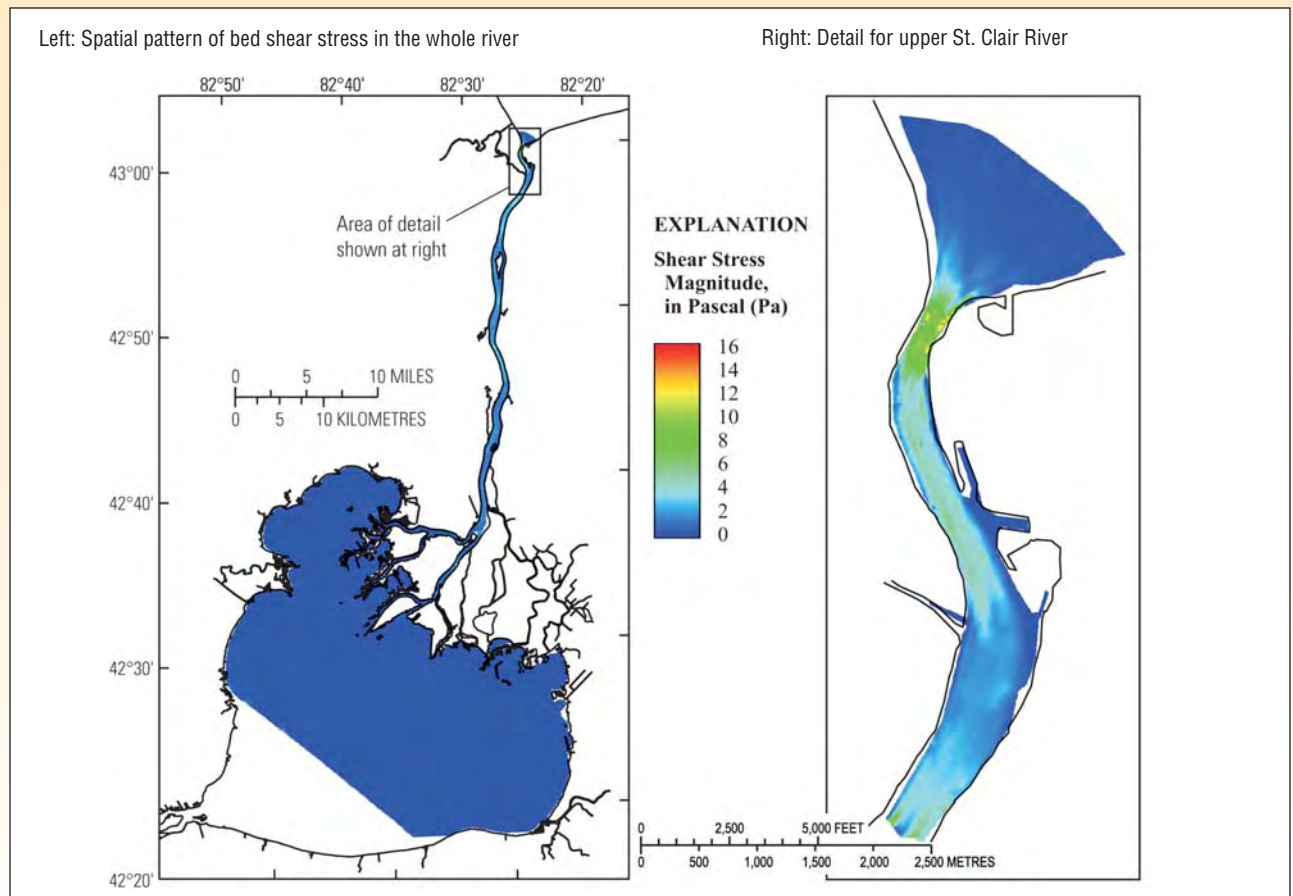
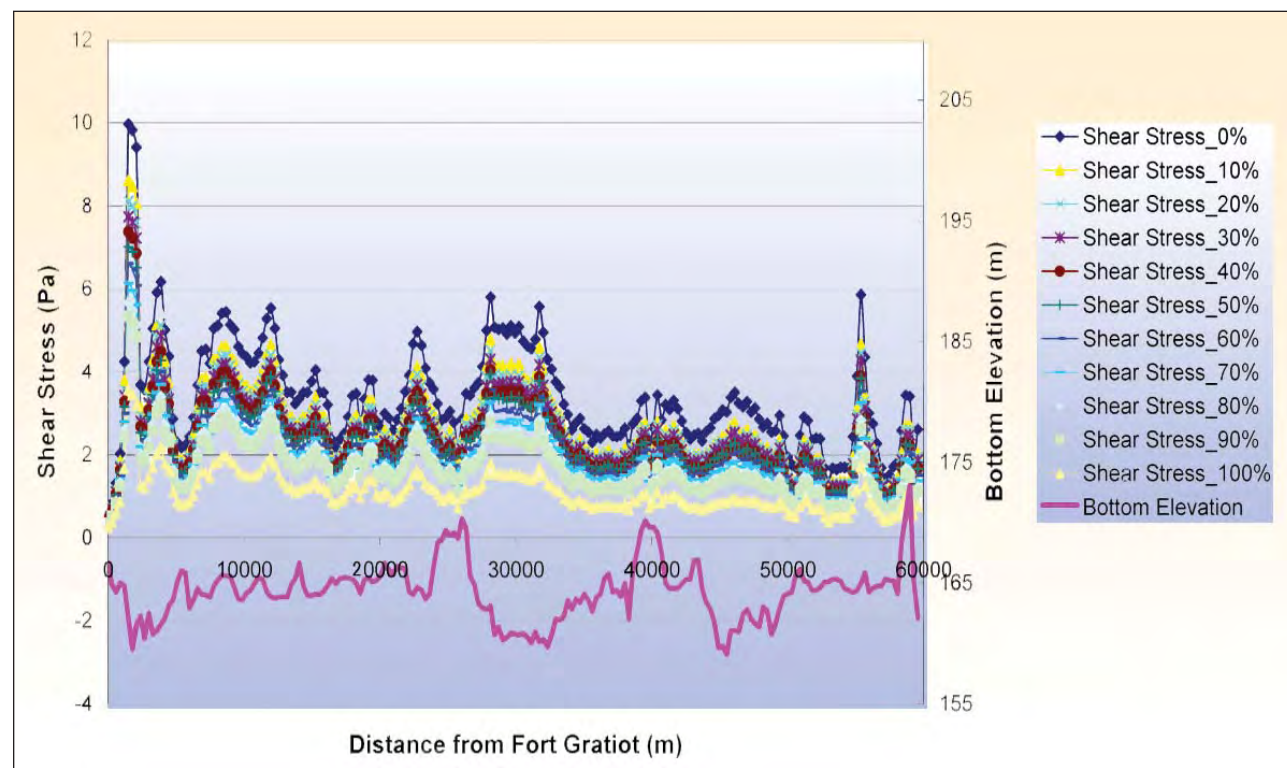


Figure 4-19 Downstream Variation of Bed Shear Stress along Centre of Channel
(at various discharges, calculated from HydroSed2D model)



The results show that maximum bed shear stress occurs in the upper river in the constricted sections upstream and downstream of the Blue Water Bridge. In this area, shear stress reaches a maximum of about 10 Pa (Figure 4-18). Along the rest of the upper river bed shear stress seldom exceeds 6 Pa, while in the lower river it is typically 2 to 3 Pa (Figures 4-18, 4-19). The results are consistent with values estimated from a simple calculation using overall river slope and average flow depth, and with the bed shear stresses computed from ADCP data. Additional computations of open water conditions as part of ice jam modelling (Kolerski and Shen, 2009) using the DynaRICE model produced almost identical patterns and magnitudes of bed shear stress along the river.

HydroSed2D is a 2-D model. As with all other 2-D models (see Chapter 5), it has its limitations in the sense that the model computes depth-averaged flow velocities and does not take into account vertical variations in the velocity distribution in both the downstream and cross-stream flow directions. The major assumption here is that the vertical pressure distribution is hydrostatic. The St. Clair River is very shallow, having a width to depth ratio of about 40. Thus the shallow water equations are generally valid. However, at some local areas, such as the first two bends near the inlet by Lake Michigan-Huron,

the effects of local features (*e.g.*, secondary flow in the bends, the two tongue-like features) can accelerate the flow. This acceleration thus induces a deviation from the hydrostatic pressure distribution condition implicit in the shallow water equations solved by the model.

To determine whether the HydroSed2D model gives a relatively accurate description of flow structure in the upper river, fully 3-D simulations were conducted at the University of Illinois as part of an independent research effort. The specific purpose of this exercise was to verify that the bottom shear stresses in the first two bends given by the 2-D model were in the appropriate range. To this end, Liu and Parker (2009) undertook 3-D computational tests with the open source CFD (computational fluid dynamics) code OpenFOAM v1.5 (OpenCFD, 2008). OpenFOAM is primarily designed for problems in continuum mechanics. It provides a fundamental platform on which to solve fluid mechanics problems. The core of the code is the finite volume discretization of the governing equations. Due to limitations of time and computational resources, only the Lake Michigan-Huron outlet area and the first two bends were included in the 3-D simulations. The bathymetry used was from the 2008 multi-beam data (Best *et al.*, 2009) (Figures 4-9 and 4-10) obtained as part of the Study. The computational domain was about 8 km

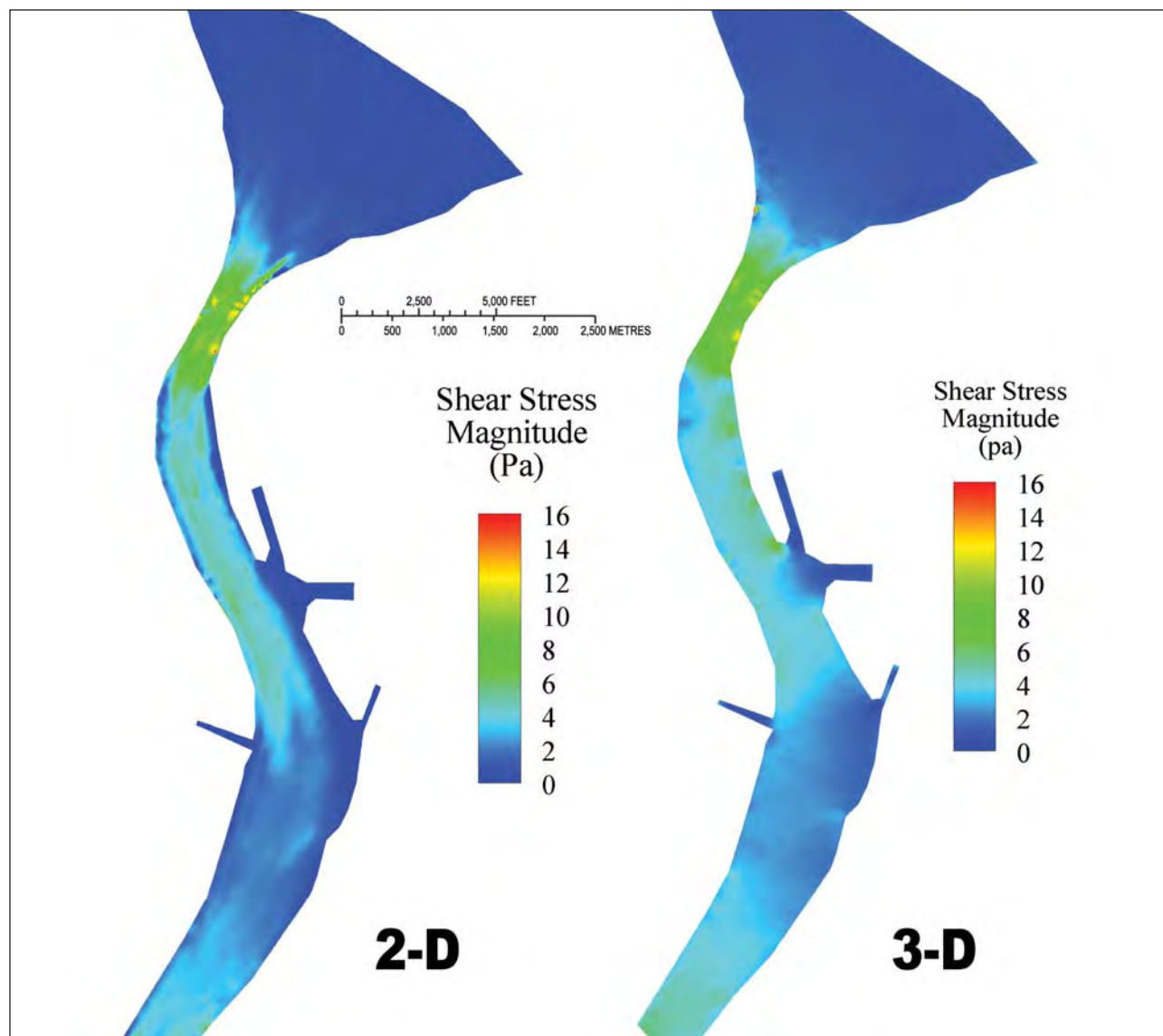
(5 mi) long and the computational mesh had around 1.5 million cells. The turbulence closure used in the model was the standard $k-\epsilon$ model (Rodi, 1983). More than 24 hours are needed for the model to reach steady state in an eight-node computer cluster.

The comparison of the bed shear stresses computed with the 2-D and 3-D models is shown in Figure 4-20. Although an exact match of the bottom shear stresses computed with the models is not possible, the basic patterns of the bottom shear stress distribution predicted by both models agree fairly well. The output map of bed shear stress in the upper 8 km (5 mi) of river predicted with the 3-D model showed an almost identical pattern and range of values as the one obtained with HydroSed2D calculations. For both models, the maximum shear stress is located at the Lake Michigan-Huron outlet area, where the

channel has a minimum width, while low shear stresses are observed in the second bend. The magnitude of the computed shear stresses also agree well, which means the roughness coefficient used (Manning-Strickler) and the flow velocity magnitude computed by the 2-D model are in the right range. Based on these comparisons, the HydroSed2D model can be expected to provide reliable estimates of the flow velocity, flow depth and bottom shear stress distribution along the whole length of the St. Clair River.

HydroSed2D was also used to assess the possible influence of changes in bathymetry at the head of the river due to excavation of the navigation channel in the lake. Results showed no apparent effects on either the spatial flow pattern or the values of velocity and bed shear in the upper river (Liu and Parker, 2009).

Figure 4-20 Comparison of Bed Shear Stress Distribution



4.7 BED MOBILITY

The potential for erosion of the river bed can be assessed using observed bed material information, bed topography and measured and modelled bed shear stress. The erodibility of non-cohesive, granular river bed material is normally determined by measuring particle diameter (an index of particle volume and mass) of individual particles. There are well-defined relationships, verified experimentally, for the critical, threshold shear stress needed to move particles of a given size. In general, critical shear stress varies directly with particle diameter. Using a very conservative (absolute lower limit for movement) estimate, the critical shear stress for 2, 8, 32, and 64 mm (0.08, 0.31, 1.3 and 2.5 in) particle diameter is 0.7, 3.5, 15 and 60 Pa respectively (Liu and Parker, 2009). In gravel deposits with a range of particle size, the median particle diameter is a good index of the maximum particle size that can be moved by the flow (because smaller particles are sheltered by the larger ones).

Given the known shear stresses and size of sediment in the river channel, it is possible to estimate where the river bed is potentially erodible. Flow entering the river from Lake Michigan-Huron is capable of transporting particles no larger than 5 mm (0.2 in) in diameter. Particle size capable of being transported increases to about 10 mm (0.4 in) as the flow constricts at the river entrance (Best *et al.*, 2009). In the upper river, most of the width of the river is covered with coarse gravel (see section 4.2), with median particle diameter typically in the range of 20 to 40 mm (0.8 to 1.6 in).

In general, given the measured and calculated bed shear stresses in the river, none of this material can be moved by the average flow in the St. Clair River, and in many cases bed shear stress is less than half of that needed to move the material (Liu and Parker, 2009; Krishnappan, 2009). The presence of vegetation in some areas reinforces this inference. However, in areas of sandy bed material along the channel margin in the upper river, shear stress is sufficient to move the bed material. This is confirmed by video observations of active small-scale ripples and swath bathymetry showing active, low amplitude dunes. In the lower river, the centre of the channel often has 15 to 25 mm (0.6 to 1 in) gravel on the bed, and the typical shear stress of 2 to 3 Pa is also less than half that needed to entrain this material. Given these bed shear stresses, the maximum size of particle that could be moved by the flow in the centre of the channel along much of the lower river is about 2 to 4 mm (0.08 to 0.15 in). However, it should be noted that shear stresses do increase under high flow conditions and under ice jams, and these may be the episodic events that contribute to sporadic erosion.

Along the entire river, the maximum shear stresses are capable of transporting sand-size particles in the centre of the channel and, in some places along the channel margins. It seems likely that there is a continuous, low level, flux of sand along the channel that accounts for deposition in the delta channels (see below).

The critical shear stress of cohesive material is not as well known. Thus, the erodibility of exposed clay till in the river bed (*e.g.*, in the upper river) is less certain. A sample of the till was obtained from the river near the Sun Oil refinery and erodibility tests were conducted with the till sample in a small flume at Ven Te Chow Hydrosystems Laboratory at the University of Illinois (Mier and Garcia, 2009). After several preliminary experiments, the conditions for initiation of motion (*i.e.*, erosion) of the fine-grained matrix of the till sample were achieved. The experiment was repeated twice and measurements of the vertical velocity profile under eroding conditions were made in two locations using a laser Doppler velocimeter (LDV), with excellent repeatability of the results. Results showed that till began to erode at shear stresses of about 4.2 Pa. Assuming that this is representative of other areas of till, it is possible that some scour of exposed till could occur in this area (along with possible abrasion by suspended particles) under normal flows. Thus, the apparent erosion of the bed (based on evidence from bathymetric change maps and occurrence of erosional grooves) could be attributed to natural erosion, but this seems to be occurring only in this one area of the river bed. It is possible that erosion here is also accelerated by ship effects (see below).

4.8 SEDIMENT TRANSPORT RATE

In the absence of entrainment of bed material larger than sand particles, the bed load of the river is negligible (Liu and Parker, 2009), except in areas of sandy bed. Direct observations of bed load transport confirm this finding (Krishnappan, 2009). Measurements by Duane in 1967 (see Krishnappan, 2009) in a cross-section at the Bay Point Light (just upstream of the mouth of the Black River and the Sarnia Marina), where bed material ranged from granules (near the Canadian shore) to gravel and cobbles (on the U.S. side), showed that bed load was all very fine sand and that the loads were typically only a few metric tonnes (mt) a day². Subsequent bed load measurements by Lau and Krishnappan (1987) in the same area, and at Port Lambton, also found extremely low bed load transport rates. In 2008, measurements were made at the Duane section, in the sections downriver from those measured by Lau and Krishnappan in 1987, and at two

2 one metric tonne is about 1.1 short tons

additional sections in the upper river near the Point Edward Casino and near the Sarnia Water Works at the head of the river. Bed load was measured in the centre of the channel and halfway to each bank in January, April and June 2008. The bed load sampler also had an attached video camera to monitor sediment movement near the sampler. Measured bed load was essentially zero, except for fine organic and shell debris and some very fine mineral particles that entered the sampler in some cases.

The HydroSed2D model results for bed load transport also show that the gravel load is practically zero at all transects along the river for which calculations were made. There is a possibility of local, clear water scour in some areas, however, there is no general movement of gravel in the river that could cause widespread, measurable changes in bed elevation and channel morphology. On top of the gravel tongue-like features in the upper river, shear stresses may be just sufficient to move bed material and produce a local bed load flux of the order of 1 mt (1.1 tons) a year – enough to cause some minor modification of the morphology with gravel movement on the upper surface and deposition on the downstream face. This is consistent with the appearance of gravel bedforms in this area (Best *et al.*, 2009) and with its observed down-channel migration, but there is the possibility that movement is also aided by ship effects (*i.e.*, increased shear stress due to propeller wash) on the bed (see below).

Sand covers a significant portion of the river bed, and is concentrated in bands along the channel margins, especially in the lower river. Based on grab samples at various locations, the sand has a D_{50} ranging from 0.35 to 0.57 mm (0.014 to 0.022 in) in the patches in the upper river. In the middle reach of the river, the sand has a D_{50} of about 0.2 to 0.3 mm (0.008 to 0.012 in). Very fine sand with D_{50} of 0.05 to 0.08 mm (0.002 to 0.003 in) has been retrieved from the downstream section.

This is consistent with the general downstream fining trend of typical river systems. Calculations of sand transport were based on two typical sand sizes (0.5 mm and 1 mm) (0.02 and 0.04 in). Underwater video transects were used to identify, for three cross-sections (one each in upper, middle and lower river), the proportion of the river bed with sand cover. Sand cover in these three sections was 12 percent, 32 percent and 50 percent, respectively. Shear stresses covering the full range of the flow duration curve were generated by HydroSed2D and used to compute sand loads. Computed annual loads are of the order of 1 million mt (1.1 million tons) a year. The method is not sufficiently accurate (because of uncertainty in particle size and sand coverage) to distinguish any clear downstream trend in average sediment load based on the sand budget. As a result, the method is not able to support a conclusion regarding net degradation or erosion. The

derived load is actually higher than that measured by direct sampling (Krishnappan, 2009) but is still extremely low. Given that the river bed is only partially sand-covered, the sand load is obviously below capacity for the river (Liu and Parker, 2009). Nevertheless, the findings suggest that some redistribution of sand along the river is possible over a period of years.

Suspended sediment in the river mostly enters the river from the lake, rather than being suspended from the river bed. There is also a contribution (perhaps 10 percent) from tributaries along the river. Concentrations and loads are generally low but vary considerably between sample dates, apparently because of weather conditions and suspension of fine sediment in the lake (Best *et al.*, 2009; Krishnappan, 2009). Suspended sediment enters the river along the lakeshore and follows both banks of the river with some lateral dispersion in the upper river, where suspended sediment is advected and diffused away from the banks by secondary flows (*e.g.*, on the outside of the first bend downstream of Blue Water Bridge), and gradually dispersed away from the banks downstream from the lake (Best *et al.*, 2009). Suspended sediment concentrations are also high over some of the areas of transverse bedforms, where upward diffusion is related to additional turbulence and ensuing entrainment generated by the bedforms.

In the upper river, measured suspended sediment concentrations are highest along the Canadian shore in the recirculation zone near the Point Edward Casino. At this location, a maximum concentration of about 100 mg/l was measured in November 2007. Other anomalously high concentrations were also measured at the other cross-sections in November 2007. On the other eight measurement days between November 2007 and September 2008, concentrations in this section were typically less than 10 mg/l. At the other sampling sections along the river, concentrations were also almost always less than 10 mg/l. This latter measurement is consistent with data collected for the USACE in 2004 and 2005 showing depth-averaged suspended sediment concentrations of less than 10 mg/l in almost all cases (Lakeshore Engineering Services, 2005, 2007). High concentrations can be associated with recent storm events over the lake. Suspended material was mainly very fine silt moving down the river as wash load. Suspended sediment loads were generally less than 10,000 mt (11,000 tons) a day, and in many cases only 1,000 to 2,000 mt (1,100 to 2,200 tons) a day or lower. Suspended loads were lower than those measured by Duane in 1967, though Duane's loads were no more than 10,000 mt (11,000 tons) a day, so that values were still comparable with, and within the range of variation of, measurements for this Study. The same is true for the Lau and Krishnappan measurements conducted in 1987.

4.9 RECONCILING BED MORPHOLOGY, BATHYMETRIC CHANGES AND SEDIMENT TRANSPORT OBSERVATIONS

Studies of bed erodibility and sediment transport indicate that there is currently no general movement of bed material in the river, negligible bed load (gravel and sand) and very small suspended sediment load that is mostly supplied by wave action in Lake Michigan-Huron. The analysis suggests that limited, local bed erosion is possible in some areas, and that this erosion, along with transport and accumulation of fine sand, could account for small areas of bed elevation change seen in bathymetric comparisons between 2002 and 2007-2008. This finding is consistent with the absence of widespread, measurable bed erosion and small (relative to measurement error) volumes of net erosion and deposition in the upper reach of the river and elsewhere.

Areas of bed elevation change that appear in the upper river include: deposition in the flow recirculation area near the Point Edward Casino on the Canadian shore; advancement of the downstream edge of one of the gravel tongue-like features in the centre of the channel; and apparent bed lowering (on an average of perhaps 10 to 20 cm [3.9 to 7.8 in] a year since 2002) of one area of exposed till in the upper river near the Black River confluence. All of these changes can be explained with the known shear stresses, flow pattern and bed material of the river. However, the appearance of flow transverse bedforms, which show evidence of slow migration, in some areas of the bed in the upper river, is at odds with some of these observations. In the upper river, bed shear stresses are generally well below the threshold, and, except in the sandy areas, are only locally even close to the threshold needed to move the material. Yet these bedforms do not appear to be relict and show signs in bathymetric comparison, and from their morphology, of being active under present-day flow conditions.

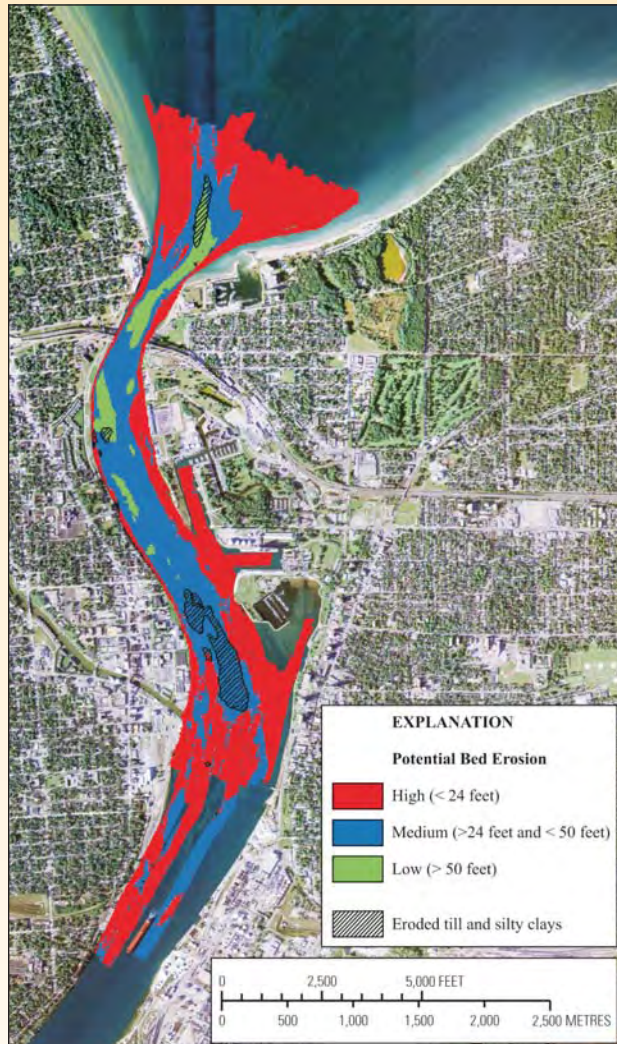
One possible explanation of this paradox of bedforms occurring in non-erodible (or marginally mobile) bed material is that the shallower areas of the upper river, and considerable lengths of the lower river, are subject to the effects of large ship passage. Deep draft (> 7.3 m [24 ft]) vessels navigate the river throughout the open water season and account for about 30 percent of all traffic (Giovannetone and Stakhiv, 2009). Although number of vessel trips has declined slightly in recent years, there has been a small increase in the proportion of tonnage carried by deep-draft vessels. Given that the total number of vessel trips is about 4,000 per year, the number of deep-draft vessel trips exceeds 1,500 per year. In some shallower parts of the lower river, this may result in the channel essentially being self-maintained by ship passage (Giovannetone and Stakhiv, 2009).

Previous studies suggest that turbulence caused by “propeller wash” from vessels with 7.6 m (25 ft) draft may cause significant bed velocity increases for depths less than twice the draft of the vessel (Wuebben *et al.*, 1984). Even this very approximate criterion indicates that much of the bed of the St. Clair River could be subject to significantly elevated bed velocity and bed shear stress from propeller wash, displacement and wave effects. The exceptions are mainly the deep pools in the upper river (Figure 4-21a). In general, up-bound ships are likely to create larger effects, because the vessel’s propeller thrust works with the river current rather than against it. Consequently, it is likely that there would be net down-channel motion of sediment, possibly at intensities sufficient to create the bedforms observed. The fact that wave-like bedforms also occur in the navigation channel in the lake and in the lower river, where shear stresses are generally extremely low, suggests that ship effects are a significant factor. Preliminary estimates are that normally-immobile coarse gravel might be moved by such effects (Liu and Parker, 2009), because ship passage could temporarily elevate bed shear stress by a factor of 1.5 to 3 times the normal values (Ye and McCorquodale, 1997; Garcia *et al.*, 1999; Waters 2009). Overlaying the Wuebben *et al.*, (1984) criterion for depth on the known substrate and bed morphology shows that most areas of flow transverse bedforms and of erosional forms in cohesive bed material occur in depths at medium or high risk of erosion from ship effects (Figure 4-21b). Therefore, there is potential for ship passage to temporarily disturb some areas of the bed sufficient to account for very low intensity bed material transport in some areas of the river, and this is the likeliest explanation for local bed changes and some of the bedforms observed in the river.

Investigators had believed that acoustic measurements in a ship’s wake might show the occurrence of sediment suspension caused by ship passage (Best *et al.*, 2009). However, while the test did clearly show the propeller wash reaching the river bed, the results indicated that it is difficult to directly measure suspension of bed material by ships using this instrumentation. Nevertheless, there is certainly an accumulation of evidence pointing to ship effects as an explanation for the observed (low intensity) bed material movement, bedform development and bed elevation changes (since 2002) in the upper river, as these effects are unlikely to result from the natural flow alone and there has been very little dredging in this area since 1962, except around the Black River (Giovannetone, 2009). Direct observation (video and velocity data) at the river bed during ship passage would be needed to analyze ship effects on sediment movement and bed erosion. However, while the potential certainly exists, a detailed investigation of the effects of ship passage has not been undertaken. The size and number of the vessels navigating the St. Clair River

Figure 4-21 Potential Bed Erosion

(a) Map of regions of potential bed erosion due to propeller-induced erosion

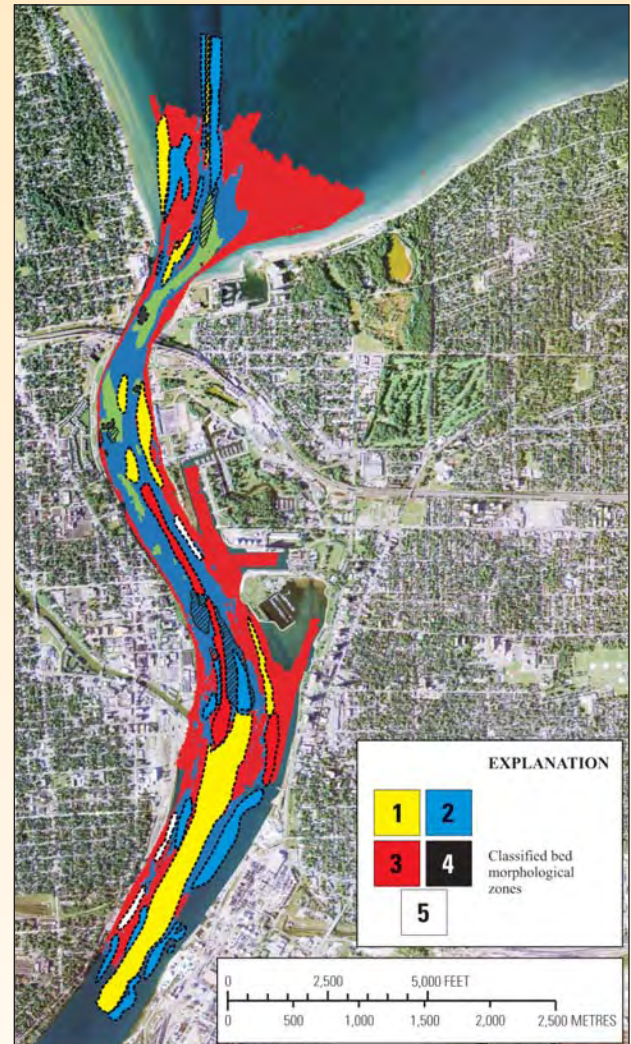


This map is based on the earlier analysis of Wuebben *et al.*, (1984) that defines the erosion risk dependent on flow depth, with the risk being high at depths <10.2 m (34ft) and low > 15 m (50 ft). This map defines three regions of risk (flow depths):

- high (red) <7.3 m (24 ft)
- medium (blue) > 2.2 m (7.3ft) <15 m (50 ft)
- low (green) >15 m (50 ft).

The areas of eroded till and silty clays are marked by the cross-hatched fill.

(b) Overlay map of (a) with classified morphological regions



The morphological regions are given by the colors in boxes 1-5, and the perimeter of their extent in different areas is denoted by a dotted line margin.

- 1 (Yellow): flow transverse bedforms
- 2 (sky blue): bedforms within cohesive and/ or consolidated material
- 3 (red): bedforms within consolidated/cohesive material with a veneer of mobile sediment
- 4 (black): scour associated with shipwrecks;
- 5 (white): vegetation.

suggests that ship-induced sediment erosion and transport could be important, deserving further consideration in future studies (Admiraal and Garcia, 1999; Waters 2009).

In the lower river, there is some evidence of bathymetric change between 1971 and 2000. This is likely to be the combined effect of maintenance dredging, local movement of finer-grained sediment under natural flows and ship effects.

It is also possible that ice jams may periodically affect bed erosion and sediment transport. The St. Clair River is subject to only occasional ice jams, though it is known that a significant ice jam occurred on the lower river in April 1984 (see Chapter 5). In general, ice jams tend to reduce sediment transport, except during the break-up of the jam. The discharge surge and flow acceleration resulting from release of the dammed water during break-up may cause short-term increases in bed shear stress, and hence sediment transport (Liu and Parker, 2009). Measurements in 1984 indicated that velocities in some areas were, for a short time, increased by up to 1 m (3.3 ft) a second. The associated increase in bed shear stresses may have been enough to erode a normally stable bed. Numerical modelling results (Kolerski and Shen, 2009) showed that bed shear stress along the river changed very little during ice jam formation (in many cases shear stresses decreased), though the shear stress may have been elevated for a few days during ice jam release. These increases are calculated to be a maximum of 1 to 2 Pa, which may have been sufficient to temporarily raise sediment transport rates in some of the fine-grained sediment in the middle and lower river, but would have had negligible effect in the gravel-cobble bed of the upper river. This range of shear stress change is of the same order as that due to natural variation in flow rates in the river (Liu and Parker, 2009).

4.10 CONCLUSIONS OF DATA ANALYSIS AND MODELLING

An understanding of the sediment regime of the St. Clair River is a vital first step in addressing the Study's central question of what factors are responsible for the lake-to-lake fall between Lake Michigan-Huron and Lake Erie. The Study's data analyses and modelling have significantly improved understanding of the sediment regime. This section summarizes the scientific findings of this work.

The St. Clair River is underlain by a substantial layer of glacial till and, in the upper river, by fluvio-glacial gravel and sand, from which the river bottom material is derived. Most of the upper river has a bed of medium to coarse gravel, with local, superficial sand deposits overlying the till. There is local exposure of till in places, especially just upstream of the mouth of the Black River. The lower river mostly has a thin veneer of gravel and sand overlying till.

The bed of the St. Clair River has not undergone any significant, general erosion since at least 2000. The river is not physically able to cause general bed erosion anywhere along its length. Total survey precision is plus or minus about 0.2 m vertically, even for contemporary survey technology. Estimates of net erosion and deposition volumes for all time periods are less than the precision of the survey. Local, isolated, ephemeral scour and deposition occur, but overall the river bed is stable (no progressive bed lowering), except for localized areas where clay till is exposed to the flow. These localized areas could experience erosion should the bottom shear stresses exceed a critical value of about 4.2 Pa.

Assessment of historical changes in river bed morphology is complicated by differences in survey methods, point density and reporting. Some significant change is apparent since 1971 on individual cross-sections, particularly in the upper river. However, there is considerable uncertainty about the extent and reliability of these 1971 data. For example, deep areas in the upper river present in both earlier and more recent surveys do not appear in the 1971 survey.

None of the measured volumetric change (erosion volume and deposition volume) was greater than the estimated error in cut-and-fill volume. This was the case even for the apparently large volumes of cut-and-fill between 1971 and 2000, and between 1971 and the multi-beam surveys. These large volumes may occur partly because of some apparent systematic negative bias in the 1971 survey. No clear pattern or trend of volumetric change (net total erosion or deposition) emerged from this analysis. Particular areas of the bed often switch from erosion to deposition between surveys.

Measurements and computational hydrodynamic modelling yield consistent estimates of bed shear stresses for normal river flow conditions. Tests with a 3-D computational model in the upper river show negligible differences from shear stresses inferred from the 2-D model.

Bed load transport is negligible because much of the upper river bed is comprised of coarse gravel requiring critical shear stresses higher than those occurring under the normal range of flow conditions. In the lower river, shear stresses are so small (<2 Pa) that only sand can be moved, and even then, the sand load is very small. The thalweg of the channel in most places in the lower river is fine to medium gravel.

This minimal bed load transport is consistent with bathymetric change since 2002 that reveals no general bed lowering and only a few isolated areas of persistent bed elevation change (both erosional and depositional) in the upper river. Overall, volumes of erosion and deposition are less than those due to survey error. Therefore, the Study concludes that there has been no significant net erosion (or deposition) in the upper river since 2002. It is difficult to draw any reliable conclusions about changes between the 1971 survey and the present day.

Major ice jams, such as the one experienced in the spring of 1984, have the potential to cause morphological change in the lower St. Clair River, where the shear stresses required to erode the bed are much lower. However, modelling of the 1984 event undertaken by the Study suggests that the ice jam breakup likely was not the major factor in changing the river bed. The release of the ice jam may have elevated the shear stress for a few days, possibly temporarily raising sediment transport rates in some of the fine-grained sediment in the middle and lower river. But the temporary increase in shear stress would have had negligible effect in the gravel-cobble bed of the upper river.

There are active flow transverse bedforms in some parts of the river, which is inconsistent with the general lack of mobility of the bed sediment. It is hypothesised that ship effects, particularly turbulence caused by “propeller wash”, have a significant role that requires further investigation. These navigation effects could result in cumulative effects on sediment transport and bed morphology over time, and deserve further study.

4.11 KEY POINTS

With respect to the primary science question regarding the St. Clair River sediment regime, the following significant points can be made on the basis of the analyses summarized in this Chapter:

- ▶ The bed of the St. Clair River has not undergone any significant, general erosion since at least 2000. Results of an earlier survey in 1971 had suggested that there was erosion throughout the river. But there are questions about the quality of data obtained in this earlier survey. Based on the results of more recent surveys, the Study found that there has been no significant erosion of the channel in the upper reach of the St. Clair River bed since at least 2000. Estimates of net erosion and deposition volumes for all time periods are less than the precision of the survey. Local, isolated, ephemeral scour and deposition occur, but overall the river bed is stable.
- ▶ Bottom shear stresses, based on the HydroSed2D and direct measurement, were determined to be insufficient to erode the bed material along the thalweg and most other areas of the river bed.
- ▶ Ship navigation effects, such as propeller wash, are the most plausible explanation of some of the active bedforms and low level bed material flux in the river, and require further investigation.
- ▶ While ice jams can affect a river’s morphology, the record St. Clair River ice jam of 1984 may not have had a major affect on the river bed, especially in the upper reach of the river.
- ▶ The Study’s approach to addressing the St. Clair River sediment regime was independently peer-reviewed. Peer reviewers confirmed the validity of the Study’s data analysis and findings, and made a number of specific suggestions for refinement, which the Study subsequently adopted.

CHAPTER 5

ST. CLAIR RIVER HYDRAULIC REGIME

Chapter 5 summarizes and integrates the findings of the various hydraulic modelling, water level gauge analyses, discharge measurements and bathymetric surveys conducted by the Study to assess whether conveyance has changed in the St. Clair River, establish when this change occurred, and determine the causes of any change.

5.1 INTRODUCTION

5.1.1 Science Questions

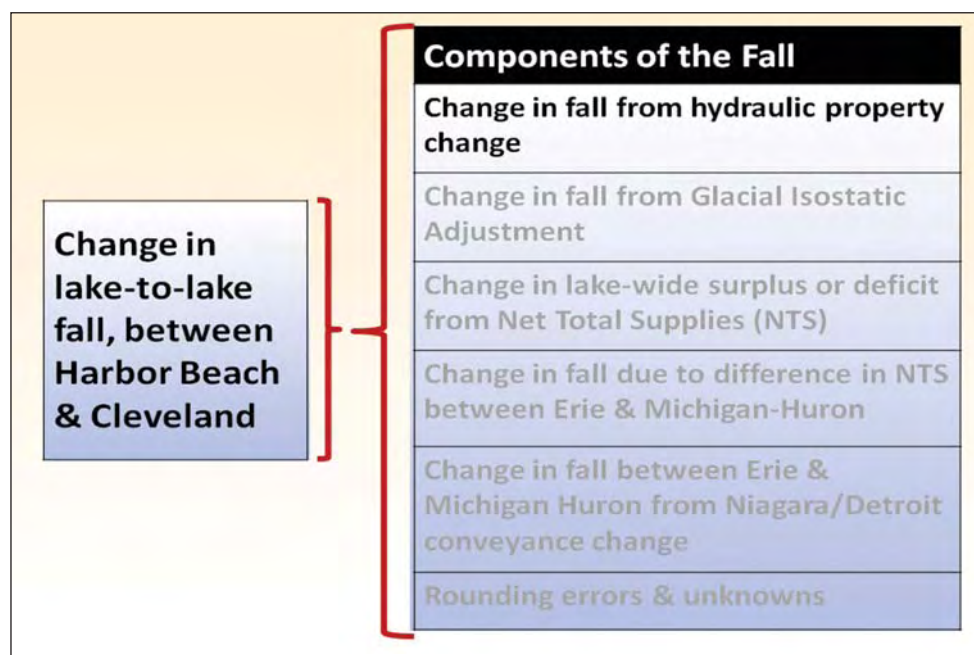
The conveyance of the St. Clair River is influenced by hydraulic properties, which can be estimated through a combination of physical measurements and analytical models. Manning's equation is one of the fundamental relationships in hydraulics that is used to illustrate the key properties of conveyance and to guide the investigations into whether the St. Clair River hydraulic regime has changed since the last major deepening of the navigation channel by dredging of the river, which was completed in 1962.

The primary and secondary science questions addressed with respect to the St. Clair River hydraulic regime are (see Figure 5-1):

What is causing the declining head difference between Lake Michigan-Huron and Lake Erie?

- ▶ Has the conveyance of the St. Clair River changed since 1962?
- ▶ If the conveyance has changed, what were the causes?

Figure 5-1 Study Approach: What factors are responsible for the change in lake-to-lake fall?



Chapter 3 described in detail the Study's strategy to address the conveyance issue. The key science question of whether conveyance has changed can be addressed by undertaking and comparing the results of a number of analytical approaches. This strategy of cross-comparisons of results from different analytical perspectives was reviewed and endorsed by the independent peer review group (Moin, 2008). Elements of the strategy are discussed in this Chapter, and include:

- application of a number of one-dimensional (1-D) and two-dimensional (2-D) hydraulic models to determine whether the conveyance has changed;
- hydraulic analysis of the river with the geometric data from different periods to establish both temporal and spatial conveyance changes;
- analysis and reconciliation of flow rating curves from different eras to explain changes;
- analysis of hydrometric data to reveal changes in flow for the same water level conditions in different periods; and
- normalizing various modelling results by developing Hydraulic Performance Graphs (HPGs) from the models to display changes in conveyance.

5.1.2 St. Clair River Hydraulic Properties

The St. Clair River is about 63 km (39 mi) in length and extends from Lake Michigan-Huron to Lake St. Clair. Over this distance, the water level falls about 1.5 m (5 ft). The average annual discharge of the river is about 5,150 m³/s (181,900 ft³/s).

The St. Clair River contains three distinct reaches (Figure 5-2). The upper-most reach starts at the outlet from Lake Michigan-Huron and ends at the confluence with the Black River about 5 km (3 mi) below the International Blue Water Bridge. The flow in this reach is complex. As water enters the river, the water surface slope increases and velocities rise to a maximum of about 2 m/s (6.6 ft/s). The river is constricted by the footing of the Blue Water Bridge on the Canadian shore and sheet piling walls on the United States shore. Immediately downstream of the bridge, there is a sharp bend in the river. The high velocity and curvature in this reach create cross-currents and minor vertical velocities near the United States shoreline. In the inside bend on the Canadian side of the river, just downstream of the Blue Water Bridge, there is a large recirculation (eddy) zone where water is stagnant at the boundary with the main channel and moving in the

opposite direction (*i.e.*, downstream to upstream) close to the Canadian shore. In this reach, the channel averages about 450 m (1,500 ft) wide and 16 m (52 ft) deep, with the maximum depth of 23 m (75 ft) occurring just downstream of the bridge. The formation of this deep section has previously been described in relation to the river's sediment regime in Chapter 4.

The middle reach of the St. Clair River starts at the confluence of the Black River and extends downstream to Algonac, where the flow separates into the many channels in the delta. This middle reach is fairly uniform in shape and alignment. The velocities in this reach are lower than in the upper reach, averaging 1.1 m/s (3.6 ft/s), and are largely in the streamwise direction. Horizontal (*i.e.*, lateral or cross-) currents are small, and there is no measurable vertical velocity. The channel is wider here than in the upper reach of the St. Clair River, averaging 650 m (2,100 ft) wide and 13 m (43 ft) deep. There are two small islands in this reach, Stag and Fawn islands, where the flow splits before once again forming a single channel.

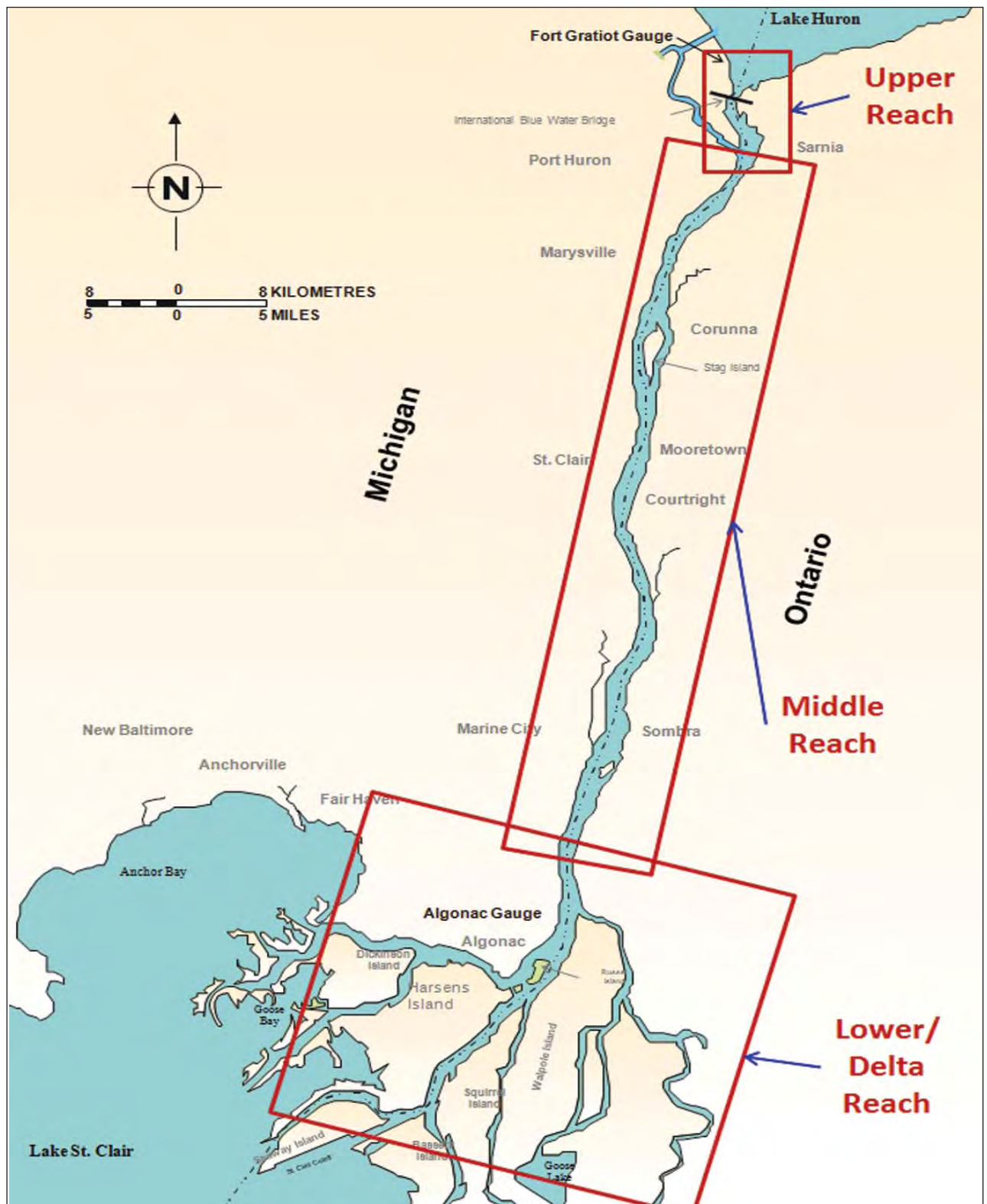
In the lower reach below Algonac, the St. Clair River splits into several channels collectively referred to as the St. Clair River delta. The North Channel of the delta contains the deepest section of the entire St. Clair River, at more than 25 m (82 ft) in depth. The South Channel contains the navigation channel and is maintained at project depth for navigation purposes.

The flow throughout the river is sub-critical, meaning that gravitational force dominates the flow. Froude numbers¹ for the St. Clair River reach a maximum of 0.17, well below a value of 1.0. A Froude number greater than one is necessary for the establishment of a critical flow control section. As a result, no single cross-section controls the rate at which water flows in the river. Rather, the flow in the St. Clair River is controlled by the difference in levels of both Lake Michigan-Huron and Lake St. Clair and the conveyance of the river. There are backwater effects in the St. Clair River from both Lake St. Clair and Lake Erie. That is, the higher the levels of Lake St. Clair and Lake Erie, relative to Lake Michigan-Huron, the smaller the discharge through the St. Clair River. These relationships are depicted in HPGs.

No single cross-section controls the rate at which water flows in the St. Clair River. Rather, the flow is controlled by the difference in levels of both Lake Michigan-Huron and Lake St. Clair and the conveyance of the river.

1 The Froude number establishes the hydraulic conditions of a river and determines whether the flow is sub-critical or supercritical.

Figure 5-2 St. Clair River Reaches



5.2 CONVEYANCE OF THE ST. CLAIR RIVER

This section deals with the basic definition of the term conveyance, its hydraulic meaning and the variety of ways of estimating this important characteristic for the St. Clair River. A brief summary is provided of all the factors that contribute towards the estimation of conveyance. In addition, a description of the techniques and methodologies that were used for calculating the conveyance of the St. Clair River is provided.

5.2.1 Factors Contributing to the Conveyance of the St. Clair River

The factors contributing to the conveyance of the St. Clair River can be described using the well known Manning's equation for steady uniform flow in open channels (Chow, 1959). While the flow in the St. Clair River is neither steady nor uniform, understanding the factors that contribute to the conveyance is easily illustrated using this equation. The Manning's equation for uniform flow is as follows:

$$Q = \frac{1}{n} A \cdot R^{2/3} \cdot S^{1/2} = K \cdot S^{1/2} \quad (1)$$

Where:

- Q : discharge of the channel (m³/s)
- n : channel roughness;
- A : cross-sectional area at the location of interest (m²)
- R : hydraulic radius (m)
- S : energy slope (m/m)
- K : conveyance (m³/s).

The hydraulic radius is a quantity that relates the cross-sectional area A to the inverse of the wetted perimeter P , which is the perimeter of the flow area in contact with the channel bed and sides. For uniform flow, the assumption is that the energy slope equals the water surface slope, which equals the bed slope (all slopes are parallel). The numerator over the ' n ' is 1.0 only when metric units are used and must take the value of 1.4859 if the conventional (U.S.) units are used.

From Manning's equation, the discharge of a channel is a function of the roughness of the bottom and sides of the channel, geometry (*i.e.*, its cross-sectional area and hydraulic radius), and the energy slope. Fundamentally, the roughness or resistance of the channel is related to the type and size of material on the bottom of the river and to the presence of vegetation and ice cover. The cross-sectional area and hydraulic radius reflect the channel's capacity to

transmit water, with the hydraulic radius changing in the presence of ice cover. The energy slope is related to the difference in water levels at the upstream and downstream boundaries (Lake Michigan-Huron and Lake St. Clair, respectively, for the St. Clair River).

The conveyance in the St. Clair River is more complex than represented by the Manning's equation. The assumption of steady uniform flow does not hold true for the St. Clair River, because the forces acting on the river from the upstream and downstream lakes are constantly changing. These changing forces disturb the energy slope of the river, causing the discharge to change. The forces can change on a short-time scale due to meteorological events or on a long-time scale due to changing net basin supplies (NBS) to the upstream and downstream lakes, and resulting changes in their water levels. The resistance of the channel also can change because of the seasonal growth and decay of weeds and the presence of ice cover on the river in most winter months.

Conveyance

The term "conveyance", in the context of the Study, is a measure of discharge carrying capacity of a channel (after Chow, V.T., 1959). In uniform flow assumptions, it is sufficient to define the conveyance at a *channel cross-section*. On the other hand, when this definition is extended to gradually varied flows under sub-critical regimes, conveyance is defined by the *reach (a linear segment of the channel) properties* rather than the section properties. The reach conveyance is commonly defined as the geometric mean of a number of section conveyances. For this Study, the term "conveyance" is defined to encompass the reach properties.

5.2.2 Determining the Conveyance of the St. Clair River

The conveyance of a river is directly related to the discharge in the river. By rearranging equation 1, conveyance is defined as discharge divided by the square root of the slope. The discharge of a river can be defined as the volume of water passing through a cross-sectional area per unit of time. To determine the discharge in a natural channel requires measured velocity and the area of a cross-section perpendicular to the flow. The measurement of discharge on the St. Clair River can be conducted in several different ways, including from a boat that measures the velocity of the water moving under the boat using either a mechanical Price current meter or through the use of acoustic techniques, such as an Acoustic Doppler Current Profiler (ADCP). The velocity in a natural, unsteady channel like

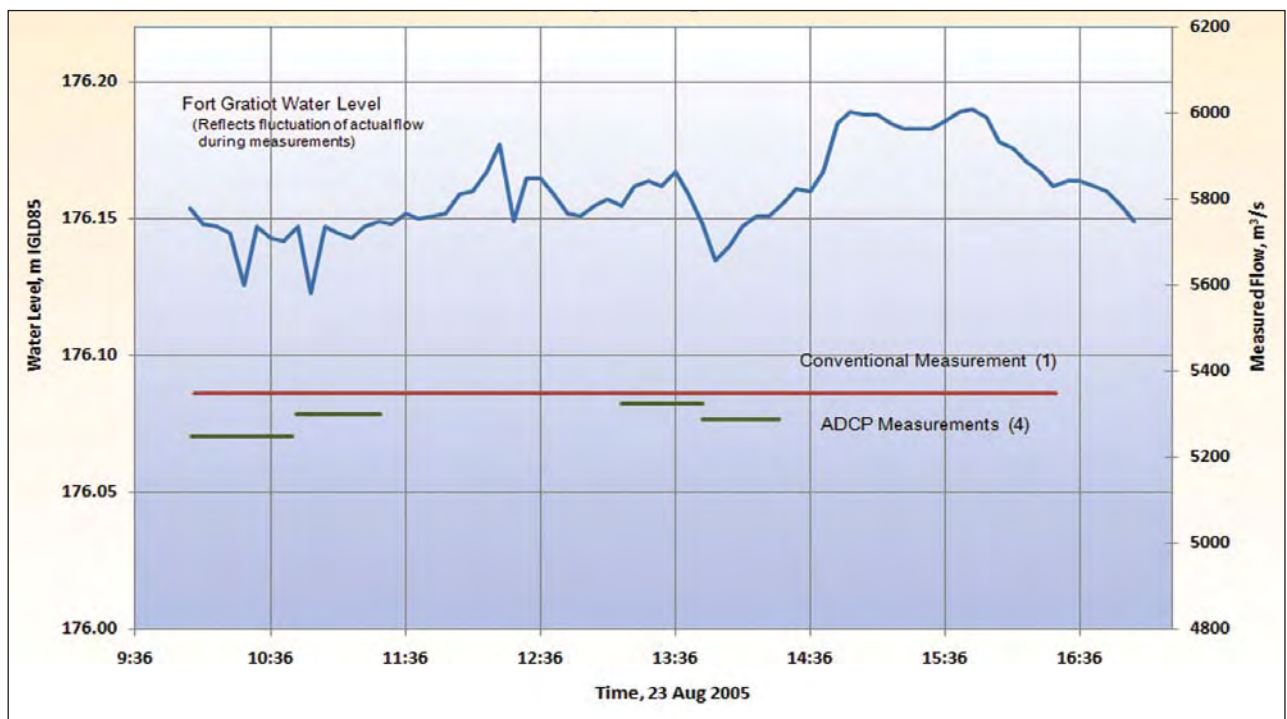
the St. Clair River is constantly changing, and so too is the discharge. Therefore, the measured discharge is only valid for a particular instant in time and represents an estimate of the true discharge.

Most discharge measurements made on the St. Clair River prior to 1996 used a Price current meter, a technique generally known as the conventional method. This method begins with the establishment of a measurement cross-section, and the division of the cross-section into a number of sub-sections, or panels, in which the water depth is measured. The velocity within each panel is measured by lowering rotating mechanical current meters into the water and measuring the velocity at one or more depths. The mean panel velocity is established from the velocity measurements within the panel. The discharge for each panel is calculated by multiplying this velocity by the area of the panel. The sum of the discharges of all the panels is the section discharge. For larger rivers, such as the St. Clair River, measuring discharge using conventional current metering techniques requires significant time and resources. The width and depth of the St. Clair River is such that the measurement sections must be divided into many panels, and velocities must be measured at typically ten depths within each panel. As a result, it can take several hours to complete one discharge measurement for an individual cross-section.

Since 1996, the discharge in the St. Clair River has been measured primarily using ADCP technology (Simpson, 2001). This technology uses an ADCP instrument mounted on the bottom of a boat that transverses the river. While the boat is moving, the ADCP emits acoustic energy into the water column below the boat. This acoustic energy reflects off tiny particles in the water, creating backscatter, which is measured by the ADCP. The ADCP can measure the velocity of the particles moving in the water and uses this information to establish the velocity of the water. Estimates of water velocity are made in a finite number of sub-sections corresponding to each emission of acoustic energy. These sub-sections are partitioned into “bins” about a half-metre deep and wide. The velocities measured in each bin and corresponding area are used to determine the flow through that bin. The sum of the flow through each bin over the entire cross-section is the section discharge. In practice, data collected on a number of successive transits of the river are averaged to estimate the discharge at a moment in time. A full ADCP measurement of discharge can be taken in less than 45 minutes on the St. Clair River, making it feasible to take multiple measurements of discharge in a short period of time, thus capturing more of the unsteadiness in the flow. Figure 5-3 compares the different lengths of time required to make conventional and ADCP measurements.

Figure 5-3 Consecutive Conventional and ADCP Discharge Measurements on the St. Clair River

Time of measurement and Average Discharge versus Water level at Fort Gratiot – August 23, 2005



Both the conventional and the ADCP methods provide a snapshot measurement of the discharge in the St. Clair River at a particular time. To be able to estimate the discharge in the river at continuous intervals of time, relationships between the infrequent measurements of discharge and the regularly measured water levels in the channel are developed. Water levels are monitored almost continuously on the St. Clair River at eight water level gauging stations operated by the U.S. National Oceanic and Atmospheric Administration (NOAA) and the Canadian Department of Fisheries and Oceans (Figure 5-4). The periodic discharge measurements are related to the water levels recorded at the time of measurements and used to develop stage-fall-discharge relations for various gauge pairs. Discharge is related to the fall between gauge pairs to capture the varying backwater conditions in the St. Clair River. These equations are periodically checked against new measurements to verify their continued representation of the measured flow, and revised if necessary. However, one of the key assumptions for relating water levels to discharge is that the conveyance of the river has not changed during the period. The stage-fall-discharge relationships are generally developed for ice-free, weed-free conditions. Variable ice and weed conditions can result in variable backwater that, in turn, can cause a retardation of the flow that needs to be considered.

A Horizontal Acoustic Doppler Current Profiler (HADCP) was installed in the river as part of the overall Study to measure the velocity continuously in the St. Clair River. An HADCP is mounted on the side of the channel to profile the velocity in the lateral plane or on the bottom of the river looking upwards to profile the vertical plane. It is important to note that these meters measure velocities, and only for a part of the flow at the section. A HADCP needs to be calibrated to produce a total flow estimate. Once a meter is installed, an index velocity rating must be developed to relate the measured velocities in the river to the channel discharge. This is accomplished by completing a series of boat-mounted ADCP measurements while operating the HADCP and a water level monitoring gauge. The velocities and discharge measured by the ADCP are related to the velocities observed by the HADCP and a relationship, similar to a stage-discharge relationship, can be established. Developing a good index velocity relationship requires a number of boat-mounted ADCP surveys collected over a range of discharges. HADCP technology is still relatively new and was not available for use in this Study. The effort to develop a good index velocity relationship will take several years to complete for the St. Clair River. Robust index velocity relationships

cannot be developed until sufficient flow measurements have been collected over a range of flows. Once fully operational and rated, the HADCP will allow researchers to compare these new measurements to existing methods for estimating discharge.

5.3 HYDROMETRIC DATA ANALYSES

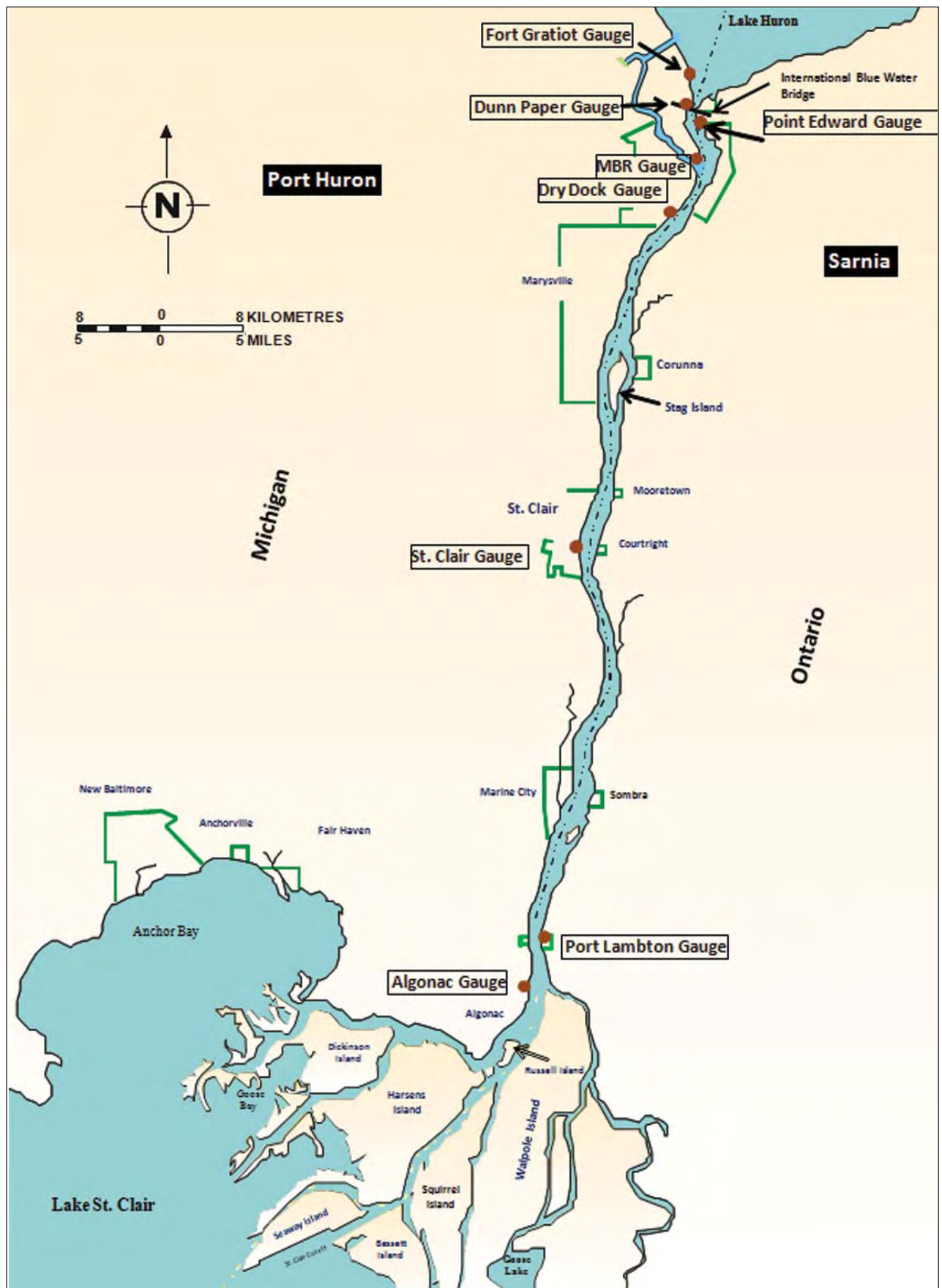
This section focuses on drawing conclusions about possible changes in conveyance in the St. Clair River from analyses of basic data, including measured water levels, discharge and bathymetry. The underlying assumption in the hydrometric data analyses is that data are homogeneous. In reality, this may not be the case. Water level data can be affected by gauge inconsistencies resulting from such factors as differential glacial isostatic adjustment (GIA), local subsidence, and adjustments due to maintenance of water level gauges. Similarly, discharge measurements, and specifically comparisons of measurements over time, can be inconsistent as a result of changes in measurement technologies, methodologies and differences in water levels regimes during the time of measurements. Lastly, bathymetric datasets are affected by changes in measurement technologies and methodologies, differences in data density, and differences in data coverage.

For the bathymetric data analyses, the degree of uncertainty in the data themselves can be quantified reasonably well, and the effect of this uncertainty on the results of the analyses can be readily assessed. In the analyses involving water levels and measured flows undertaken as part of this Study, the assumptions and caveats were noted, and it was assumed that the effects of any inconsistencies in these datasets were negligible when compared to the effects caused by possible changes in conveyance over time.

5.3.1 Water Level Data Analysis

The conveyance of water in a channel is very closely related to the water levels in the channel and the slope of the water surface profile in the reach. For various flows in a reach, the water surface profiles tend to be parallel. That is, the fall in water level between water level gauges is nearly constant, being less sensitive to changes in flow magnitude than the water levels themselves. If changes are detected in the slope of the fall between gauges, this could indicate a change in the channel characteristics and thus a change in the conveyance of the channel between these gauges. In the St. Clair River, a change in the water level slope between gauges may also be influenced by persistent changes in hydrology on the upstream or downstream lake.

Figure 5-4 St. Clair River Water Level Gauge Locations



There are eight water level gauges on the St. Clair River that have been continuously active over the period of the Study (Table 5-1). The data for the U.S. gauges were obtained from NOAA. NOAA water level gauging stations consist of 1.8 m (6 ft) diameter wells at FG, DD, SCP (see Table 5-1 for explanation of abbreviations), dual 30.5 cm (12 in) wells at DP and MBR, and a 25.4 cm (10 in) well at AL. The wells are connected to the river with either an intake line, if the well is located a distance from the river, or holes drilled through the well, if the well is immediately adjacent to the river. Inside the well, the water level is the same as it is in the river and float recorders record the water level referenced to benchmarks of known elevation. There is generally one primary and one secondary recorder at each gauge. Some of the secondary recorders use pressure transducers (DD and AL) instead of float recorders. All of the U.S. gauges have recorded at six-minute intervals since the mid 1990s. Prior to the mid 1990s, the recording intervals varied from five to 15 minutes. The recorded water level is the mean of 181 instantaneous measurements centered on each tenth of an hour. At gauge stations where there is potential drawdown due to high velocities in the river, such as at Fort Gratiot (FG), special precautions are made to align the intake so that flow can pass evenly around the intake and negate drawdown or buildup of water. Data for Canadian gauges were obtained from the Department of Fisheries and Oceans (DFO). The two Canadian gauges, one at Point Edward and the other at Port Lambton, use 0.9 m (36 in) stilling wells.

The wells are connected to the river through 5 cm (2 in) diameter pipes. No special configuration is needed at the intakes to avoid drawdown due to high velocities. Inside the wells, the primary instruments are float/counterweight instruments with digital recorders and the secondary instruments are pressure sensors. The gauges record the instantaneous water level inside the well (equivalent to the river water level) at three-minute intervals.

Several analyses were completed using the fall in the water levels between gauges over time. To eliminate the possible influence of ice retardation on the fall, monthly water level data were used only for months considered open water months (i.e., with no recorded ice cover). The water levels used in these analyses are monthly mean levels in metres on International Great Lakes Datum (IGLD) (1985).

As part of this Study, Holtschlag and Hoard (2009) performed statistical analyses to detect trends in the water level fall along the river defined by the gauges listed in Table 1. In any given ice-free season (typically, April through November), the average flows in all reaches are approximately equal. For any adjacent pair of reaches, the conveyance K is inversely proportional to the square root of the surface gradient hf/L , where hf is the drop in water level and L is the length of the reach. It was possible, therefore, to calculate the *ratio of conveyance* in two adjacent reaches from the observed water level data. Repeating the calculation of conveyance ratios over the period of record yields a time series of conveyance ratios, from which

Table 5-1 St. Clair River Water Level Gauges

| Water Level Gauge/ Operating Agency | Abbreviation | Modelling Reach | Reach # | Reach Length km (mi) |
|--|--------------|--------------------|---------|-------------------------|
| Fort Gratiot, NOAA | FG | | | |
| | | FG-DP | 1 | 0.45 (0.28) |
| Dunn Paper, NOAA | DP | | | |
| | | DP-MBR | 2 | 3.91 (2.43) |
| | | DP-PE | 2.1 | 1.47 (0.91) |
| Point Edward, DFO | PE | | | |
| | | PE-MBR | 2.2 | 2.44 (1.52) |
| Mouth of Black River, NOAA | MBR | | | |
| | | MBR-DD | 3 | 3.89 (2.42) |
| Dry Dock, NOAA | DD | | | |
| | | DD-SCP | 4 | 15.6 (9.70) |
| St. Clair State Police, NOAA | SCP | | | |
| | | SCP-PL | 5 | 18.5 (11.50) |
| Port Lambton, DFO | PL | | | |
| | | PL-ALG | 6 | 5.09 (3.16) |
| Algonac, NOAA | ALG | | | |

Note: Distances between gauges taken from Holtschlag and Hoard (2009)

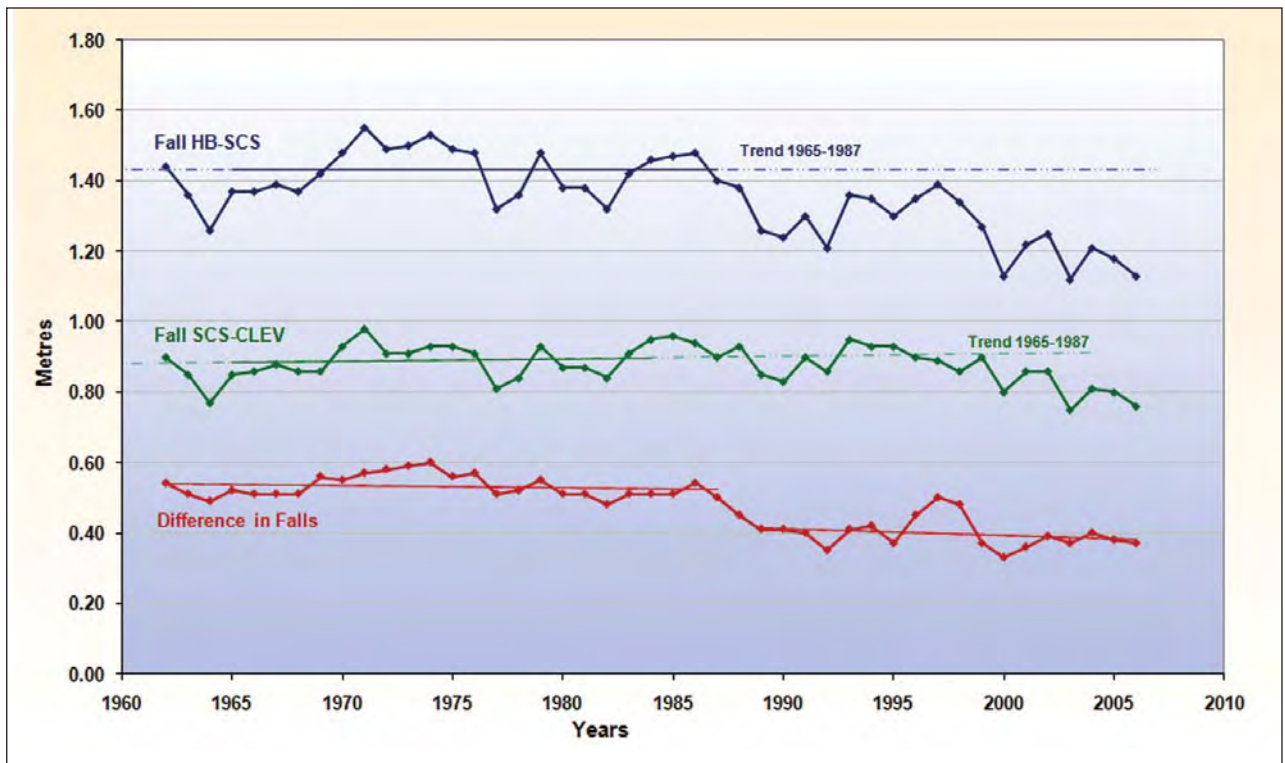
statistical trends may be observed. The results of this water level fall and conveyance ratio analyses indicate statistically significant trends in fall and conveyance ratios over the period 1962-2007 for reaches 1, 2.1, 2.2, and 4 (see Table 5-1 for the reach numbers). For reaches 1 and 2.2, the trend indicated an increasing fall, and for reaches 2.1 and 4, the fall tended to decrease. The conveyance ratios showed conveyance decreasing over time in reaches 1 and 2.2 relative to downstream reaches, and increasing in reaches 2.1 and 4 relative to downstream reaches. Reaches 3, 5 and 6 appeared to be stable.

These results may be affected to some degree by water level gauge instability caused by any number of factors, as outlined above, though these issues were assumed to be negligible. The results also may be affected by river flow, which is not taken into consideration in this comparison. Nonetheless, because all reaches pass essentially the same annual flow in any particular year, regardless of possible trends in flow, the fact that both positive and negative trends are observed in water level fall and conveyance ratios in a number of reaches supports the hypothesis that conveyance in the St. Clair River has changed. With this gauge data analysis, no attempt was made to identify times or amount of change.

Quinn (2009) performed analyses using both the water level fall between lake gauges and the fall between gauges on the St. Clair River. In contrast to investigations by Holschlag and Hoard (2009), Quinn attempted to identify the time periods of potential conveyance changes. This lake level fall analysis used water levels recorded at the Harbor Beach, MI (HB) on Lake Michigan-Huron, St. Clair Shores, MI (SCS) on Lake St. Clair, and Cleveland, OH (CLE) on Lake Erie. For the analysis of fall between gauges in the St. Clair River, data for all the river gauges listed previously were used except for those data from Point Edward, ON. The four month June-September average water level was used to determine annual falls between gauges and to derive gauge relationships.

Quinn's lake-to-lake fall analysis used the difference in fall between water levels at HB and SCS gauges and the fall between SCS and Gibraltar (later changed to CLE) gauges. The differences between the annual falls are plotted against time in Figure 5-5. There is a notable change in the difference in fall around 1988. Before and after 1988, the difference in fall shows a very slight downward trend, a small part of which is attributable to GIA (see Chapter 6 for a more detailed discussion of the effects of GIA on the lake-to-lake fall). Between 1985 and 1989, the difference

Figure 5-5 Water Level Fall between Lakes and Difference between Falls



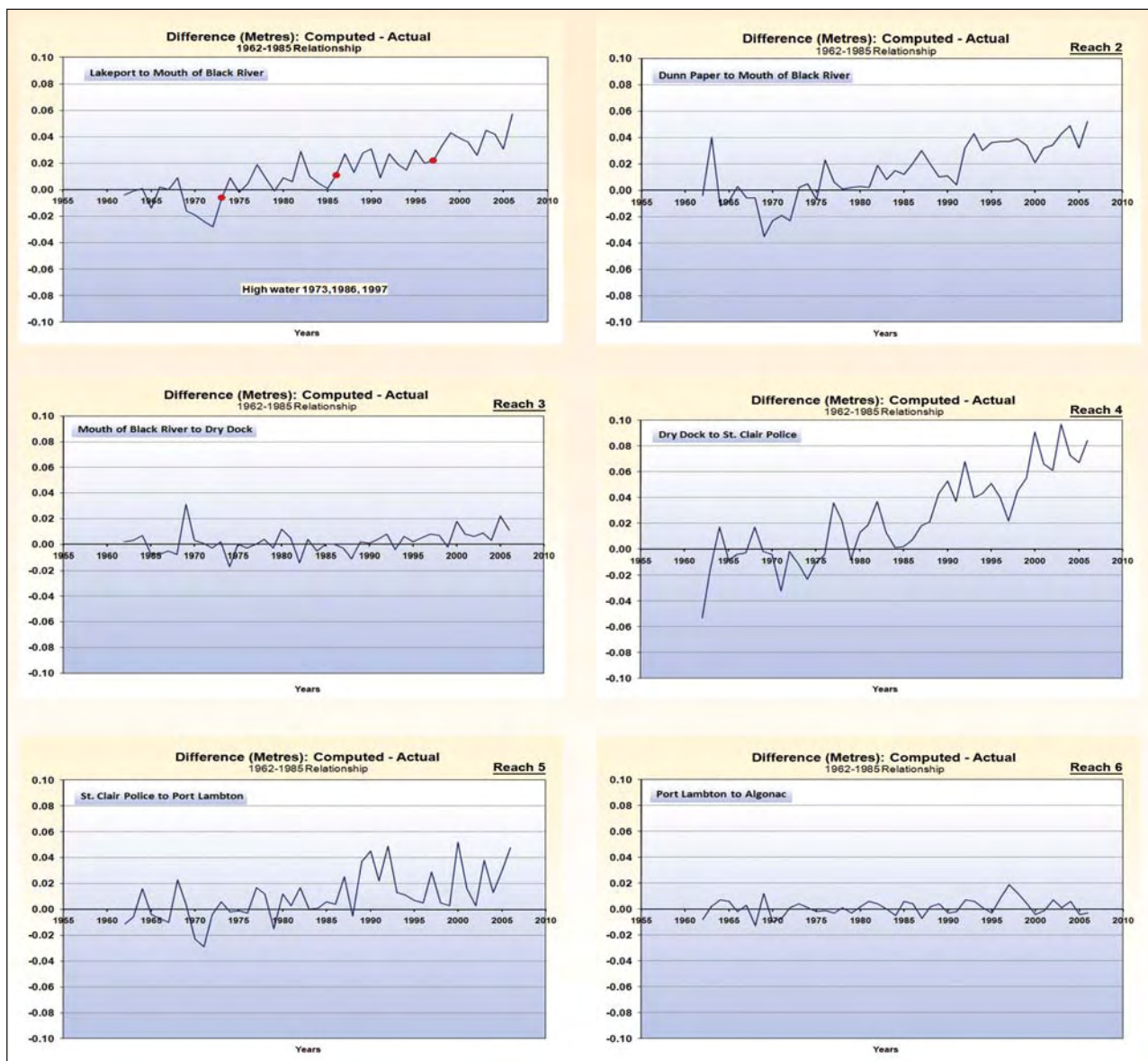
in fall decreased dramatically by about 8-10 cm (3.1-3.9 in), indicating an increase in conveyance. This could indicate that the flow regime in one or both of the St. Clair River and Detroit River changed significantly sometime before 1988. Due to the large storage capacity of the lakes, it takes time for any episodic change in conveyance to manifest itself in the observed water levels. Therefore, only an approximate date of some time in the mid-1980s can be estimated from this analysis.

To evaluate possible conveyance changes in the St. Clair River specifically, Quinn evaluated changes in the water level relationship between water level gauges. Regression equations were developed relating water levels at pairs of gauges, using recorded water level data from 1962-1985.

These equations were used to compute water levels at a gauge based on recorded levels at a downstream gauge for the period 1962-2006. The *computed* levels, which represent an assumed stable 1962-1985 regime for the reach, were compared to the *recorded* levels. The differences between the computed and the observed water levels are shown in Figure 5-6.

Changes in the difference between the levels indicate that some change has occurred in the reach defined by the gauge relationship. However, visual patterns may also indicate a problem with the recorded levels at one or both gauges, changes in seasonal retardation (aquatic plant growth), or changes in backwater effects. The reaches Quinn found with the most notable changes were: reach 2,

Figure 5-6 St. Clair River Gauge Relationships, Difference between Computed and Actual Water Levels



which shows a decrease in fall of about 4 cm (1.6 in) since about 1982; reach 4, with approximately an 8 cm (3.1 in) decline since 1977; and reach 5, with a decline of about 2 cm (0.8 in) since 1989.

While gauge relationships are very useful for determining the possibility and approximate timing of conveyance changes in reaches between gauges, they cannot be used to assess accurately the quantitative effects of the change, because these relationships do not include river flow in assessing changes. As a result, these values only approximate decreases in fall between reaches.

The values do not translate directly to a change in fall between Lake Michigan-Huron and Lake St. Clair, because they would be greatly attenuated by backwater before they reached Lake Michigan-Huron. To assess the water level changes in a channel reach requires the use of the same flow for assessing pre- and post-change conditions.

In summary, the various analyses using recorded water levels to detect possible changes in conveyance between gauges agree that some change in conveyance has occurred on the St. Clair River. The reaches in which the conveyance has most likely changed are reaches 1, 2, 4, and 5 (as measured by the gauge pairs of FG-DP, DP-MBR, DD-SCP and SCP-PL, respectively). The most likely time of significant change in conveyance was between about 1985 and 1989. Smaller changes in the fall relationship between gauges occurred around 1973-1977 and 1998-2000.

From the above analysis, two observations can be made:

- The lake-to-lake water level differences provided a range of 8 to 10 cm (3.1 to 4 in) in the drop of Lake Michigan-Huron attributable to conveyance change starting in mid-1980s.
- Gauge-to-gauge relationships from the paired water level gauges in the Lakeport to Algonac reach show a change in channel characteristics that led to a drop in Lake Michigan-Huron beginning mostly in mid-1980s. This drop was about 4 cm (1.6 in) between Dunn Paper and the Mouth of Black River gauges, another 8 cm (3.1 in) between Dry Dock and St. Clair Police gauges and finally another 2 cm (0.8 in) between St. Clair Police and Port Lambton gauges, for a total decline of 14 cm (5.5 in).

5.3.2 Measured Flow Data Comparisons

In contrast to the water level analysis conducted by Quinn that used comparisons of changes between adjacent stream gauges, Bruxer (2009) performed an analysis on discharge measurements and corresponding water level data available from 1962-2006. This analysis identified pairs of flow measurements taken over time having similar boundary conditions. This was achieved by sorting all flow measurement data, including water levels at the time of measurement, in order of their time of collection. Each flow measurement was then compared to all other measurements taken at some time after it, and matching pairs were identified in one of two ways.

First, all pairs of flow measurements separated by more than one year and having a difference in downstream water level at St. Clair Shores on Lake St. Clair of less than 5 cm (2 in) and a difference in measured discharge of less than 100 m³/s (3,531 ft³/s) were identified ("Dataset 1").

Second, all pairs of flow measurements separated by more than one year and having a difference in downstream water level at St. Clair Shores and a difference in upstream water level at Fort Gratiot of less than 5 cm (2 in) were identified ("Dataset 2").

Each of these two resulting sets of paired measurements were considered to have the same boundary conditions, and the differences in their measured Fort Gratiot water level or measured discharge, respectively, were used to help identify possible changes in conveyance over time.

Bruxer found that, despite possible biases and random errors caused by differences in measurement techniques, weed growth and meteorological effects on individual measurements, among other factors, the vast majority of measurement pairs indicated increases in conveyance over time. About 69 percent of all pairs in "Dataset 1" indicated an increase in conveyance, while only 13 percent showed a decrease in conveyance. Similarly, 54 percent of all pairs in "Dataset 2" indicated an increase in conveyance, with only 18 percent showing a decrease. The magnitude of potential conveyance changes could not be quantified accurately due to the limited availability of measured data and uncertainties in the analysis resulting from unknown or unquantifiable additional factors. However, these results illustrate that the system is dynamic, and the results support the hypothesis that conveyance has changed, and increased, over time. Even though the measured discharge record is sporadic, Bruxer also suggested the possibility that the measurement data could be used to investigate the times and locations of changes. For example, initial comparisons of discharge measurements indicate changes in

conveyance may have occurred prior to the mid-1980s, though this cannot be determined with certainty due to data limitations, particularly the lack of measured flow data available from 1985 to 1996.

5.3.3 Bathymetric Data Analysis

The bathymetry of the St. Clair River has been measured as far back as 1859 and was generally undertaken to aid navigation. Many early depth surveys were more concerned with mapping shallow hazards than obtaining the true depth of the river. As a result, many early surveys are considered to be “shallow biased” (*i.e.*, the shallow areas were more carefully measured than the deeper areas).

The last bathymetric survey made of the St. Clair River before the major dredging for the 27-foot (8.2 m) project in the early 1960s was completed in 1954. Portions of the river were not surveyed in 1954 because it was determined that a survey completed in 1929 provided sufficient coverage. The 1954 survey covers the river from Lake Michigan-Huron to above the Belle River at Marine City, and from upstream of Russell Island near Algonac into the St. Clair delta. After the completion of the dredging for the 27-foot (8.2 m) project, the next bathymetric survey was completed in 1971. The 1971 survey is the earliest bathymetric survey used in the Study’s analyses, given that it was undertaken during the period of interest for the Study (1962-present) and that it covers the entire river.

To address questions concerning ongoing geomorphic processes in the St. Clair River, the Study conducted an analysis of select bathymetric datasets spanning 36 years (Bennion, 2008). The Study utilized six sets of bathymetric surveys spanning the years 1971 to 2007. Data for the entire river from Fort Gratiot to Algonac are available for 1971, 2000, and 2007. The data from 2002, 2005, and 2006 cover only the upper four km (2.5 mi) of the river, from the head to just below the mouth of the Black River. The 2002 and 2007 surveys collected high density, high resolution data, using multi-beam acoustic sounding instruments. The 2000 dataset is less dense, having been collected with single-beam instruments. The 1971 and 2000 data were only collected along cross-sections or transects of the river, which were about 100 to 300 m (328 to 984 ft) apart. The density of the measured points in the 2007 dataset is vastly different than the number of points measured in the 1971 and 2000 surveys. The errors associated with the survey methods used to collect and process the data, the varying extents of the bathymetric surveys, and the resolution of the data can all influence the uncertainty of any comparisons made. This uncertainty, therefore, had to be considered in this analysis, and is discussed at length in Chapter 4.

Bennion compared both changes in point elevation and changes in volume over time. A comparison of point elevation can indicate location, magnitude and trends of statistically significant elevation differences but does not allow for the quantification of overall changes in volume. Bennion found that the accuracy of available data was not sufficient to reliably detect widespread geomorphic change throughout the St. Clair River at the scale required. The issue of how data values were rounded and binned in the 1971 and 2000 datasets and the differences in density, location and range of surveyed values contribute to this uncertainty. However, given these limitations, the 1971 dataset is the only one available for providing a historical context and therefore was used for comparison purposes.

Figure 5-7 highlights areas of the upper river where change was consistently indicated by the high-density data against the low-density 1971 survey. It also illustrates the proximity of these areas to other river features.

5.3.4 Influence of the Detroit River on St. Clair River Hydraulic Regime

Changes in conveyance in the Detroit River could account for a portion of the drop in the Lake Michigan-Huron to Lake Erie head difference. Sellinger and Quinn (2001) showed a change in the hydraulic regime of the Detroit River after 1988. Their hypothesis is that this change is attributable to the introduction of the zebra mussel and subsequent increases in weed growth due to increased water clarity. Noorbakhsh (2009) used the same procedure that Quinn (2009) used in the St. Clair River to derive gauge relationships for the Detroit River for the period 1962-1985. Only water levels for the month of May were used, because aquatic plant growth significantly retards the summer flows. Relationships were developed for the reaches between the Windmill Point and Fort Wayne gauges (WP-FW), the Fort Wayne and Wyandotte gauges (FW-WYN), and the Wyandotte and Gibraltar gauges (WYN-GIB) (Figure 5-8). The differences between the computed levels and the observed levels are shown in Figure 5-9. Differences in relationships appear to occur in all three reaches in 1998. This likely is due to a persistent change in the backwater effects from Lake Erie during this period (Figure 5-5). The changes in the relationships on the St. Clair River beginning in the late 1990s also may be related to the change in backwater.

Figure 5-7 Areas of Geomorphic Change in the Upper St. Clair River and Associated River Features

Upper St. Clair River Zones of Elevation Loss and Elevation Gain

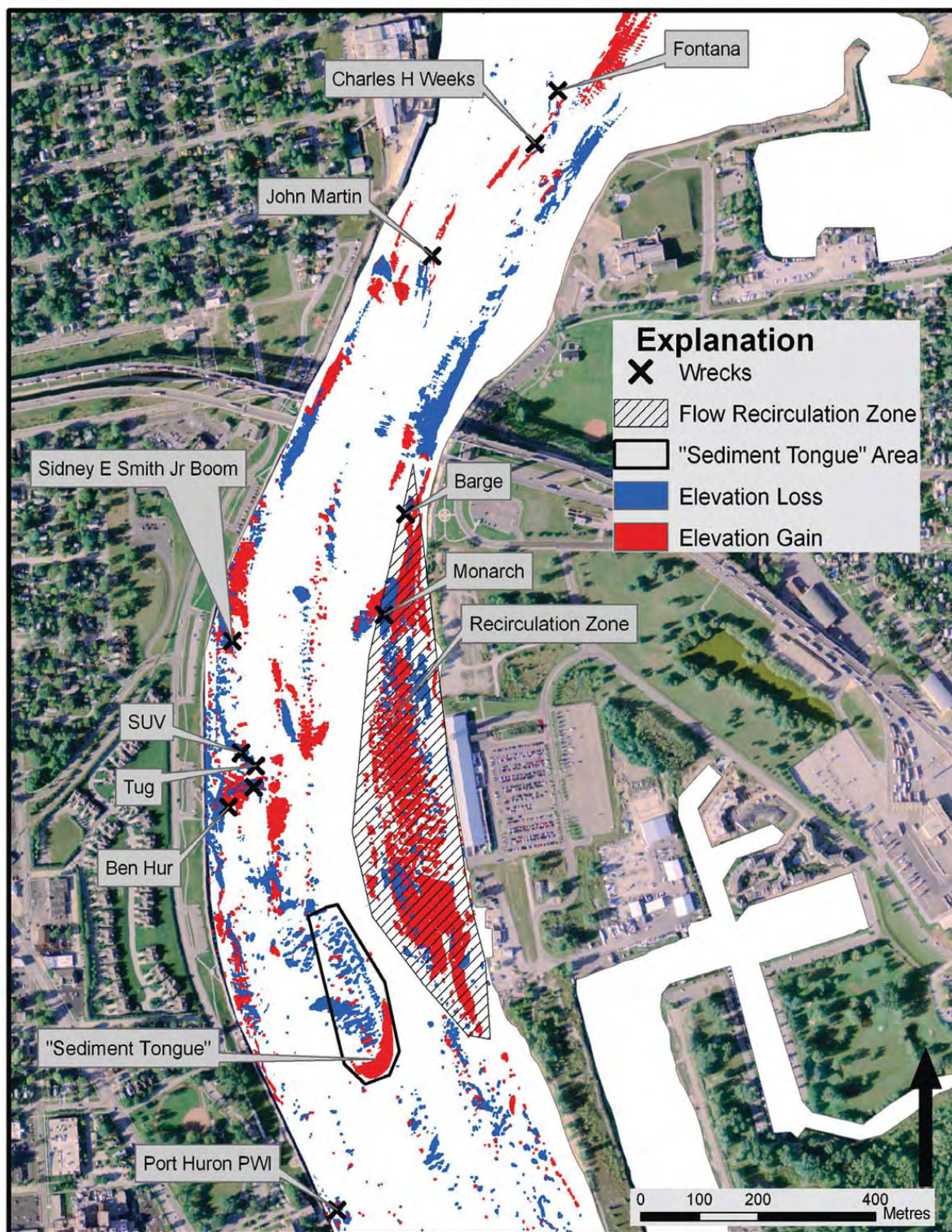


Figure 5-8 Detroit River Water Level Gauge Locations

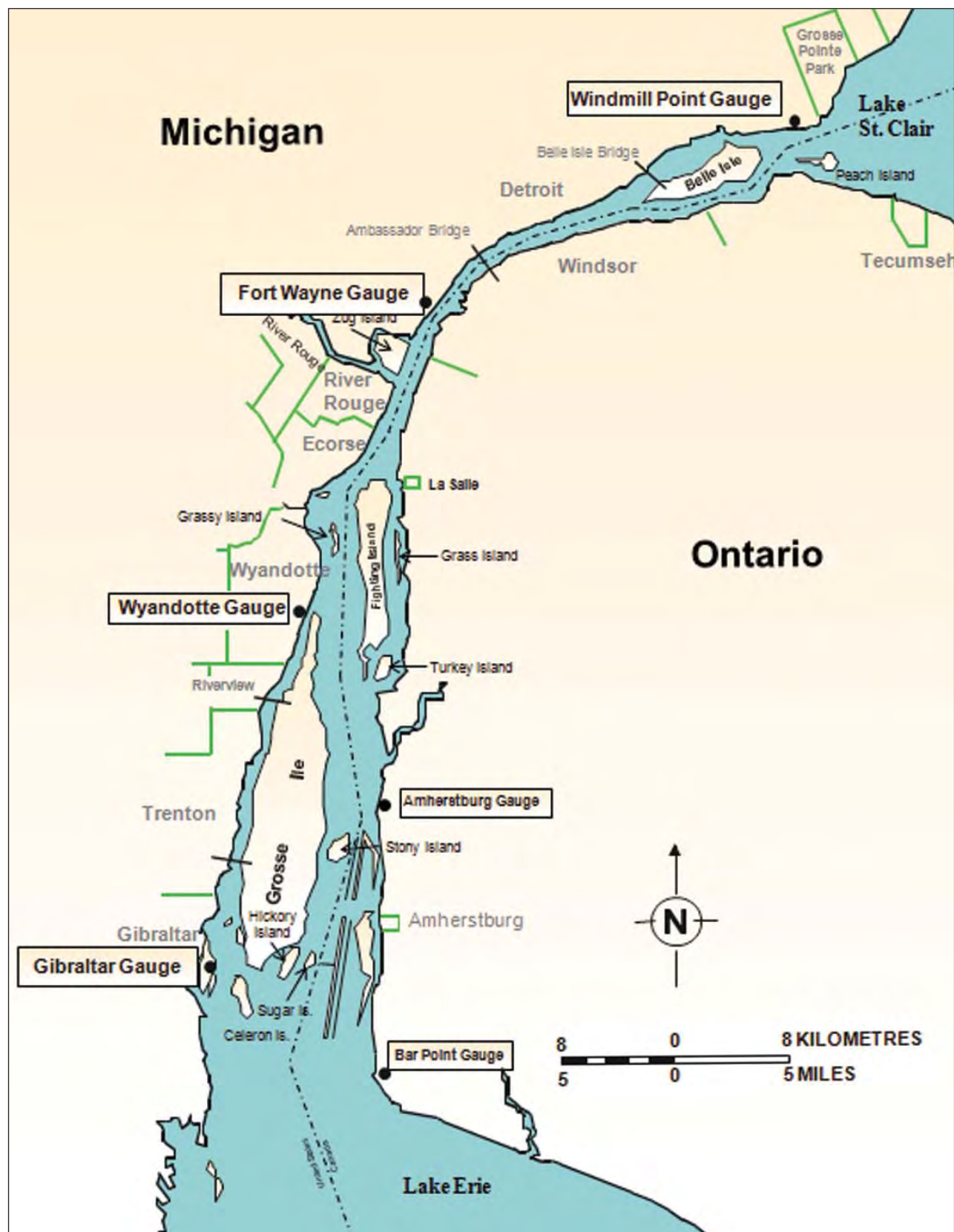
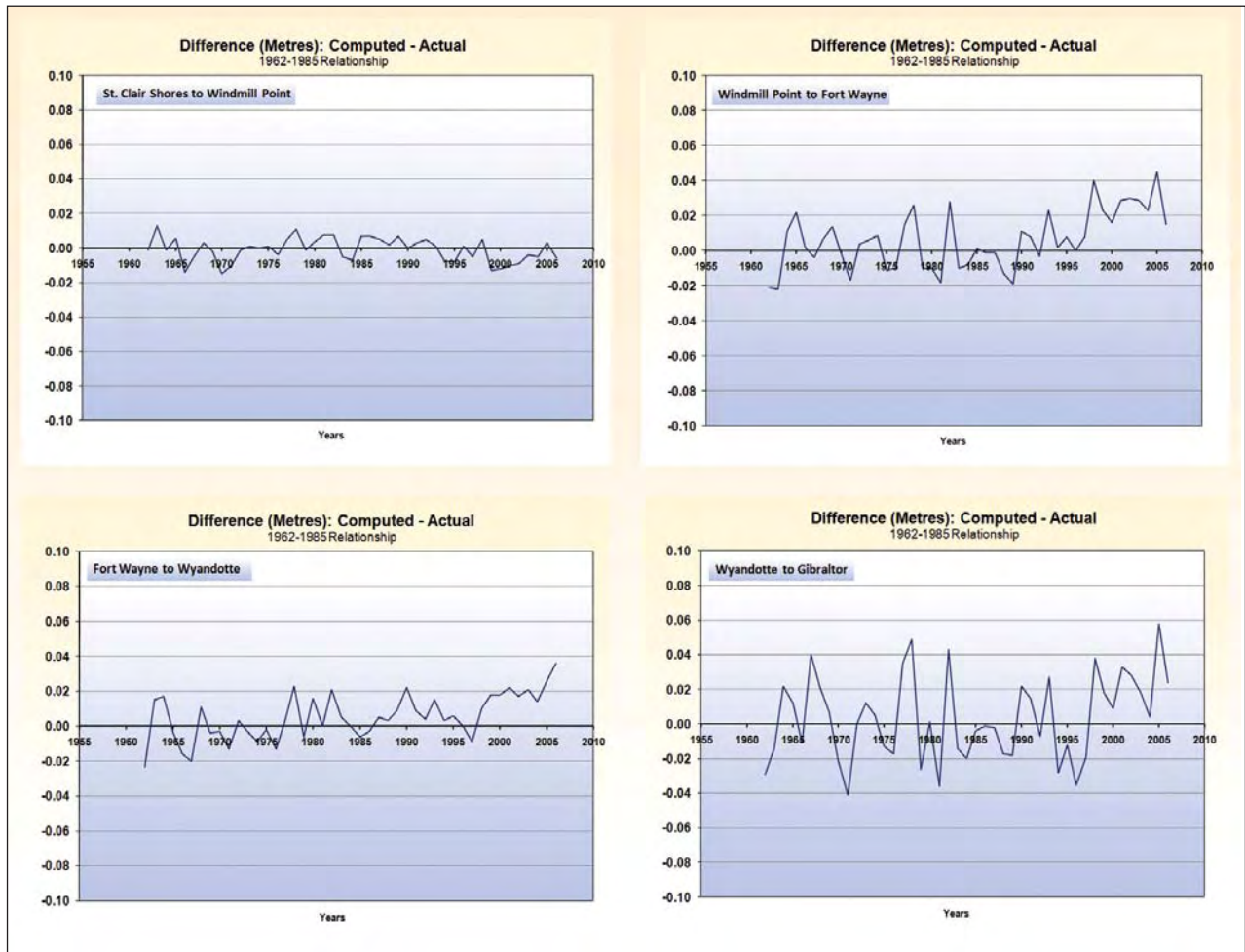


Figure 5-9 Detroit River Gauge Relationships, Difference between Computed and Actual Water Levels



Unfortunately, there is insufficient evidence to make any certain conclusions regarding changes in conveyance in the Detroit River, and currently not enough data are available to investigate these changes further. For example, multi-beam data for the Detroit River were not collected in 2007 as they were for the St. Clair River, making any comparisons using hydraulic models similar to what was done for the St. Clair River inappropriate. Furthermore, the head difference diagrams between the lakes (Michigan-Huron, St. Clair and Erie) indicate that the majority of the drop between Lake Michigan-Huron and Lake Erie has occurred between Lake Michigan-Huron and Lake St. Clair, and not between Lake St. Clair and Lake Erie.

5.3.5 Conclusions from Hydrometric Data Analyses

The Study's hydrometric data analyses used basic data, including water levels, discharge measurements and bathymetry, to identify possible changes in conveyance over time. The underlying assumption in each of the hydrometric data analyses involving water levels and discharge measurements was that the data were homogeneous. In the bathymetric data analysis, the uncertainties caused by the discrepancies between datasets were quantified to the extent possible and were documented to be large.

The general conclusion from these hydrometric analyses is that the conveyance in the St. Clair River has changed since the last dredging project in 1962. Significant changes in the water level relationships between gauges can be seen in a number of reaches. Comparisons of measured discharge values over time indicate that the overall conveyance has increased. In addition, bathymetric data comparisons show that the channel changed between 1971 and 2007 (with the caveat that the survey errors in 1971 were large). Water level relationship analyses indicate that changes in conveyance may have occurred episodically and in different reaches of the river, with periods of change being: 1973-1977; 1985-1989; and 1998-2000. These changes are a result of other causes and not the 1962 dredging. Discharge measurement comparisons indicate changes may have occurred prior to the mid-1980s, though this cannot be confirmed due to the lack of measured discharge data available from 1985 to 1996. Analysis of change in water level fall between Lake Michigan-Huron and Lake St. Clair indicates some significant change may have occurred prior to 1988, with an estimated effect of decreasing the fall by 8 to 10 cm (3.1 to 3.9 in).

Evidence regarding changes in conveyance in the Detroit River was not strong enough to make any firm conclusions. However, other related evidence, including the fall diagrams between the lakes, indicates that the majority of any drop between Lake Michigan-Huron and Lake Erie has occurred between Lake Michigan-Huron and Lake St. Clair.

Table 5-2 summarizes the range in conveyance change produced from these different analytical approaches. These different approaches indicate that the conveyance of the St. Clair River has been increased by 8 to 14 cm (3.1 to 5.5 in) over the time period of the Study.

Table 5-2 Estimates of Lake Michigan-Huron Water Level Impacts from Data and Flow Analyses

| Type of Analysis | Estimate of Change cm (in) |
|------------------------------|-------------------------------|
| Lake-to-lake head difference | 8 to 10 (3.1 to 3.9) |
| Gauge-to-gauge relationship | Up to 14 (5.5) |

5.4 HYDRAULIC MODELLING ANALYSES

As described in section 5.3, the hydrometric data analyses used basic measured data to try to detect conveyance changes in the river. The findings suggest that there have been changes in the conveyance of the St. Clair River since the 1962 dredging, but not attributed to the dredging, since the changes occurred at least a decade later. In this section, hydraulic modelling is used to assess whether there has been a change in conveyance and provide a higher level of confidence to the findings.

To address the conveyance issue, the Study utilized a number of hydraulic models to quantify the change. The hydraulic models used bathymetry and shoreline information to characterize the geometry of the river, together with water level and discharge data to supply boundary conditions, for calibration and validation.

This section describes the selection of the hydraulic models and the types of scenarios that were evaluated. There were several different categories of scenarios tested using multiple hydraulic models. The first utilized historical bathymetry datasets for the St. Clair River to estimate conveyance change post-1962. Next, scenarios were executed to evaluate the effect of small-scale, sub-surface features, such as deep sections, or raised sediment features, on the conveyance of the river. Similarly, scenarios were developed to quantify the potential effects of GIA that could be altering the bed slope of the St. Clair River.

Sensitivity analysis was conducted on all of the hydraulic models to determine the relative importance of factors influencing the conveyance change calculations. Uncertainty analysis was completed for only one of the hydraulic models (RMA2), due to time and resource constraints. The uncertainty analysis helped quantify the propagation of uncertainty in the bathymetry datasets and its effects on the estimate of conveyance change.

Inverse modelling was employed as well. This method assumes that the bathymetry of the channel remains constant over the time period of simulation and the model's conveyance factors were estimated using water level and discharge data available since 1962. This approach provides an additional estimation of change in conveyance in the St. Clair River. Finally, a hydraulic model that can simulate the reduction in conveyance due to ice was used to look at the possible effects of ice on the conveyance of the St. Clair River.

5.4.1 Selection of Hydraulic Models

The Study used several hydraulic models to investigate potential changes in the conveyance of the St. Clair River. The choice of models was based on several criteria. The first and most important was the suitability of the model's fundamental assumptions relative to the conditions present in the St. Clair River and for the basic questions that needed to be answered. The flow (and conveyance) in the St. Clair River can be adequately characterized with a 2-D hydrodynamic model. With a 2-D model, the velocity profile in the vertical plane is replaced by a depth averaged velocity vector, and the vertical accelerations are assumed negligible. A 2-D model describes the physical flow phenomenon in the river by allowing the surface elevation to vary so as to satisfy the flow hydrodynamics, by describing the true velocity profile across the river, and by making no assumption regarding the horizontal direction of the velocity.

The Study collected detailed ADCP velocity data at sections throughout the river, and the choice of model was based, in part, on the information provided by these data. Figure 5-10 provides a map indicating the locations of the ADCP cross-sections. Figures 5-11 through 5-16 illustrate the velocities measured at a number of cross-sections in the upper-most portion of the river. The cross-section is shown as looking downstream so the Canadian shore of the river is on the left side of the section. The colour shown depicts the magnitude of the streamwise velocity and the velocity vectors indicate the magnitude and direction of the secondary velocities. The vertical component of the vectors is exaggerated by multiplying the velocity by the amount specified on the plot, so as to compensate for the very low vertical velocities.

It is evident that the flow in the upper-most reach of the St. Clair River beginning at the entrance at Lake Michigan-Huron near Fort Gratiot to the mouth of the Black River is complex, though the flow is predominantly in the streamwise direction. There is a constriction and accompanying acceleration of velocities near the International Blue Water Bridge (Figures 5-11 through 5-13). Immediately downstream, there is a bend creating strong cross-currents, and on the Canadian side of the river there is a recirculation (eddy) zone (Figures 5-14 and 5-15). Vertical velocities exist and are measurable in portions of this reach, but are two orders of magnitude smaller than the streamwise currents and, therefore, can be ignored for the purposes of this analysis.

From the mouth of the Black River to the upstream end of the delta, currents are primarily in the streamwise direction. Cross-currents are present in some sections, though typically are an order of magnitude smaller than the streamwise currents. Velocities are higher in the centre of the channel than near the shorelines, and there are no measureable vertical velocities in this section of the river (Figure 5-16).

Below Algonac, the flow in the river splits into the St. Clair River delta channels before entering Lake St. Clair. Velocities in the delta section of the river are lower than the upper reaches of the St. Clair River, as the slope decreases and the river transitions to Lake St. Clair.

While a 2-D model is a reasonable choice of model for the St. Clair River, the Study concluded that a 1-D model is more than adequate for the task. A 1-D model can be justified in this case, because the flow in the river is predominantly in the streamwise direction and vertical velocities are negligible in most of the river. More importantly, the basic question to be addressed is whether conveyance has changed. This question can be adequately addressed by using either a 1-D or 2-D model because, for the longest portion of the river (the section below the mouth of the Black River), there are negligible cross-currents, and there is only minor horizontal variation in velocity across the cross-section. In the upper section of the St. Clair River, where there is a major constriction and recirculation zone, expansion and contraction coefficients can be specified and an ineffective flow area option can be utilized to help account for some of these features.

Other considerations in the selection of which hydraulic models to apply were: data requirements; computational requirements; and guidance from the independent peer review.

Significant amounts of data are required to develop, calibrate, validate and execute a hydrodynamic model. The collection of hydrometric data, especially velocity and discharge data, was less prevalent historically than it is today. While there are good records of water levels in the St. Clair River system over the Study period (1962 to present), only limited discharge and velocity data are available. Historically, limited velocity data exist and are insufficient to rigorously calibrate and validate a three-dimensional (3-D) model, which is different from 2-D models in that it computes a vertical velocity component. Furthermore, measurement uncertainties are compounded in a 3-D model. As was demonstrated in Figures 5-11 to 5-16, there is a very weak vertical velocity component in the St. Clair River, which has little bearing on the computation of discharge and conveyance. A strong reliance was instead placed on water level and discharge data to calibrate and validate the hydraulic models utilized in the Study. These types of data support 1-D and 2-D models better than they do 3-D models.

Figure 5-10 **Locations of ADCP Cross-Sections**

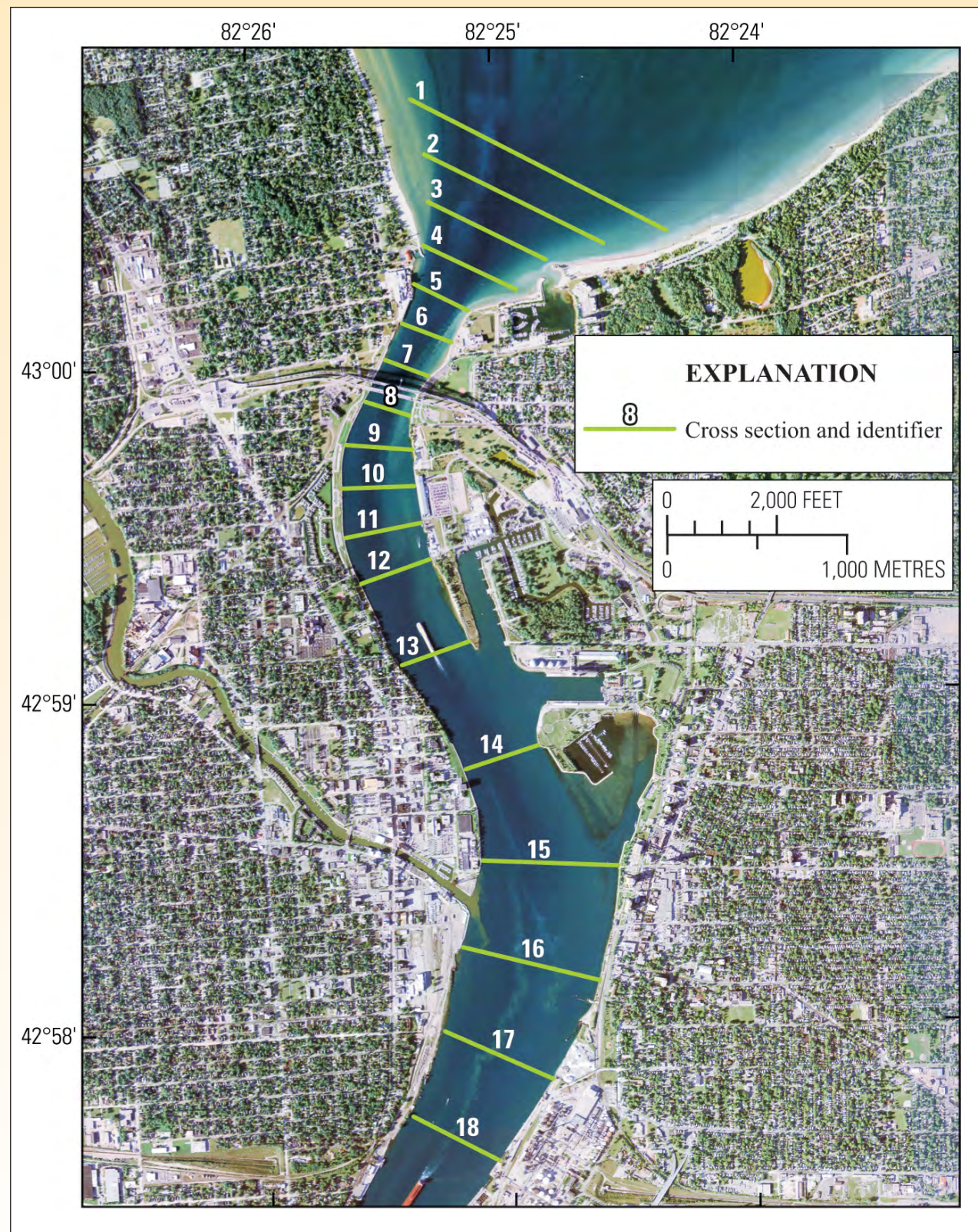


Figure 5-11 ADCP Cross-Section 6

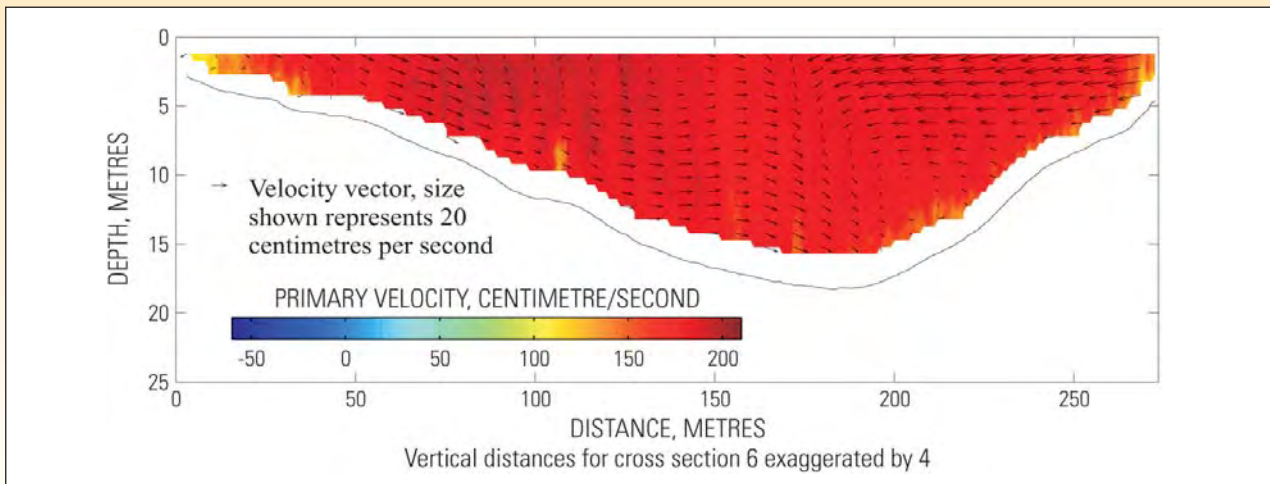


Figure 5-12 ADCP Cross-Section 7

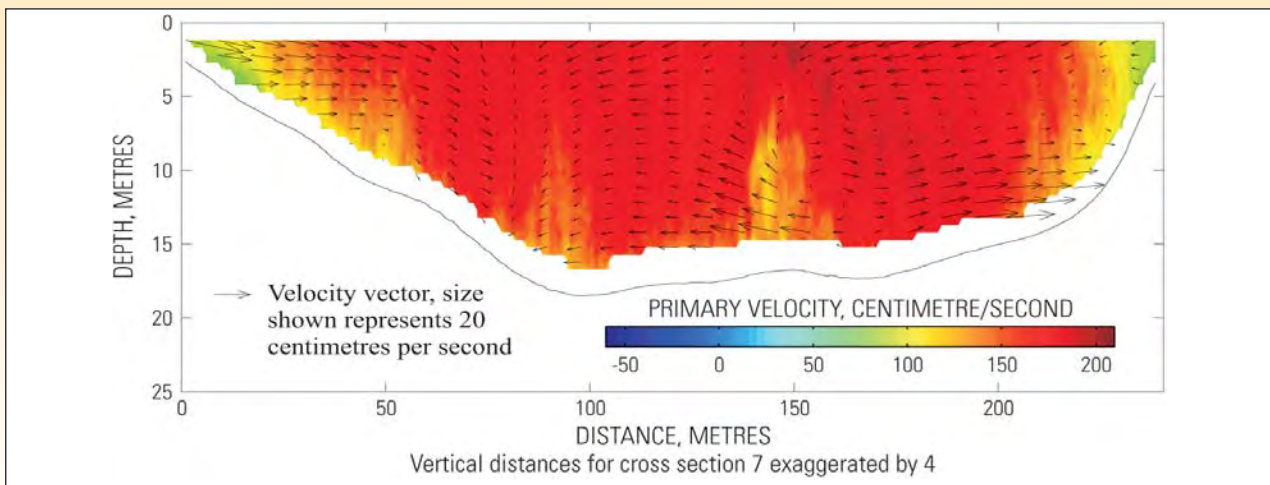


Figure 5-13 ADCP Cross-Section 8

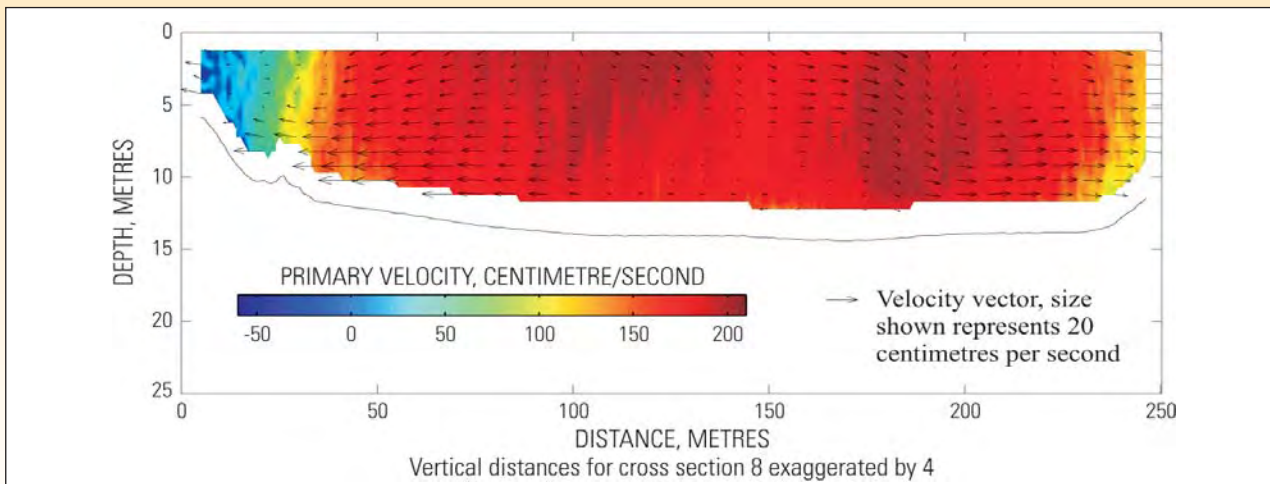


Figure 5-14 ADCP Cross-Section 9

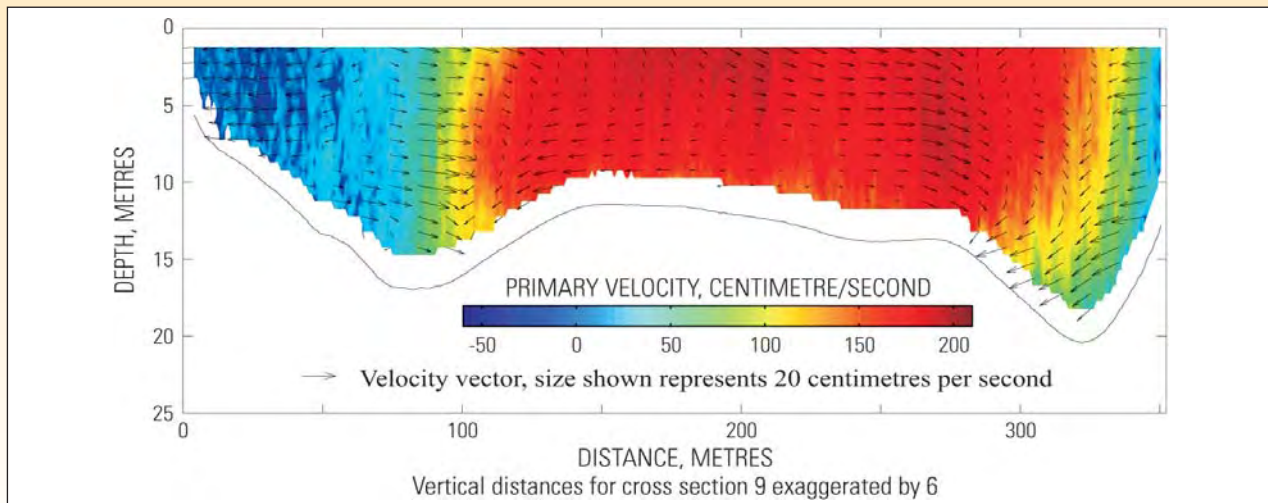


Figure 5-15 ADCP Cross-Section 10

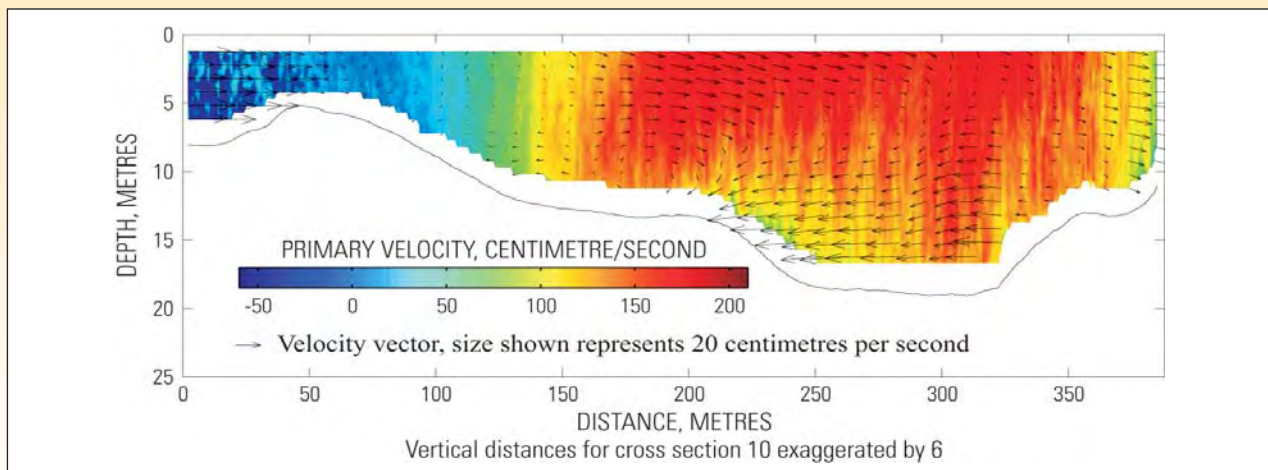
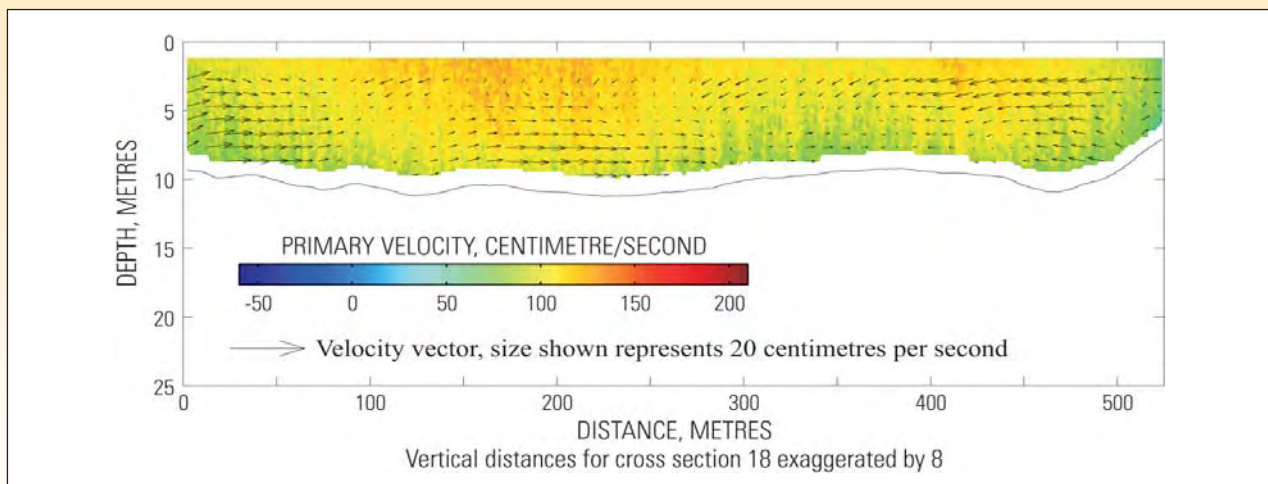


Figure 5-16 ADCP Cross-Section 18



With regards to the computational requirements of models, a 1-D model tends to execute its numerical computations in far less time than a 2-D model, and 3-D models have even greater computational requirements. Furthermore, even with recent advances in computation power, the length of the simulations still can be significant, and some of the analyses conducted in the Study involved the simulation of decades of hourly conditions or a large number of repetitive solutions for uncertainty analysis.

Lastly, all models selected for use in the Study have been widely applied and referenced in peer reviewed journals. The independent peer review established by the International Joint Commission agreed and supported the Study strategy that the 1- and 2-D models are sufficient and adequate to answer the science question related to conveyance change.

Given these considerations, the Study chose one 1-D model and three 2-D models to support the analysis of the hydraulic regime of the St. Clair River. However, the Study did develop and employ a 3-D coupled hydrodynamic and sediment transport model to confirm that the strength of tertiary currents to exacerbate erosion causing stress was negligible.

The 1-D model selected was the Hydrologic Engineering Center's River Analysis System (HEC-RAS), developed by the U.S. Army Corps of Engineers (USACE) (Brunner, 2008). This model has historically been used as the standard 1-D model in many applications. In this Study, it was used in several analyses, including evaluating the effects of channel geometry changes, inverse modelling to detect changes in conveyance over time, and evaluating the effects of ice on conveyance.

The first of three 2-D models used in the Study was the Resource Managements Associates 2-D, finite-element model, RMA2, which is maintained by the USACE (Donnell *et al.*, 2005). The second 2-D hydraulic model used in the Study was Telemac-2D, developed by the Laboratoire National d'Hydraulique et Environnement d'Electricité de France (EDF). Similar to RMA2, this model simulates 2-D, depth-averaged velocities on a finite-element grid. A third model, HydroSed2D, was utilized primarily to calculate shear stresses on the bottom of the St. Clair River for sediment transport purposes and, secondly, to assess changes in discharge of the river over time.

The selection of a hydraulic model, as discussed above, deals primarily with addressing the key science question on conveyance. There are also other considerations in selecting the type of model. To answer related science

question on the morphodynamic aspects of the St. Clair River, consideration needs be given to the tertiary circulation, particularly around the first bend of the river, where there is lake-to-river transition potentially causing helical-type flows in the presence of the seawall immediately below the Blue Water Bridge on the U.S. side. These aspects are discussed in detail in Chapter 4 and documented by Liu and Parker (2009). In using the 2-D HydroSed2d model, Liu and Parker compared the circulation and the strength of the critical shear stress in this reach to the Mouth of Black River. By developing and employing a 3-D coupled hydrodynamic and sediment transport model (based on OpenFOAM code), the Study confirmed that the strength of tertiary currents to exacerbate erosion causing stress was negligible. Furthermore, the results on bottom shear from both 2-D and 3-D modelling were very similar. This analysis confirmed the Study contention that a 3-D model was not required to address the science question.

5.4.2 Bathymetric Change Analyses

The hydraulic models were calibrated and validated using observed water levels and flows in the St. Clair River. The models were subsequently used to evaluate a number of scenarios to investigate whether the conveyance in the St. Clair River has changed over time. The first scenarios involved the systematic substitution of historical bathymetry into the hydraulic models and the evaluation of changes in computed water levels and flows under historical conditions.

Full river bathymetry datasets were available for the years of 1971, 2000, and 2007. Partial river datasets were available for 2002, 2005, 2006, and 2008. There are other historical bathymetry datasets available for the St. Clair River outside the period of interest, but these datasets were not utilized in the present analysis. Significant differences exist between the datasets in terms of data extent, collection methodology, density and uncertainty. These differences (noted in section 5.3.3 and more fully documented and explained by Bennion, 2008), have a significant effect on model results and must therefore be considered. For example, the bathymetric dataset from 1971 is composed mostly of single-beam transects, with sparse additional data points located at random throughout the channel. Transects are spaced along the St. Clair River approximately 100 m (328 ft) apart or greater, and the soundings in these transects are spaced approximately 20 m (65.6 ft) apart or greater across the channel. The 2007 data, on the other hand, are high-density, multi-beam data, with soundings reported on a 1.5 m by 1.5 m (4.9 by 4.9 ft) grid. A summary of the differences in the various datasets is presented in Table 5-3.

Table 5-3 Summary of Bathymetric Datasets Used in Modelling Analysis

| Dataset | Type | Transect Spacing | Data Point Spacing | Transect Orientation | Grid Spacing | Data Extent |
|---------|-------------|-------------------------|--------------------------|----------------------------|----------------|--|
| 1971 | Single-beam | ~100 m (328 ft) or more | ~20 m (65.6 ft) or more | Perpendicular to flow | – | Fort Gratiot to Algonac |
| 2000 | Single-beam | ~100 m (328 ft) or more | ~7.5 m (24.6 ft) or more | East-west, except in delta | – | Fort Gratiot to Lake St. Clair, including delta |
| 2002 | Multi-beam | – | – | – | 1.5 m (4.9 ft) | Upper River (Fort Gratiot to just below Black River) |
| 2005 | Multi-beam | – | – | – | 1.5 m (4.9 ft) | Upper River (Fort Gratiot to just below Black River) |
| 2006 | Multi-beam | – | – | – | 1.5 m (4.9 ft) | Upper River (Fort Gratiot to just below Black River) |
| 2007 | Multi-beam | – | – | – | 1.5 m (4.9 ft) | Fort Gratiot to Algonac |
| 2008 | Multi-beam | – | – | – | 0.5 m (1.6 ft) | Upper River (Fort Gratiot to just below Black River) |

To assess these effects quantitatively, two additional bathymetry datasets were created and evaluated using the 1-D and 2-D models. Two “simulated single-beam” datasets were created from the 2007 high-density multi-beam data. The first of these was a single-beam dataset extracted from 2007 data at only those data points collected in the 1971 single-beam dataset. The second was a single-beam dataset extracted from 2007 data at only those points collected in the 2000 single-beam dataset. The 2007 surface overlaid with the 1971 data points is shown in Figure 5-17. Any points from 1971 or 2000 located beyond the extent of the 2007 data were given the same elevation as in the original dataset. In this way, the 2007 data could be compared directly to either the 1971 or 2000 data, without differences in the type of data affecting results.

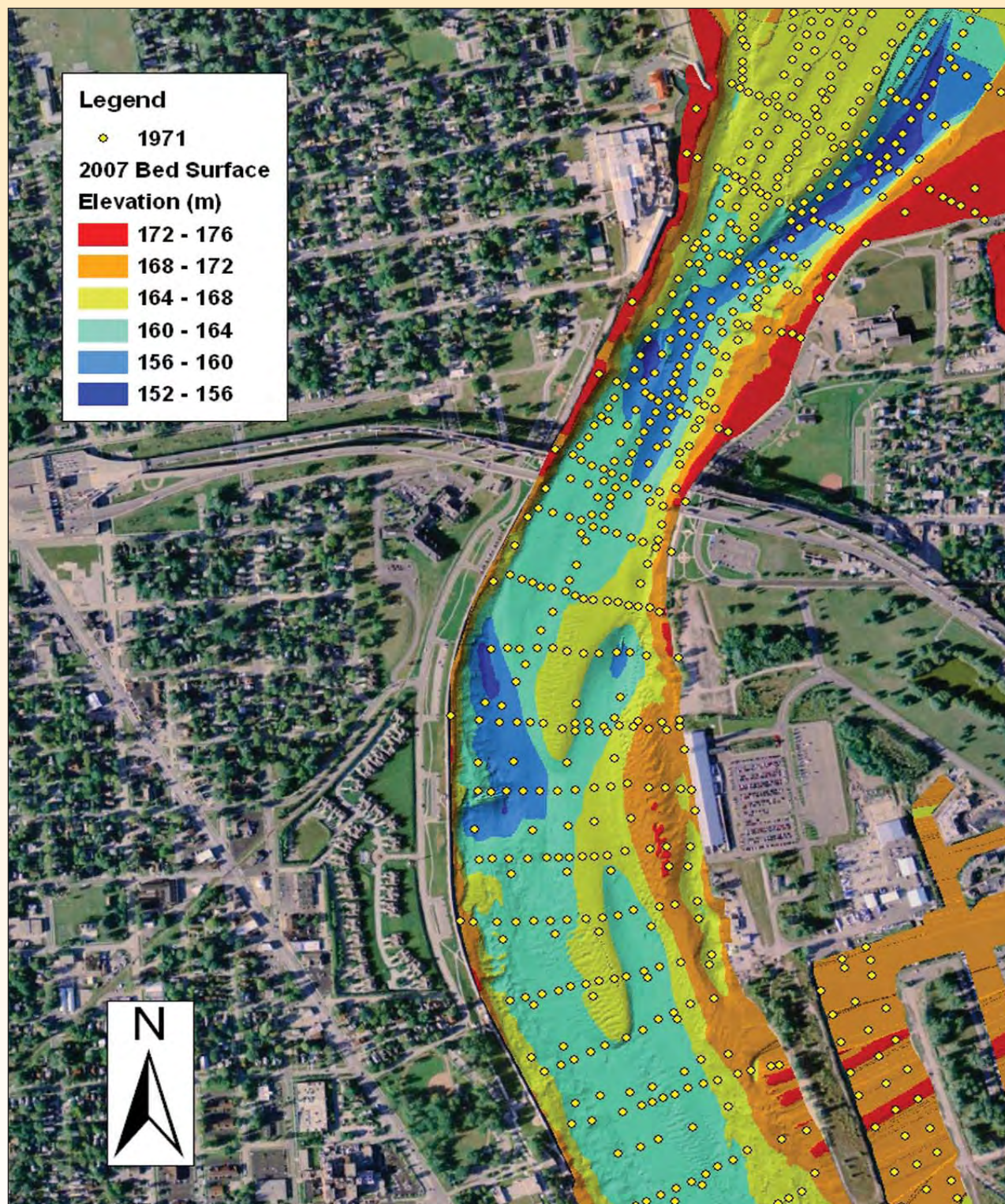
Multiple comparisons were made between the different bathymetries with each of the different models. The various bathymetry datasets were substituted into each model and the models were simulated under average boundary conditions. All other variables affecting conveyance were assumed to remain constant (*e.g.*, channel roughness, shoreline location and elevation). From these simulations a number of estimates of changes in conveyance were obtained. The results are summarized in Table 5-4. Using bathymetry data of equal density, the analysis found that since 1971 the water level of Lake Michigan-Huron has decreased from 9 to 13 cm (3.5 to 5.1 in) due to an increase in conveyance. In terms of discharge, the models indicated that, for the same Lake Michigan-Huron and Lake St. Clair water levels, the St. Clair River could now convey between 250 and 275 m³/s (8,829 and 9,712 ft³/s) more water than it could in 1971, assuming equal upstream and downstream levels.

**Table 5-4 Computed Changes in Fort Gratiot Water Level
cm (in)**

| Scenario | Model | | | |
|--|------------|------------|------------|-------------|
| | HEC-RAS | RMA2 | TELEMAC-2D | HydroSed-2D |
| 2007 SSB1971 vs 1971 | -10 (-3.9) | -12 (-4.7) | -13 (-5.1) | |
| 2007 MB vs 1971 SB | | -23 (-9.1) | -25 (-9.8) | |
| 2007 MB vs 2000 SB | | -7 (-2.8) | | |
| 2007 SSB2000 vs 2000 whole river | | 3 (1.2) | | |
| 2007 SSB2000 vs 2000 above Black River | | | 0.6 (0.24) | |
| 2007 SSB1971 vs 1971 above Black River | | -3 (-1.2) | | |
| 2007/08 MB vs 1971 SB | | | | -9 (-3.6) |

Note: MB – Multi-beam bathymetry; SB – Single-beam bathymetry; SSB1971 – Simulated Single-Beam Bathymetry using locations of 1971 soundings; SSB2000 – Simulated Single-Beam Bathymetry using locations of 2000 soundings.

Figure 5-17 2007 Surface Overlaid with 1971 Data Points



To illustrate the effect of using bathymetry of different densities, the results of three simulations conducted using the full resolution multi-beam bathymetry compared to simulations using single beam bathymetry are also presented in Table 5-4. With these simulations, the level of Lake Michigan-Huron appears to have decreased by 23 to 25 cm (9.1 to 9.8 in). However, this increase in computed conveyance is solely a product of comparing bathymetry datasets collected at two different densities and is therefore not an appropriate comparison.

Using year 2000 bathymetry and year 2007 bathymetry sampled at the same density as the 2000 data (2007SSB2000), the models indicate the level of Lake Michigan-Huron has increased by 1 to 3 cm (0.4 to 1.2 in) from 2000 to 2007. Therefore, it can be concluded that since 2000, the conveyance of the St. Clair River has actually decreased.

All of the models show that the conveyance increased in the river from 1971 to 2007, but the amount varies from model to model and simulation to simulation. The Study standardized the data on which the simulations were based (bathymetry) and the simulations (by using the same water levels and flows for boundary conditions). However, there are differences in each of the models as to the characterization of the bathymetry by the models, the location and characterization of the boundaries of the models, and the assumptions required to develop and execute the models. These differences create minor variations in the estimates of conveyance change. It is not possible to say which estimate is the more accurate. Therefore, only a range of conveyance change estimates are provided, though collectively they provide a high degree of confidence.

A second type of experiment was conducted with the hydraulic models to explore the combined effect of different bathymetries and changing channel roughness. This was accomplished by substituting the 1971 bathymetry into the models and calibrating the model roughness parameters using conventional discharge measurements taken during the 1968 through 1973 period. The premise was that channel roughness in 1971 could have been

different than it was in 2007 due to erosion or other causes and possibly a different bed composition. Channel roughness cannot be measured directly and is usually estimated through the process of calibration. Once the models were calibrated to the 1971 era, the simulated water level from these models was compared to the models calibrated for 2007. Results from Faure (2009b) suggest that the channel may have become rougher since 1971, and thus compensated for some of the change in conveyance seen between 1971 and 2007 resulting from the changes in bathymetry. However, Bruxer (2009) showed that any calibration and subsequent comparisons of models for different years based on measured flow data would be biased by the arbitrary choice of data used to calibrate the models being compared. In RMA2, Manning’s roughness coefficients are used as calibration parameters, and they are therefore adjusted to fit simulated model results to observed data. As such, the roughness coefficients partially represent the actual roughness of the bed material. However, calibration also causes them to account for additional factors, such as uncertainty in the measured water level and flow data, and other characteristics of the flow regime not well represented by the model. A calibrated model is therefore adjusted to fit the data.

Three calibrations were performed on each of the 1971 and two 2007 models (2007 at full density and 2007 at 1971 density) using arbitrarily chosen measured flow and water level data from the same approximate time period as the model bathymetry data and having the same approximate boundary conditions. Table 5-5 shows a comparison of the difference in simulated Fort Gratiot water levels for 1971 and the two 2007 models, and the average difference in observed Fort Gratiot water levels between these two years as determined from the data used in the calibration. Despite uncertainties in the calibration, the differences in simulated results are almost exactly the same as the average difference observed in the calibration data. Had different data been chosen for calibration, the differences in calibrated model results would simply reflect the average difference in the data chosen for calibration. Even a comparison of two perfectly calibrated models having no

Table 5-5 Comparison of Differences in Simulated and Average Observed Fort Gratiot Water Levels
m (ft)

| Measurement Type | Comparison | Calibration 1 | Calibration 2 | Calibration 3 |
|---|------------------|---------------|---------------|---------------|
| Difference in Fort Gratiot water level simulated by calibrated models | 1971-2007 | 0.08 (0.26) | 0.03 (0.10) | 0.07 (0.23) |
| | 1971-2007SSB1971 | 0.09 (0.30) | 0.04 (0.13) | 0.08 (0.26) |
| Average difference in Fort Gratiot water level from observed data | 1971-2007 | 0.09 (0.30) | 0.04 (0.13) | 0.08 (0.26) |

calibration error would be biased by the arbitrary choice of measured data, and would therefore provide no additional information than the measured data themselves regarding whether conveyance has changed. This analysis is limited, given that the data, as well as the calibrations themselves, are not free of error.

The RMA2 modelling completed by the Study was reviewed by Baird and Associates, who previously used RMA2 to estimate conveyance change in the St. Clair River (Baird, 2005). Baird evaluated a different set of scenarios and assumptions than those used by the Study. Even though they used the same 1971 and 2000 bathymetric data to complete their analyses, it was not evident how these data sets were used, and how the initial boundary conditions were set in their model. Based on their suite of modelling assumptions, Baird estimated the conveyance of the river to have increased, resulting in a drop of Lakes Michigan-Huron water level of 23 cm (9 in) between 1971 and 2000. However, the Study also utilized the 1971 and 2000 bathymetry with the RMA2 model and calculated a change in Lake Michigan-Huron water level of 16 cm (6.3 in).²

5.4.3 Effects of Small-Scale Features on Hydraulic Control on St. Clair River

The effects of small-scale features on river conveyance were evaluated, including the effects of apparent scour holes in the upper St. Clair and other bedforms that may be migrating through the river. The Study conducted a number of cut and fill scenarios with the 1-D and 2-D models. These scenarios simulated the effects of filling the deeper sections in the river to determine how the conveyance of the river would change. The model results showed that these small-scale features have little effect on conveyance in the river (Bruxer and Thompson, 2008; Faure, 2009a; Giovannetone, 2008). Furthermore, it was demonstrated that the conveyance in the St. Clair River is not controlled by any one section. Though velocities and Froude numbers in the upper portion of the river are slightly greater than those downstream, the Froude numbers range from only 0.05 to 0.17 and are not high enough to cause critical flow control sections, which require a Froude number of 1 or greater. As part of the Study, Liu and Parker (2009) demonstrated that dredging 4 m (13 ft) of material over a 10 km (6.2 mi) section of the river from the upper portion, middle portion or lower portion of the river produces essentially the same change in conveyance. Faure (2009a) showed that lowering the river by the same amount (10 cm or 3.9 in) from the upper half (Fort Gratiot to St. Clair State Police) or the lower half (St. Clair State

Police to Algonac) resulted in the same effect on conveyance. These results are expected, given that the river is subcritical throughout its length and flow is controlled by the overall channel and the water levels of Lake St. Clair and Lake Michigan-Huron.

5.4.4 Effects of Glacial Isostatic Adjustment on Hydraulics in St. Clair River

The Study also investigated the effect of GIA on the hydraulics of the St. Clair River. Gradient changes of the river bed due to GIA between Sarnia-Port Huron at the head of the St. Clair River and Bar Point on Lake Erie seem to be negligible according to the contours in Figure 2-8 in Chapter 2. However, the contours are estimates only, and as such are not definitive. Therefore, though uncertainty remains due to GIA, the beds of the St. Clair River and Detroit River may be gradually increasing in slope over time, which would tend to increase the discharge in the river.

Based on the discussion in Chapter 6 regarding backwater due to the relative movement between the outlet of Lake Erie relative to the outlet of Lake Michigan-Huron, and assuming the western end of Lake Erie is subsiding at a rate of 10 cm (4 in) a century relative to the outlet of Lake Michigan-Huron, the resulting increase in bed slope between Fort Gratiot at the head of the St. Clair River and Bar Point at the outlet of the Detroit River would be between 0 and 3.5 cm (1.4 in) since 1962. If the more extreme assumption is made that all of this change occurs in the St. Clair River portion of the Michigan-Huron-Erie corridor, then this should capture the maximum effect due to GIA on St. Clair River discharge that might be reasonably expected.

With this in mind, the Telemac-2D and HEC-RAS models were utilized to simulate a lifting of the river bottom at Fort Gratiot (Lake Michigan-Huron) relative to the bottom of Lake St. Clair by first 2.5 cm (1 in) and then 5 cm (2 in). The lake bottom of Lake St. Clair was assumed static for these simulations. The elevations of the nodal (2-D model) or cross-sections (1-D model) between these locations were adjusted linearly to account for this change in slope. The results of these simulations indicate that any possible change in slope that has occurred since the dredging in 1962 is small, with only a negligible effect on discharge over this time.

2 The Study Board undertook a comprehensive review to identify possible reasons for the different estimates of conveyance change determined by the Study and the 2005 Baird Study. A report on the Study Board's conclusions is available through its website <http://www.iugls.org>.

5.4.5 Sensitivity and Uncertainty Analysis

Sensitivity analysis is important because it quantifies the influence of the model inputs and assumptions on the results. Assumptions required in 1-D modelling include cross-section spacing, near-shore bathymetry interpolation method, and the size and locations of ineffective flow areas. For 2-D models, assumptions include grid size, interpolation methods, and boundary elevation data.

The Study conducted simulations to evaluate the influence of these assumptions and ensure that they did not affect the estimates of conveyance change. Full description of the sensitivity analysis performed on the hydraulic models in the Study are included in the Study's technical reports (Giovannettone, 2008; Bruxer and Thompson, 2009; Faure, 2009a; and Liu and Parker, 2009).

Hydraulic models utilize observed bathymetry, water level and discharge data to describe the geometry of the river and to supply the boundary conditions necessary for the simulations. These quantities are measured in the field with varying degrees of accuracy. This introduces significant degrees of uncertainty in the measurements. Survey error exists in the bathymetry data and results from limitations of the measurement equipment, boat movements during the survey, and the referencing of the measurements to the local datum. The magnitude of the survey error is greater in older bathymetry data than more recent data largely as a result of improvements in measurement techniques (see Table 5-6). Additional error is introduced when the raw bathymetry data used in the hydraulic models are necessarily interpolated to the model cross-sections (1-D) or finite element mesh (2-D). Interpolation methods differ, but essentially all involve converting the finite measured survey point elevations to elevations at the

locations of model cross-sections and mesh nodes. Due to the lower density of the data, the interpolation errors are substantially larger for single-beam bathymetry than for multi-beam bathymetry.

The Study quantified how the errors in bathymetry affect the estimates of change in conveyance of the St. Clair River through uncertainty analysis (Bruxer and Thompson, 2009). Uncertainty analysis is a time-consuming and computationally-demanding process, and therefore was only performed using the RMA2 model of the St. Clair River. A Monte Carlo uncertainty analysis was completed on the RMA2 model geometries. In this analysis, thousands of randomly generated probabilistic representations of the model geometry were each evaluated using the RMA2 model. All variables other than bathymetry were kept constant in this analysis, and average boundary conditions were assumed for all model simulations. This logic follows from the simulations summarized in Table 5-7 that evaluated a change in conveyance due to changes in bathymetry alone.

Through the statistical evaluation of the thousands of simulations performed, the conveyance change estimate as defined by the change in Lake Michigan-Huron water level between 1971 and 2007 was found to be approximately 11.5 +/- 2.7 cm (4.5 +/- 1.1 in) and the change between 2000 and 2007 was approximately -2.8 +/- 2.4 cm (-1.10 +/- 0.94 in). Expressed as a discharge, this indicates that flows in the St. Clair River have increased by 275 +/- 68 m³/s (9,712 +/- 2,401 ft³/s) from 1971 to 2007, and decreased by 74 +/- 61 m³/s (2,613 +/- 2,154 ft³/s) from 2000 to 2007 for the same drop in water levels. These estimates were obtained from simulations executed using 2007 bathymetry sampled at the same density as the 1971 and 2000 data (Bruxer, 2009).

Table 5-6 Errors in Bathymetry Data

| Bathymetry Year | Survey Error | Interpolation Error | Total Error |
|-----------------|--------------|---------------------|-------------|
| 1971 | 0.30 (0.98) | 0.89 (2.92) | 0.93 (3.05) |
| 2000 | 0.30 (0.98) | 0.77 (2.53) | 0.81 (2.66) |
| 2007 | 0.15 (0.50) | 0.23 (0.75) | 0.28 (0.92) |

Note: Errors expressed are standard errors in m (ft)

Table 5-7 Conveyance Change Estimate and Uncertainty as a Function of Water Level

| Conveyance Change Estimate (water level) | Mean WL Difference m (ft) | Standard Error m (ft) | 95 % Confidence Interval m (ft) |
|--|---------------------------|------------------------|----------------------------------|
| 2007 SSB1971 vs 1971 | -0.115 (-0.38) | 0.027 (0.089) | 0.053 (0.184) |
| 2007 SSB2000 vs 2000 | 0.028 (0.092) | 0.024 (0.079) | 0.047 (0.155) |

5.4.6 Hydraulic Modelling Analysis Using Inverse Modelling Approach

The HEC-RAS model of the St. Clair River, using the 2007 multi-beam bathymetry, was used to investigate conveyance changes over time through an inverse modelling approach (Holtschlag and Hoard, 2009). In this analysis, the null-hypothesis that the conveyance in the river has not changed since the 1962 dredging was tested by recalibrating the 2007 model. The recalibration was achieved by estimating the effective channel roughness in several reaches of the St. Clair River for each year when water level and flow measurements were available between 1962 and 2006. With this method, trends in effective channel roughness over time can be used to infer changes in conveyance, though the actual cause of the change (*e.g.*, actual bed roughness, cross-sectional area, hydraulic radius) could not be identified.

This inverse 1-D hydrodynamic modelling approach was used to estimate a partial annual series of effective channel-roughness parameters in reaches forming the St. Clair River for 21 years when flow measurements were sufficient to support parameter estimation. Monotonic, persistent but non-monotonic, and irregular changes in estimated effective channel roughness with time were interpreted as systematic changes in conveyances in five out of seven reaches. Time-varying parameter estimates were used to simulate flow throughout the St. Clair River and compute changes in conveyance with time. Over all boundary condition sets, results showed that relative simulated flows increased significantly with the year of parameterization from 1962 to 2002 by as much as 10 percent. Simulated flows decreased, however, about 4.2 percent from 2002 to 2007. Overall, using this ‘inverse modelling’ approach, the net change in conveyance between 1962 and 2007 showed an increase of 5.8 percent or approximately 320 m³/s (11,301 ft³/s), if the mean discharge is taken as 5,500 m³/s (194,233 ft³/s). The uncertainty in these estimates resulting from uncertainties in measured flows and water levels was not quantified, but is expected to be small.

5.4.7 Computation of Conveyance Change from HEC-RAS Modelling

As noted in section 5.4.2, one of the key observations made when comparing bathymetry from different periods is the change in physical features of the St. Clair River. For example, the river appears deeper in 2007 when compared to 1971 in reaches downstream of the mouth of the Black River. To evaluate the impact of the changes on the conveyance of the river, the Study applied one of the features

available in the HEC-RAS model. The term ‘K’ in Equation (1) in section 5.2.1 defines the term “conveyance” based on the physical attributes of the cross-section. The channel properties that define the conveyance at a location are the cross-sectional area, hydraulic radius and Manning’s roughness coefficient. The sectional conveyance values are then integrated over the channel reach by computing the geometric mean of the conveyances of all the sections.

The Study had conducted hydraulic modelling by constructing 1-D HEC-RAS model of the St. Clair River with bathymetry from 1971 and 2007. This analysis relied on the design of HEC-RAS runs for both 1971 and 2007. One variable that is available in the model output at each of the 368 cross-sections is the computed value of conveyance. These values were tabulated both for 1971 and 2007 channel configurations and the geometric mean for all cross-sections were computed and compared.

Comparing the reach based conveyance between Fort Gratiot and Algonac, it was found that the conveyance in 2007 was larger than in 1971. This value of increased conveyance was about 2.5 to 3.2 percent greater than for the 1971 value. This represented an average increase of 140 to 265 m³/s (4,940 to 9,350 ft³/s) of discharge over the corresponding 1971 bathymetry (Stevenson, 2009).

It should be noted that while this increase in conveyance represents a physical reality, the hydraulic conditions that produce this level of increased flows are of a transitory nature. Chapter 8 discusses these considerations in more detail.

5.4.8 Effects of Ice on St. Clair River Conveyance

As part of the Study, the USACE Cold Region Lab investigated the effects that ice has on the flow of the St. Clair River, using HyDAS, a state-space model with data assimilation (Daly, 2002; 2003; Daly and Vuyovich, 2006). This project investigated changes in conveyance of the St. Clair River over time that could have been caused by ice jams on the river. HyDAS assimilates the observed water surface elevations and adjusts the channel conveyance factors based on differences between the calculated and observed stages. The model was calibrated to reflect the conditions in April through October 2006. The model was then applied to the complete period of record where stage and flow data were available (1959-1968, 1979-1985 and 1996-2006). The results included a time series of channel conveyance factors, which were compared to the channel conveyance found during the calibration period.

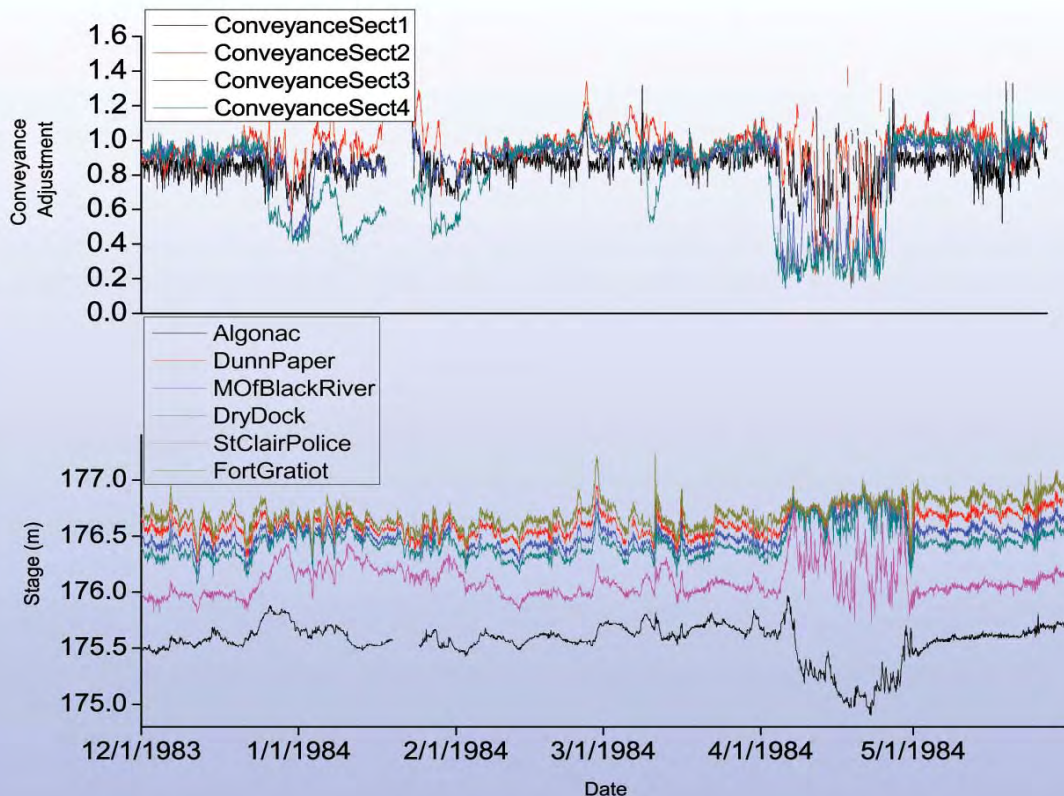
The HyDAS modelling project found that the conveyance of the St. Clair River was reduced in almost all winters in response to the formation of a stationary ice cover in the channel. Generally, the greatest effect of ice was in the downstream-most sub-reach from St. Clair State Police to Algonac gauges. Wintertime conveyance reductions also could be seen in the other sub-reaches, though the severity progressively decreased from downstream to upstream. This likely reflects the pattern of ice cover formation on the St. Clair River, which typically starts downstream and progresses upstream with the upstream extent of the ice cover reflecting the winter severity and the quantity of ice entering from Lake Michigan-Huron.

As seen in Figure 5-18, for the winter of 1983-1984, the largest conveyance reduction occurred when a particularly severe ice jam (known as the “record St. Clair River ice jam”) formed on the St. Clair River during the month of April (Derecki and Quinn, 1986). This ice jam produced the largest overall conveyance reduction by a significant margin in the sub-reach from St. Clair State Police to

Algonac gauges compared to all other winters. Relatively large reductions in conveyance also were seen in the next two upstream reaches.

The conveyance of the sub-reach from Algonac to St. Clair State Police displays interesting trends when viewed over the entire period of record. For the most recent 10-year period of stage data, 1996-2006, the conveyance displays annual variations reflecting the presence of ice and perhaps other factors, but there is no overall trend. During the earliest period, 1959-1968, the conveyance is significantly less than the conveyance of the most recent period. Again, there are annual variations reflecting the presence of ice, but no overall trend. In the middle period, 1979-1985, however, there is a marked increase in conveyance with the channel conveyance reaching the value of the most recent period immediately following the April 1984 ice jam. These findings suggested that this ice jam may have had a significant and long-term effect on the conveyance of the St. Clair River. However, more direct corroboration was needed to achieve reasonable certainty about the postulated role of the 1984 ice jam (Beltaos, 2009).

Figure 5-18 Influence of 1984 Ice Jam on St. Clair River Conveyance and Stages



Kolerski and Shen (2009) applied a model called DynaRICE (Dynamic River ICE) to the St. Clair River to determine if the 1984 ice jam could have increased the bed shear stress sufficiently to cause wide-scale erosion, thereby increasing conveyance. The DynaRICE model is a 2-D ice dynamic model for analyzing dynamic transport and jamming of surface ice in rivers and lakes. The model simulates the coupled dynamics of surface ice motion and water flow, including the flow through and under ice rubble. The model was used to estimate velocities that would have been present under the ice during the 1984 ice jam and consequently the change in bed shear stress. Secondly, the shear stresses generated during ice jam break up were calculated, because often it is during the break up of an ice jam that maximum shear stresses are formed (Beltaos, 2009).

The analysis by Kolerski and Shen (2009) concluded that the ice jam may not have had a significant direct impact on the channel conveyance. This is reasonable, given that the backwater effect of the jam was not significant, as it was constrained by the limited level difference between Lake Michigan-Huron and Lake St. Clair and the large depth of river flow relative to the jam thickness. In fact, the pre and post-jam conveyance values for the 1984 ice season did not change significantly (Daly, 2009), however, the report did show a general trend of increased conveyance before and since 1984. One possible indirect contribution of ice jams to the conveyance increase is the excess water stored in Lake Michigan-Huron during a jam (Derecki and Quinn, 1986). This increase in water storage produces higher lake water levels and temporarily larger discharges into the St. Clair River. Analysis with coupled ice-sediment models would be needed to clarify whether there is a potential for bed change during such ice jam events.

5.4.9 Conclusions from Hydraulic Modelling Analyses

The hydraulic modelling analyses indicate the St. Clair River conveyance has increased between 1971 and 2007. The increase in conveyance is estimated to have caused Lake Michigan-Huron water levels to be lowered by 9 to 13 cm (3.6 to 5.1 in).

In terms of discharge, the St. Clair River can now convey 250 to 275 m³/s (8,830 to 9,710 ft³/s) more water than it could in 1971, given the same set of Lake Michigan-Huron and Lake St. Clair water levels. However, because of the nature of the hydraulic relationship between head and discharge, the relative levels between the lakes adjust to the new hydraulic regime and a new lower water level equilibrium is established, typically within two to three years.

Typically, this results in a lower average conveyance than what the potential channel conveyance capacity would suggest from modelling results. In other words, the relationship between bathymetry and conveyance is non-linear, as can be demonstrated by the HPGs (see section 5.5.1). This change in conveyance can be attributed solely to changes in channel bathymetry occurring at some point between 1971 and 2007. Uncertainty analysis quantifying the propagation of uncertainty in the bathymetry datasets through to the estimate of conveyance change between 1971 and 2007 predicted a change in Lake Michigan-Huron water level between 1971 and 2007 of approximately 11.5 +/- 2.7 cm (standard error) (4.5 +/- 1.1 in). Expressed as a discharge, this indicates that flows in the St. Clair River have increased by 275 +/- 68 m³/s (9,710 +/- 2,400 ft³/s) for the same water level differences in 1971 and in 2007.

The hydraulic models indicate that the conveyance change has reversed slightly since 2000, with the level of Lake Michigan-Huron increasing by 1 to 3 cm (0.4 to 1.2 in) between 2000 and 2007. Uncertainty analysis on this estimate predicts an increase in Lake Michigan-Huron water level between 2000 and 2007 of approximately 2.8 +/- 2.4 cm (1.1 +/- 0.95 in) and a decrease in the discharge of 74 +/- 61 m³/s (2,610 +/- 2,150 ft³/s). Hydraulic model tests showed that small scale, sub-surface features like deep sections of the river have little effect on conveyance in the river. The flow in the St. Clair River is not controlled by any one section, but rather by the conveyance in the entire channel and the difference in levels between Lake Michigan-Huron and Lake St. Clair.

GIA rates in the St. Clair River are small. Simulations indicate that any possible change in slope that has occurred in the St. Clair River since the navigation channel dredging in 1962 is small, with a negligible effect on discharge over this period.

Inverse 1-D hydrodynamic modelling detected persistent and irregular changes in conveyances in five out of seven reaches of the St. Clair River. Time-varying parameter estimates were used to simulate flow throughout the St. Clair River and compute changes in conveyance over time. Results show the relative simulated flows increasing significantly with the year of parameterization from 1962 to 2002, sometimes by as much as 10 percent. Simulated flows decreased, however, about 4.2 percent from 2002 to 2007. Overall, the net conveyance change between 1962 and 2007 is estimated at 5.8 percent, or about 320 m³/s (11,301 ft³/s).

Direct conveyance analysis from 1-D modelling indicates an increase of 2.5 to 3.2 percent in the capacity of the river to discharge flow between 1971 and 2007. This is approximately 140 to 265 m³/s (4,940 to 9,350 ft³/s) of flow.

Ice modelling on the St. Clair River quantified the possible effect of river ice on the conveyance of St. Clair River. It suggested that while the “record St. Clair ice jam” of 1984 may not have had a significant direct and sudden effect on the conveyance of the St. Clair River, seasonal ice jams may have a more gradual, cumulative effect. Ice jams can result in increased water storage and higher lake water levels upstream, leading to larger discharges into the St. Clair River. The combination of the ice-jam followed by the record water levels in 1985 and 1986 were not investigated. These changes in levels are within the timeframe of the changes seen in the gauge relationships and the lake-to-lake relationship.

5.5 CONVEYANCE CHANGE ANALYSIS USING HYDRAULIC PERFORMANCE GRAPHS AND TRADITIONAL RATING CURVES

This section focuses on analyses that used theoretical mathematical relationships, derived using periodically measured flows in the St. Clair River, to compute estimated flows based on recorded levels. Both HPG and traditional stage-fall-discharge relationships were used to investigate whether measured flows could identify changes in the conveyance of the St. Clair River since 1962.

As with other analyses in the Study, there is a degree of uncertainty that can be attributed to the measured data being used to derive the graphs and relationships that were used in these investigations. Uncertainty in the data comes from many sources, including historical data record keeping, limits of the measuring equipment, malfunction of measuring equipment, and evolving hydraulic theories. The measurement of a water level may seem to be relatively straight forward, but local conditions, location of the gauge, datum changes, GIA, and gauge malfunctions can all affect the long-term record and contribute to the uncertainty of any analysis that uses the measured data.

Similarly, the quality of flow measurements depend on the equipment, weather, field crews, and the theories used to translate point velocities to flow in the entire river section. How well a measured flow relates to recorded water levels may depend on how long it takes to make a measurement. The water level regime (high water levels or low water levels) during the period of time for which a relationship is derived may influence the comparison between relationships. Each of these issues has the potential to affect the results or data comparisons.

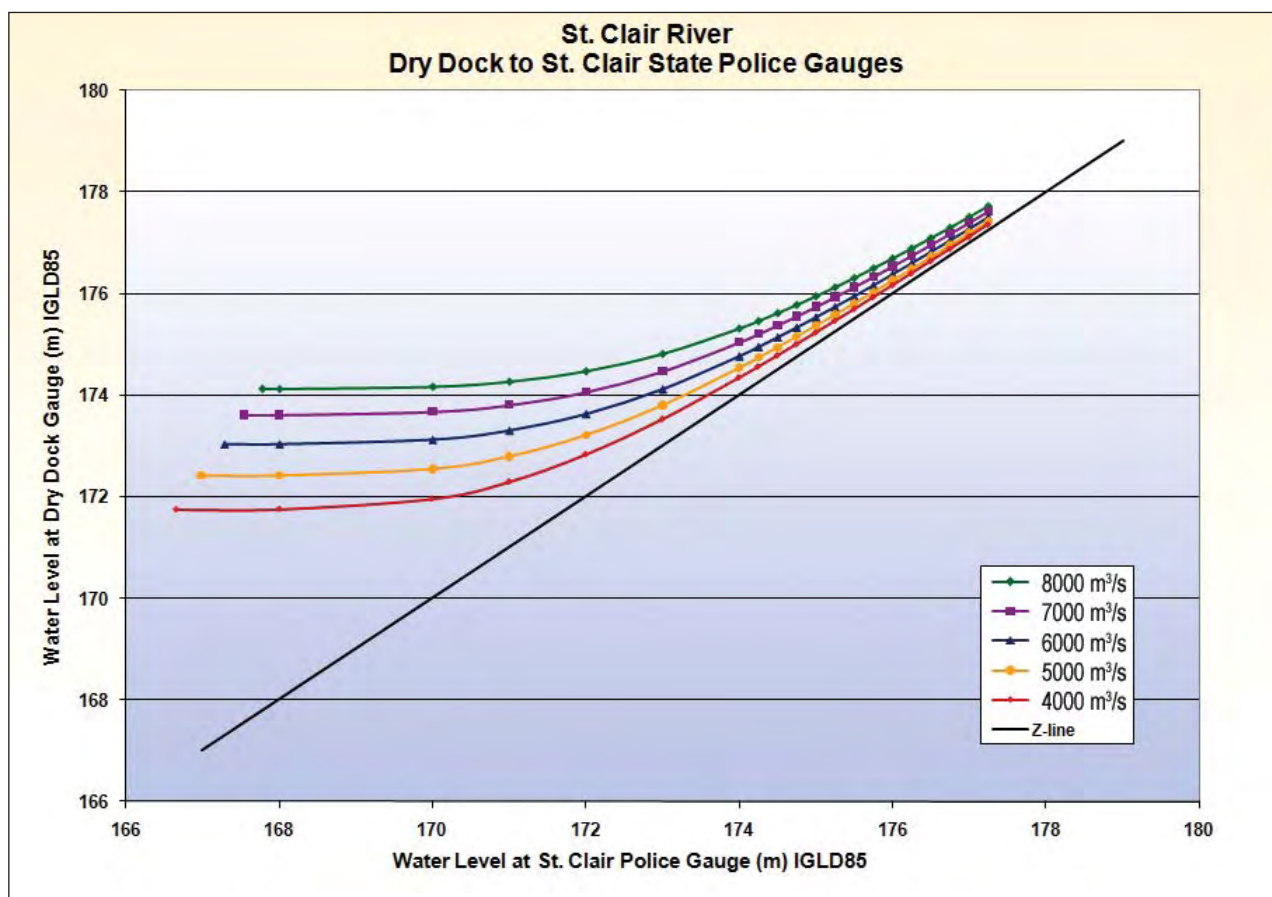
Discharge measurements in the St. Clair River were collected in 1962-1964, 1966, 1968, 1973, 1977, 1979, 1981-1985 and 1996-2006. All measurements were made during non-winter months. A variety of methods, equipment and measurement section set-ups were used over the years. Before 1996, the discharge measurements used in these analyses were made using conventional mechanical flow meters. Since 1996, discharge measurements on the St. Clair River have used ADCPs. From concurrent conventional and ADCP measurements made on the St. Clair River in 2005-2006 and on the Niagara River in 1995 and 1998, it is assumed that the two methodologies produce similar results. However, the differences in the time it takes to make a conventional measurement compared to the much faster ADCP measurements may affect how well the measured flows relate to water levels recorded in the river.

5.5.1 Hydraulic Performance Graphs

A HPG is a set of curves that relate water levels at the upstream and downstream ends of a channel reach to channel discharge, thus providing a tool for describing and visualizing the backwater profiles of a given river reach under a full range of hydraulic scenarios (González-Castro and Ansar, 2003). Figure 5-19 is an example of an HPG for the St. Clair River.

During development of the Study’s modelling strategy, the Study emphasized the use of HPGs as an integrator and visualization tool. While Figure 5-19 can be utilized for presenting the modelling results, the true value of the HPG tool is seen when the results of hydraulic models from two different eras are placed on the same graph.

Figure 5-19 Sample HPG for the St. Clair River



In this regard, the Study ran hydraulic and sediment models using bathymetry from 1971 and 2007 to display HPG. Using the RMA2-based hydraulic model as an example, the HPGs are presented in Figure 5-20. A separation between the HPGs from the two eras indicates a conveyance change. If the 1971 HPG is above the 2007 HPG, then the conveyance has increased between 1971 and 2007, and vice versa. The degree of conveyance change is derived from the vertical shift in the two graphs. From Figure 5-20, the drop in water level, shown as ‘ Δ ’ at the upstream end (Fort Gratiot in this case), for an average flow of 5,680 m^3/s (200,430 ft^3/s), is approximately 12 cm (4.7 in). Figure 5-20 also indicates these HPG graphs shift differently for different flow rates ranging from 4,720 m^3/s (166,600 ft^3/s) to 6,620 m^3/s (233,600 ft^3/s) and are functions of the water surface elevation at the downstream boundary. The HPGs shift for downstream elevation of 175.16 m (574.52 ft) range from 10.2 cm (4.0 in) at 4,720 m^3/s (166,600 ft^3/s) to 14.7 cm (5.8 in) at 6,620 m^3/s (233,600 ft^3/s). If the year 2000 bathymetry based RMA2 model is also plotted on the same graph, it will plot slightly above the 2007 HPG, indicating a slight reversal in the conveyance between 2000 and 2007.

As discussed in Chapter 8, the HPG can also provide an integration platform for various modelling approaches for cross-model visualization.

As part of this Study, Schmidt *et al.* (2009) developed HPGs for the St. Clair and Detroit Rivers and computed flows for the period 1962-2006. The water levels and flows used to construct the curves for the St. Clair River were generated using a 1-D hydraulic model. This 1-D model, based on 2007 bathymetry data and calibrated using discharge measurements collected from 1996 to 2006, is the same model calibrated by Giovannettone (2008) for projects described in previous sections. The HPGs based on this model were used to generate the St. Clair River flows from 1962 through 2006. From 1962 to 1968, these HPG-based flows did not compare well with the measured flows. This could be an indication of conveyance change. To determine more representative flows for the 1962-1968 period, the 1-D model was recalibrated using only discharge measurements from 1962-1968. This model was used to generate another set of HPGs to represent this period. Figure 5-21 shows how the HPG generated flows compared to the measured flows.

Figure 5-20 Using HPGs from Different Eras to Estimate Conveyance Change

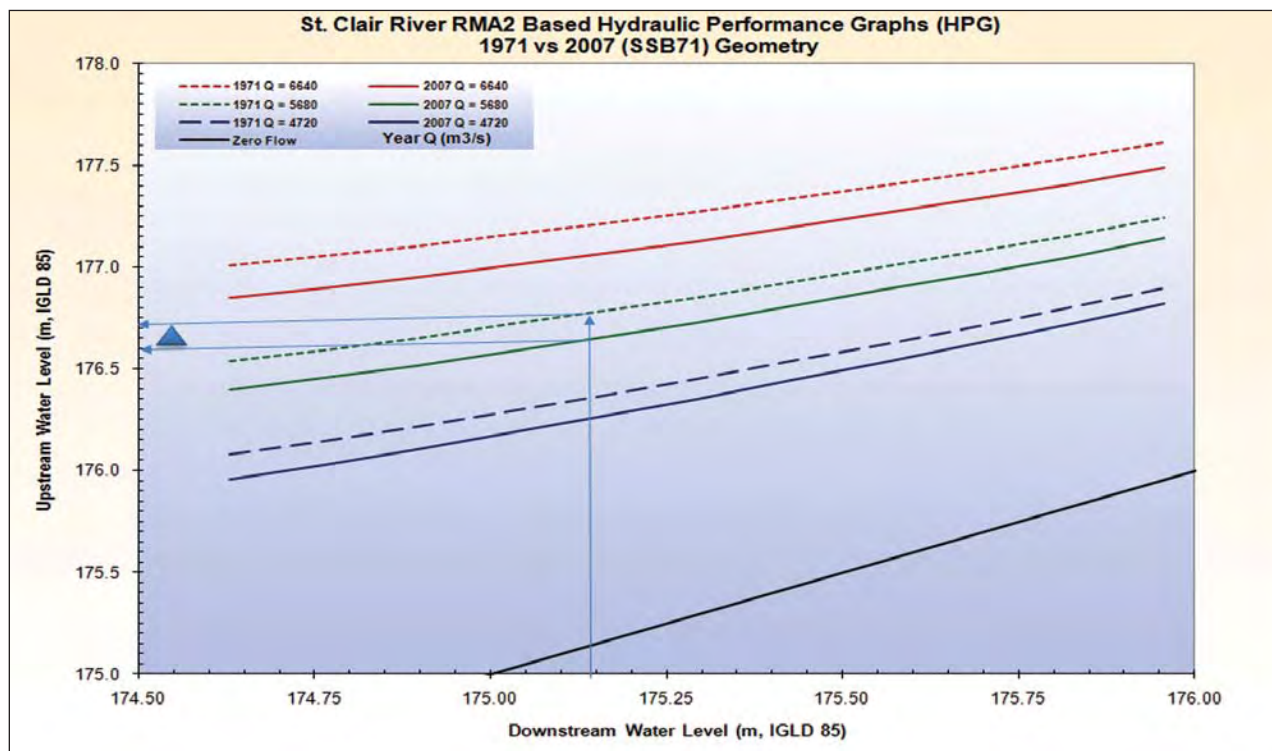
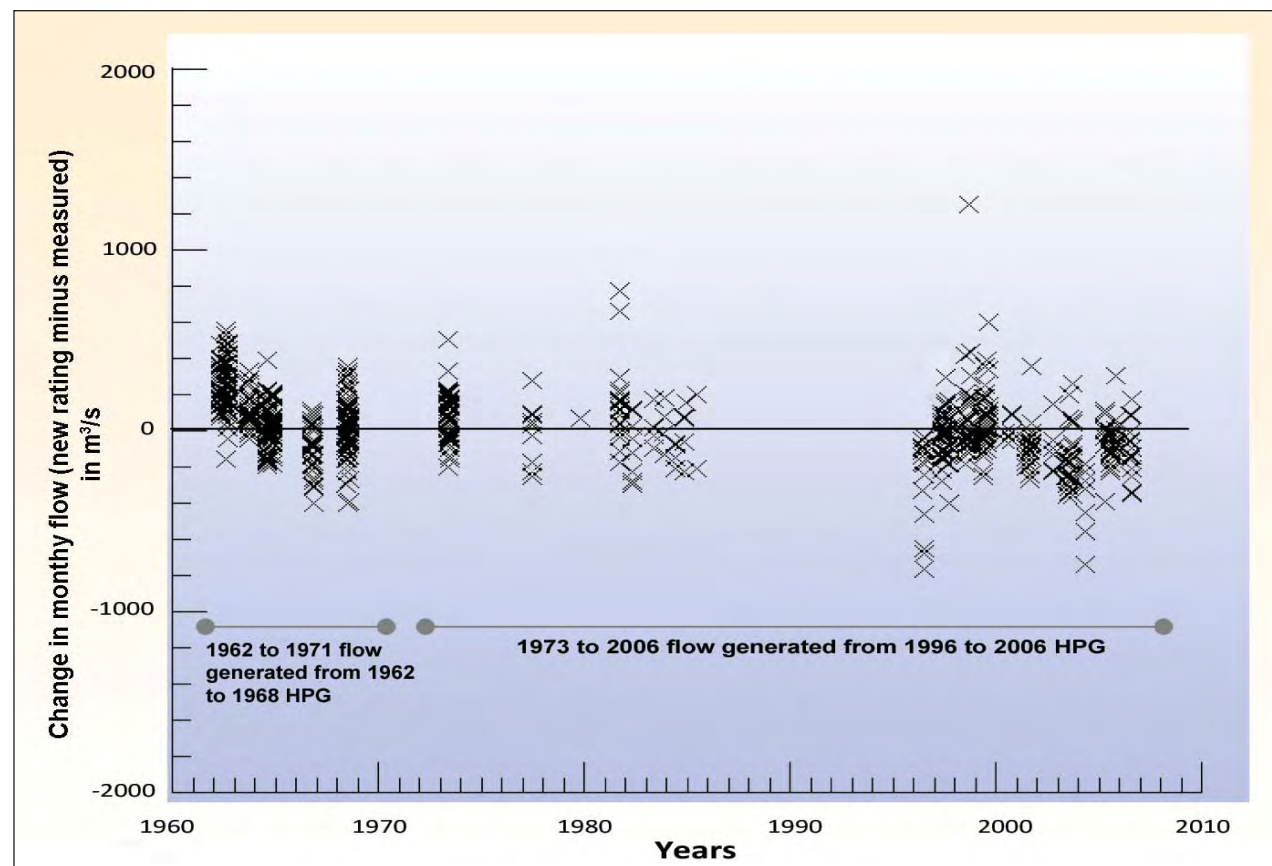


Figure 5-21 Difference between Computed (HPG-based) Flows and Measured Flows



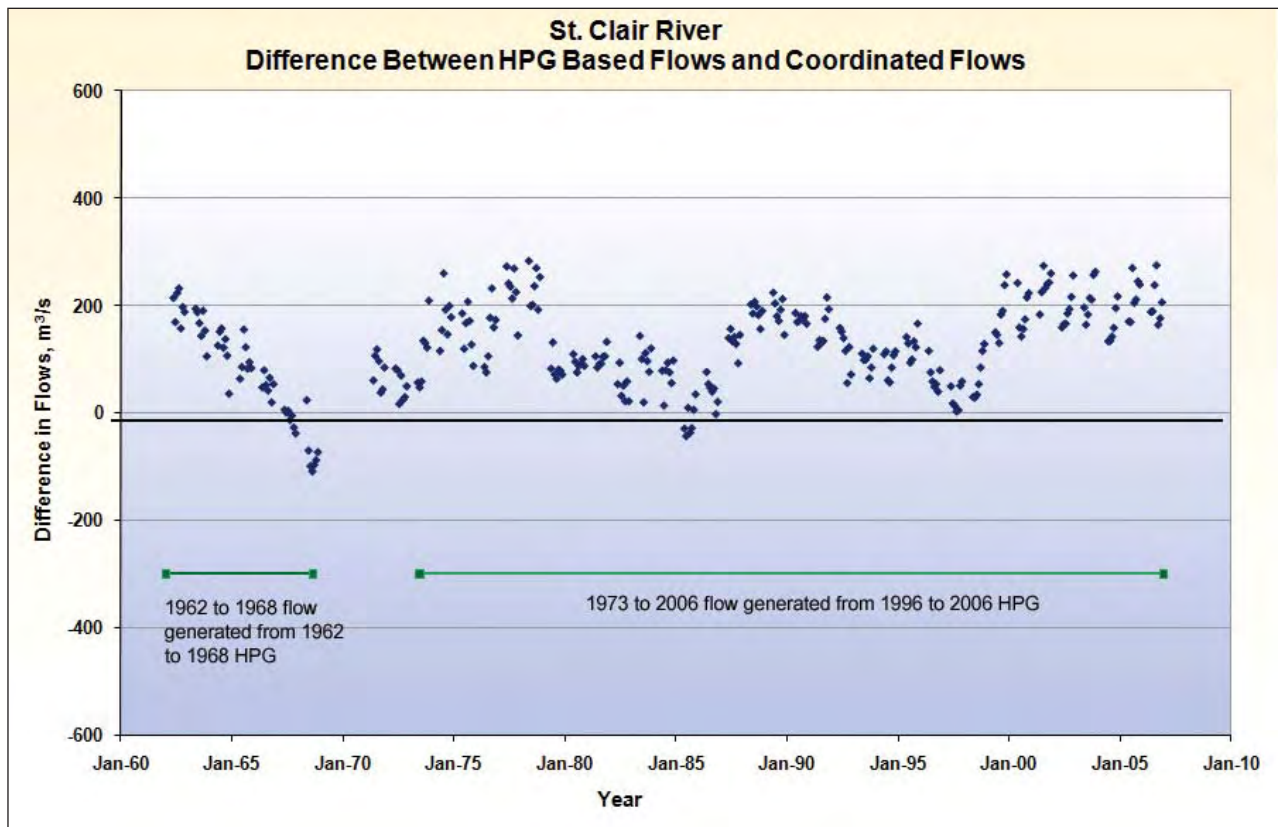
The overall uncertainty in the flows developed from HPGs was estimated based on the residuals between the computed and measured flows. This includes uncertainty from the measured water levels, uncertainty in the measured discharges, and model error that results from the HPG not being a perfect representation of the actual behavior of the river. For the St. Clair River, the standard error for the period 1962-2006 is 197 m³/s (6,957 ft³/s). This standard error is based on using the two different sets of HPGs. For the period between 1962 and 1968, the standard error is 181 m³/s (6,392 ft³/s). For the period 1996 to 2006, the standard error is 217 m³/s (7,663 ft³/s). These standard errors are not dissimilar to the estimates of conveyance change determined through hydraulic modelling.

The HPG-based flows generally are higher than the flows presently coordinated by the ad-hoc Coordinating Committee on the Great Lakes Basic Hydraulics and Hydrology Data (CCGLHHD) (Figure 5-22), particularly when water levels on Lake Michigan-Huron are low. The presently coordinated flows from 1979 to 2006 are partially based on stage-fall-discharge equations that were

derived in 1983 using flow measurements from 1959-1982. If conveyance has changed since 1983, these stage-fall-discharge equations would not adequately represent the present regime, whereas the HPG base data should. The differences between the HPG-based flows and the coordinated historical flows are often within the error of the measurements on which the HPGs are based. Schmidt *et al.* (2009) noted that there was not enough information to determine when a change in channel conditions may have occurred on the river.

The analyses showed that the uncertainty in historical flow measurements and the limited data available need to be considered in any comparison of computed flows over the period. The HPG development was limited by the lack of measured discharges for large portions of the period in question (*e.g.*, no discharge measurements were available between 1985 and 1996). The HPGs were derived using open-water conditions. The process of choosing appropriate reaches and HPGs for winter months, when ice is in the river, needs to be refined.

Figure 5-22 Difference between HPG-Generated Flows and Historical Coordinated Flows



5.5.2 Stage-Fall-Discharge Relationships

Stage-fall-discharge relationships, like HPGs, relate the water level at an upstream and downstream gauge to flow within the reach. In this case, least-squares regression is used to fit a curve through the measured data. The form of the equation traditionally used is patterned after Manning's equation. The equation is generally in the form:

$$Q = a(H_d - base)^b (H_u - H_d)^c \quad (2)$$

Where:

| | |
|-------------------|--|
| Q: | discharge |
| H_u and H_d : | the levels at the upstream and downstream gauges |
| Base: | an estimated effective river bottom elevation; and |
| a, b and c: | empirically-fitted parameters. |

Fay and Kerslake (2009) developed sets of stage-fall-discharge rating equations for two periods: 1962 to 1985, based on conventional measurements of stream flow; and 1996 to 2006, during which time ADCP measurements were collected. Comparing the measured flows to flows derived from the two sets of stage-fall-discharge equations (Figure 5-23) shows some indication of increased conveyance over time. The flows computed using rating equations based on the 1962-1985 discharge measurements do not fit the measured flows well after 1968. The flows computed using the 1996-2006 based rating equations, in general, best fit the measured data from 1973-2006. This suggests that a change in conveyance may have occurred prior to 1973.

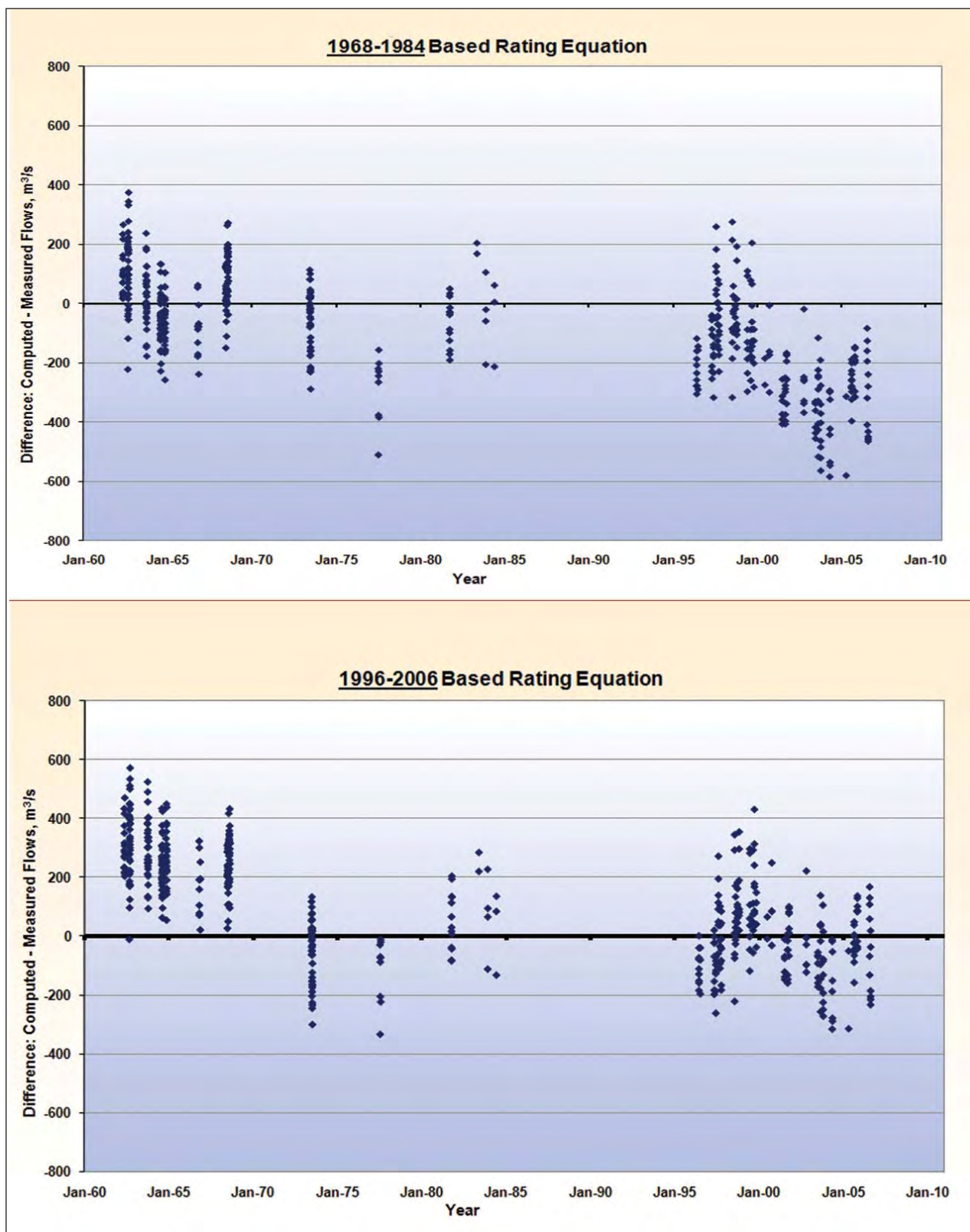
Using the two sets of equations and monthly mean water levels for ice-free months, Fay and Kerslake (2009) computed two sets of flows for the period 1962-2007. These computed flows were compared to the level of Lake Michigan-Huron (Figure 5-24) (Noorbakhsh, 2009).

The stage-fall-discharge equations reported by Fay and Kerslake (2009) also can be adapted to produce the HPGs similar to the hydraulic models. Using the stage-fall relationships to produce a series of discharges from the conventional discharge measurements from the earlier period and comparing this series with similar equations for a later period derived from ADCP measurements, an estimate of conveyance change can be made.

For the St. Clair River, the Study developed HPGs for all of the 10 gauge pairs corresponding to Conventional and ADCP equations. Figure 5-25a illustrates two sets of graphs for plausible ranges of flow and water levels between Fort Gratiot and Algonac. The HPGs are plotted with the upstream level on the vertical axis and the downstream level on the horizontal axis. Therefore, a higher line on the graphs indicates a greater fall is required to produce the same flow (*i.e.*, the conveyance capacity is less). As indicated in Figure 5-25a, for a given flow, in most cases, a higher upstream water level (or greater fall) is needed with the Conventional equations than with the ADCP. This finding shows that there has likely been an increase in the conveyance of the river between the two time periods (1962 to 1985 and 1996 to 2006). In a scenario of a flow of 5,500 m³/s (194,100 ft³/s), the drop in water level at Fort Gratiot for the later period (1996-2006) is about 7 cm (2.8 in) when compared to the HPG from the earlier period (1962-1985). Figure 5-25b presents the HPGs for the two periods between the Mouth of Black River (MBR) and Algonac. Unlike the Fort Gratiot to Algonac relationship, where there is a reversal at the very high and unlikely flows, MBR to Algonac shows a consistent shift in the HPGs. This behavior points toward the need for careful evaluation at the flow coordination stage. However, it should also be noted that there were no flows as high as 7,000 m³/s (247,205 ft³/s) in the dataset used to develop the stage-fall-discharge equations. As a result, the computed flows may not be accurate at these extremely high values. Similarly, there were no flows in the datasets as low as 4,000 m³ (141,260 ft³/s), so the equations may not be accurate at such low extremes.

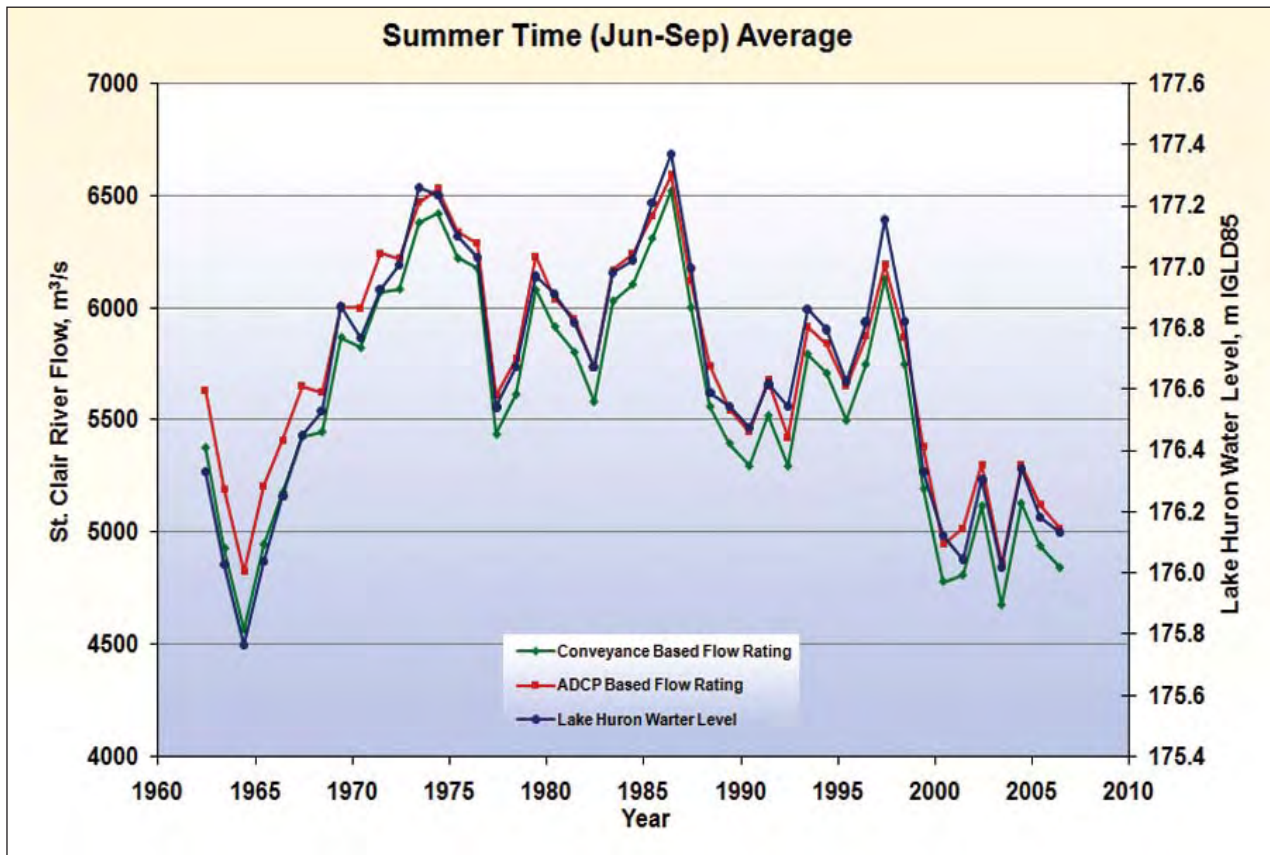
The fluctuation of the flows computed using the 1962-1985 equations mirror the level fluctuations until about 1973. After that time, the flows computed using the 1996-2006 curves compare more favourably. This is another indication that there may have been a change in the flow regime beginning in about 1975. The average differences (1962-1985 and 1996-2006) for the individual equations ranged from 75 m³/s (2,649 ft³/s) (PE-PL) to 275 m³/s (9,712 ft³/s) (DP-PL). The 170 m³/s (6,003 ft³/s) is the average difference for the set of 10 equations, with the 1996-2006 based equations giving higher flows.

Figure 5-23 Comparing Flows Computed Based on Rating Equations to Measured Flows



(One set of computed flows is based on ratings for 1962-1985 (conventional measurements) and one set is based on ratings for 1996-2006 (ADCP measurements).)

Figure 5-24 Comparing Computed Flows to the Level of Lake Michigan-Huron at Lakeport Gauge



Note: The conventional based ratings were derived using discharge measurements from 1968-1985. The ADCP based ratings were derived using discharge measurements from 1996-2006.

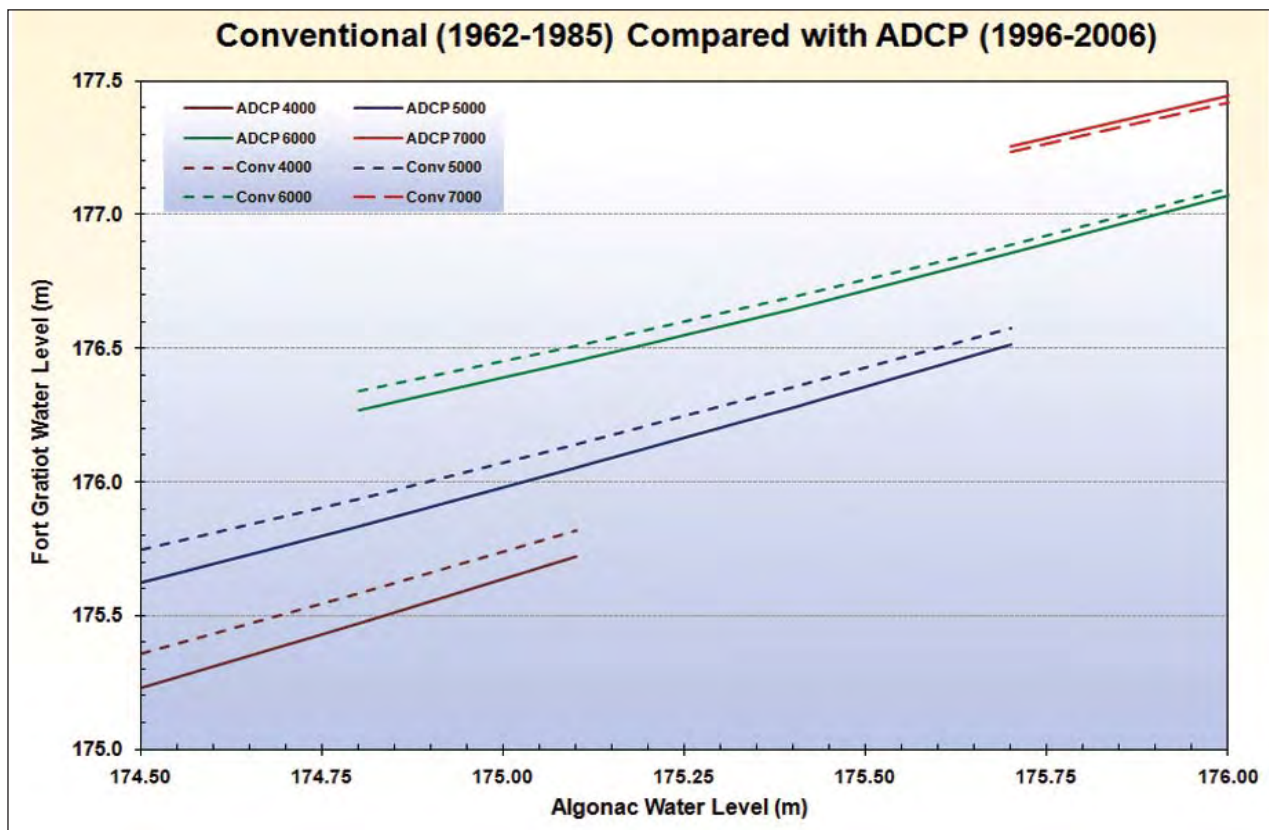
This would represent an increase in flow of about 3 percent. The significance of the 170 m^3 ($6,003 \text{ ft}^3/\text{s}$) difference should, however, be tempered by the fact that it is roughly the same magnitude as the standard error of the individual regression equations and assumes that the different measurement technologies do not bias the results. It demonstrates the difficulties in drawing any definitive conclusions when the computed changes are well within the computed uncertainty bounds. There is also uncertainty associated with the analysis of measured water levels and discharges, as well as the fact that, like all mathematical models, the stage-fall-discharge rating equations are not a true representation of the physical system.

5.5.3 Conclusions of Hydraulic Performance Graphs and Traditional Rating Curves Analyses

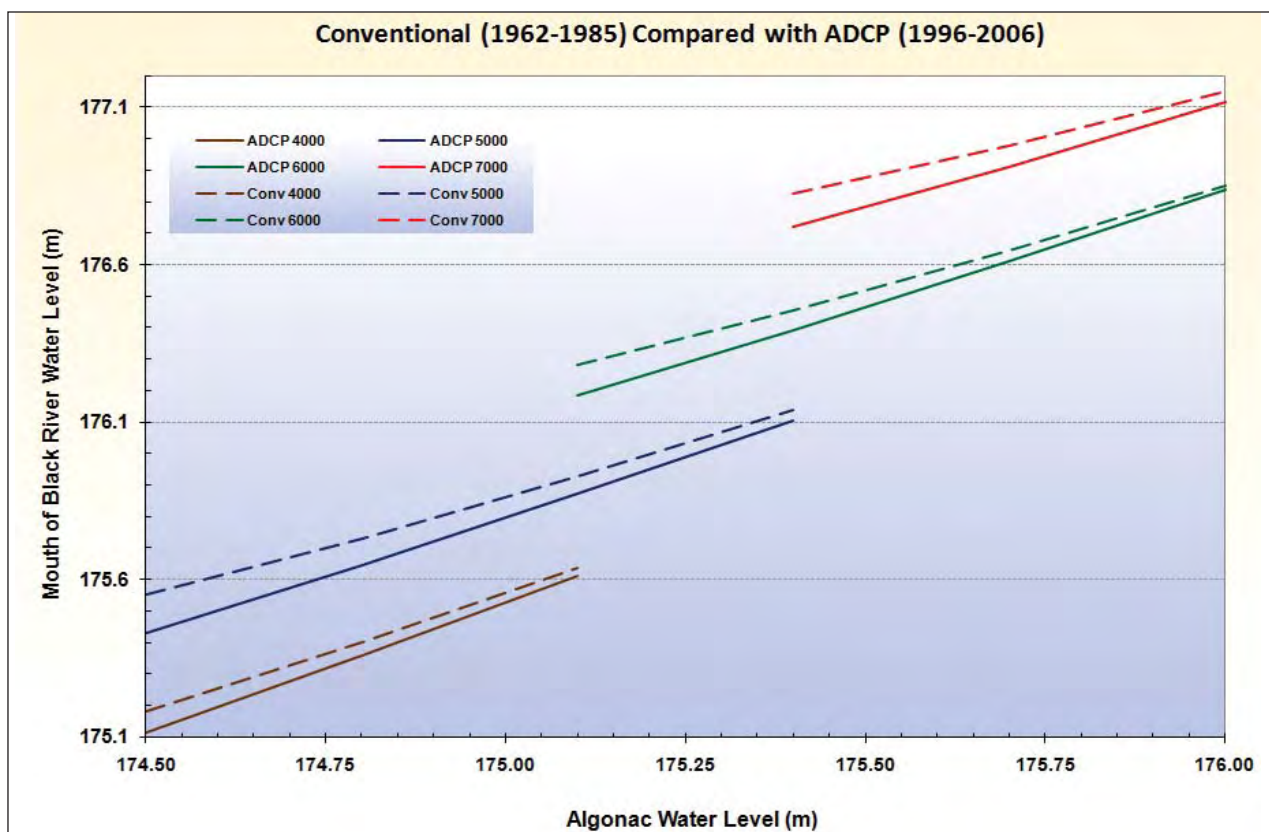
Stage-fall-discharge equations and HPGs, derived using measured discharges and water levels, both suggest that there has been a change in conveyance in the St. Clair River. Both approaches show a change in the relationship between water levels and measured flows sometime in the early 1970s. The stage-fall-discharge analysis indicates that the flow may have increased by an average of about $170 \text{ m}^3/\text{s}$ ($6,003 \text{ ft}^3/\text{s}$), or about 3 percent for the same water levels, after the early 1970s. Taken by themselves, the results of this analysis may not have been conclusive, since the computed changes were well within the error bounds of the analysis. However, they do provide further support to the finding that there has been a conveyance change, given that these independent analytical approaches generally support the direction and magnitude of changes derived from other analytical perspectives.

Figure 5-25 Hydraulic Performance Graph from the Stage-Fall-Discharge Equations

(a) Fort Gratiot to Algonac



(b) Mouth of Black River to Algonac



The use of HPGs and revised discharge equations provide additional supporting evidence of conveyance change in the St. Clair River. These findings are summarized in Table 5-8.

5.6 CONCLUSIONS OF DATA ANALYSIS AND MODELLING

Table 5-9 summarizes the findings of the extensive hydro-metric data and flow analysis and hydraulic modelling undertaken by the Study. This work included six modelling projects and five data and flow analysis projects. Each project looked at the same question from a different analytical approach and perspective. As indicated in Table 5-9, all 11 projects found a common direction and general magnitude of conveyance change.

Table 5-8 Summary of Conveyance Change Estimates from HPG and Discharge Equations

| Method of Analysis | Decline in water level cm (in) | Increase in flow m ³ /s (ft ³ /s) |
|--------------------------------------|-----------------------------------|--|
| Hydraulic performance graph analysis | 12 (4.7) | 290 (10,200) |
| Stage-fall-discharge analysis | 7 (2.8) | 170 (6,000) |

Table 5-9 Impact of Conveyance Change on Decline in the Head Difference Between Lake Michigan-Huron and Lake Erie: Summary of Modelling and Data Analysis Results

| | Type of Analysis | Water Level Change* cm (in) | Flow Change m ³ /s (ft ³ /s) |
|-------------------------------|-------------------------------------|-----------------------------------|--|
| Modelling | | | |
| 1 | 1-D Basic HEC-RAS Modelling | 10 (3.9) | 290 (10,233) |
| 2 | 1-D Inverse HEC-RAS Modelling | – | 320 (11,292) |
| 3 | 1-D Conveyance analysis** | 2.5 to 3.2% | 140 - 290 (4,940 to 10,233) |
| 4 | RMA2 2-D Modelling | 12 (4.7) | 290 (10,233) |
| 5 | TELEMAC 2-D Modelling | 13 (5.1) | – |
| 6 | HydroSed 2-D Sediment Modelling | 9 (3.5) | – |
| Data and Flow Analysis | | | |
| 7 | Lake-to-lake water level analysis | 8 to 10 (3.1 to 3.9) | – |
| 8 | Gauge-to-gauge water level analysis | Up to 14 (5.5) | – |
| 9 | Flow generation with HPG*** | – | 170 (6,000) |
| 10 | HPG analysis | 12 (4.7) | 290 (10,233) |
| 11 | Discharge equation analysis | 7 (2.8) | 75 to 275 (2,646 to 9,704) |

* Positive values expressed as a decline in water level

** Change expressed as percent change in conveyance since 1971

*** Value reported from dynamic simulation of flows; average change reported.

Based on these results, the Study concludes that the increase in conveyance of the St. Clair River is estimated to have caused Lake Michigan-Huron water levels to be lowered by 7 to 14 cm (2.8 to 5.5 in) between 1963 and 2006.

Note that the values for the associated steady state flow change of the St. Clair River listed in Table 5-9 are not sustainable even for short periods of time.

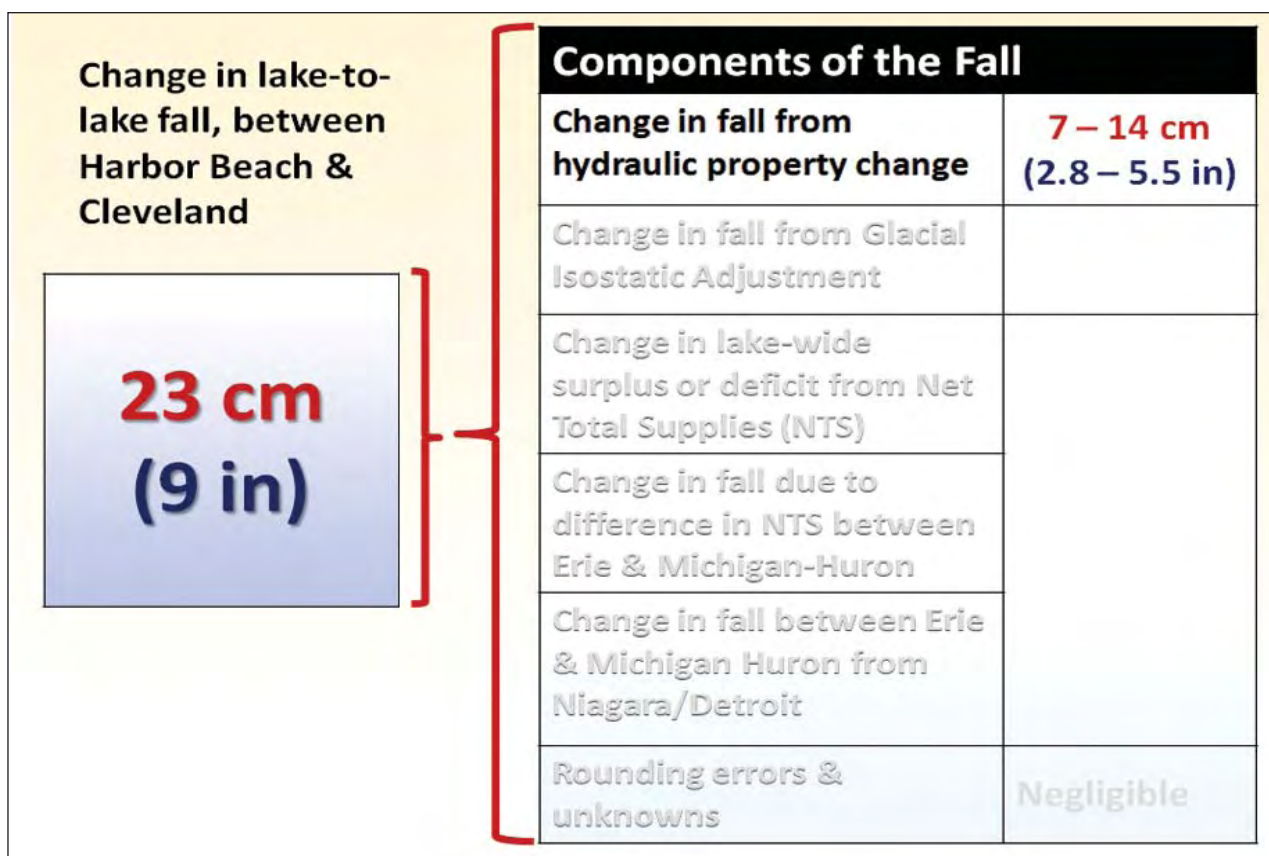
5.7 KEY POINTS

With respect to the science questions regarding the St. Clair River hydraulic regime, the Study finds that the following significant points can be made on the basis of the analyses summarized in this Chapter:

- There has been a change in the conveyance of the St. Clair River, sometime since the last navigational dredging project in 1962, based on the findings of multiple hydraulic modelling and data and flow analyses. The increase in conveyance is estimated to have caused Lake Michigan-Huron water levels to be lowered by 7 to 14 cm (2.8 to 5.5 in) between 1963 and 2006 (Figure 5-26). Each of the Study's 11 independent analytical approaches supported this range.

- The increased conveyance change seems to have stopped, and even reversed, after 2000. The timing of when the conveyance change occurred is difficult to determine with certainty due to a lack of reliable historical data. Different analyses suggest that the change could have occurred in the mid-1970s, in the mid- to late-1980s, and again in the late-1990s. Hydraulic modelling showed that conveyance change has actually reversed slightly since 2000, with the level of Lake Michigan-Huron increasing by 1 to 3 cm (0.4 to 1.2 inches) between 2000 and 2007.
- The changes in the river bed were not confined to a particular section of the river. Analysis and modelling using data collected at water level stations along the St. Clair River indicated that there were changes in conveyance in many, but not all, reaches of the river. In some of these reaches, conveyance increased over time, while in others conveyance decreased. Localized features of the channel, such as deep sections, have little effect on conveyance in the river. The flow in the St. Clair River is not controlled by any one section, but rather by the conveyance in the entire channel and the difference in levels between Lake Michigan-Huron and Lake St. Clair.

Figure 5-26 Study Findings: What factors are responsible for the change in lake-to-lake fall?



- ▶ Overall, the change in conveyance in the St. Clair River since 1962 has been episodic and likely the result of a combination of several factors. Data limitations forced the Study to consider possible changes only since 1971. The Study determined that while the record ice jam of 1984 was not the key contributing factor in the river's change in conveyance, it did appear to play some role. Fluctuations between extreme highs and lows of upper Great Lakes water levels, such as those experienced in the mid-1980s, also could have contributed to the increase in the river's conveyance.
- ▶ The Study's approach to addressing the St. Clair River hydraulic regime was independently peer-reviewed. Peer reviewers confirmed the validity of the overall approach, though they recommended that investigators undertake additional analysis of conveyance change in the river from both modelling and data analysis perspectives. The Study adopted this recommendation and conducted the additional analyses, thereby strengthening confidence in the Study's finding with respect to the relative contribution of conveyance change to the total change in lake-to-lake fall.

CHAPTER 6

GLACIAL ISOSTATIC ADJUSTMENT IN THE UPPER GREAT LAKES BASIN

Chapter 6 presents the analysis and findings of the Study's work on the effects of glacial isostatic adjustment (GIA) on the head difference between Lake Michigan-Huron and Lake Erie, and on the implications of GIA for St. Clair River conveyance and water balance calculations.

6.1 INTRODUCTION

6.1.1 Science Question

As noted in Chapter 3, the Study Board originally planned to analyze and present GIA effects under the hydraulic regime analysis, though it was recognized that GIA also had implications for the analysis of hydroclimatic issues. However, over the course of the data analysis, it was determined that the effects of GIA are likely more important than previously believed, in part because of the methodological limitations of past studies. Moreover, it was recognized that GIA effects, which are ongoing throughout the Great Lakes basin, will need to be better understood and incorporated in future studies of Great Lakes water levels, particularly as the implications of climate change are brought into the analysis.

As a result, the Study Board decided to profile the analysis and findings of GIA effects in a separate chapter in the final report.

The key science question addressed with respect to the effects of GIA in the upper Great Lakes basin is (see Figure 6-1):

How has GIA affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?

The primary GIA analysis focused on using the correct water level data to represent the change in head difference between Lake Michigan-Huron and Lake Erie over time, recognizing and accounting for the effects of GIA and the use of the International Great Lakes Datum (IGLD) on recorded water level data.

The Study also needed to address the sensitivity of results to the water level averaging period used and the level of rounding applied to apparent relative vertical movement rates, water level estimates and their differences.

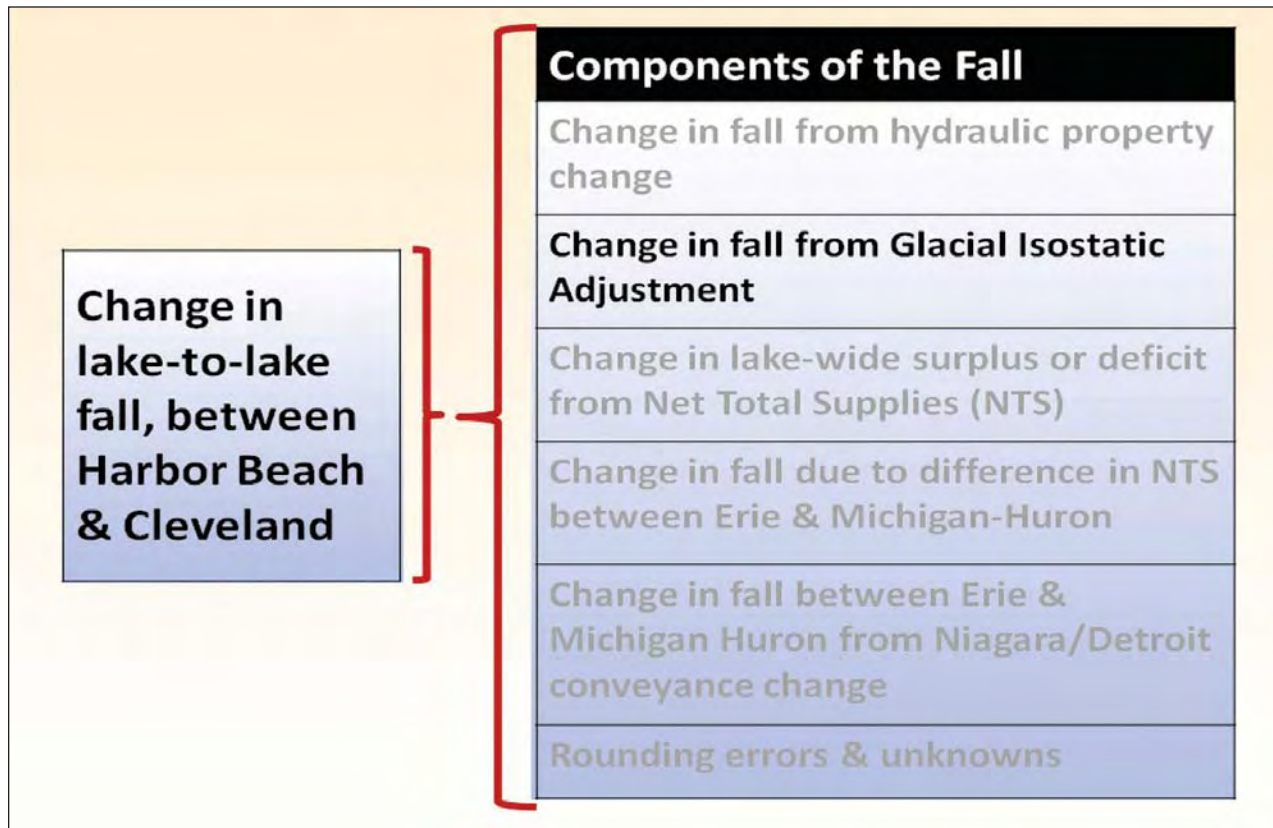
Finally, due to differential GIA, portions of each of the Great Lakes are either rebounding or subsiding relative to their outlets. As a result, each of the lakes is potentially storing or decanting a small amount of water over time due to the differential tilting of their lake basins. Therefore, the Study undertook an analysis to determine whether the effect of GIA on water balance and net basin supply (NBS) calculations was significant and needed to be addressed as part of the analysis.

6.1.2 Background on GIA

During the last period of continental glaciation, which ended in North America about 10,000 years ago, the tremendous weight of the glacier that covered most of the Great Lakes region depressed the earth's crust underneath it. 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 glacier was thicker and remained longer over the areas that became the northern and eastern portions of the Great Lakes basin. As a result, the land in these regions is continuing to rise relative to the centre of the earth (geocentre). At the same time, areas

Figure 6-1 Study Approach: What factors are responsible for the change in lake-to-lake fall?



in the southern and western portions are falling relative to the centre of the earth, as the former “forebulge” area subsides.

Satellite-based Global Positioning System (GPS) measurements taken over the past several years are consistent with this interpretation, showing that the areas formerly beneath the glacier are rising and the forebulge is subsiding in an absolute sense (*i.e.*, relative to the earth’s geocentre) (Henton *et al.*, 2006, Sella *et al.*, 2007). Studies of historical beach ridges on Lakes Superior, Michigan and Huron (*e.g.*, Baedke and Thompson, 2000) suggest that the subsiding forebulge may be a more recent phenomenon.

This GIA process of uneven crustal adjustment (also known as post-glacial rebound) continues today, though at different rates across the Great Lakes basin, affecting water depths throughout each lake. In general, GIA has the effect of gradually tilting the Great Lakes basin over time. This tilting has several implications for water levels. GIA affects land-to-water relationships around each of the Great Lakes, as well as the elevation differences and hydraulic relationships between them. The effect 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.

6.1.3 Study Approach to Determining GIA Effects

A key element of the Study’s approach to determining GIA effects was the recognition that there are two different types of GIA effects to consider:

- the *apparent effect* of GIA on recorded water levels resulting from the change in the land-to-water relationship at water level gauging stations around Lake Michigan-Huron and Lake Erie relative to their lake’s outlet over time due to differential relative crustal movement around each lake; and
- the *physical effect* of GIA due to the impact of absolute and relative vertical movement of key locations on and between Lake Michigan-Huron and Lake Erie on the absolute water levels of the two lakes (*i.e.*, their actual surface elevation at any given time relative to mean sea level).

Apparent and Physical Effects of GIA

The *apparent* effect of GIA on water levels results from the change in the land-to-water relationship around each lake due to the “tilting” of the earth’s crust. Depending on the shoreline location, water levels can appear to be falling or rising over time compared to local frames of reference, such as piers and large rocks, even though the absolute elevation of the water level relative to sea level may not have changed.

The *physical* effect of GIA results from the impact of movement of the earth’s crust on the absolute water levels of the two lakes (*i.e.*, their actual surface elevation at any given time relative to mean sea level).

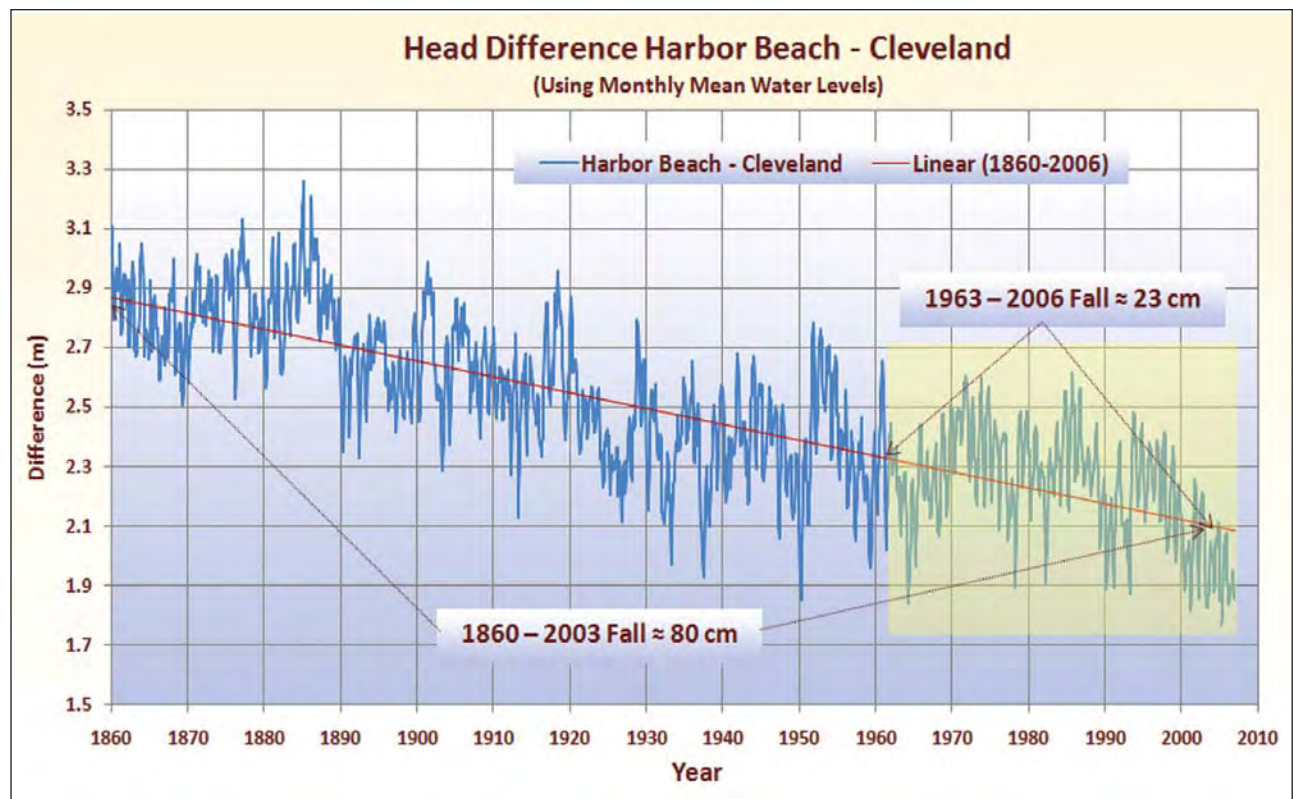
Water levels recorded at Harbor Beach, MI on Lake Michigan-Huron (located about 100 km [62 mi] north of the outlet of the lake) and at Cleveland, OH on Lake Erie have been used in past studies to determine the head difference between Lake Michigan-Huron and Lake Erie over time because of their long period of published records beginning in 1860 (*e.g.*, Baird, 2005). However, the ongoing tilting of the Great Lakes basin due to GIA affects the land-to-water relationship around each lake and can have an effect on the water levels recorded at individual water

level gauging stations. Therefore, the Study undertook a review of the effect of GIA on recorded water levels to determine if the reduction in head differences based on water levels recorded at Harbor Beach and Cleveland as shown in Figure 6-2 properly reflects the changed head difference between Lake Michigan-Huron and Lake Erie over time. The linear regression (trend) line in Figure 6-2 is not intended to suggest that the change shown or the processes behind it are linear in nature. Nevertheless, comparing linear regression trend lines is an appropriate method of investigating the effect of GIA on water levels, as this is generally considered to be a linear process (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data [CCGLHHD], 1977).

To address the science question, the Study needed to consider both the apparent and physical effects of GIA. The Study approached this question using the following steps:

1. Reviewing the current state of knowledge regarding the absolute and relative vertical velocities of the earth’s crust due to GIA in the Great Lakes region.
2. Determining how GIA affects actual water levels on a lake relative to mean sea level as well as water levels recorded with respect to IGLD at locations around each lake over time.

Figure 6-2 Head Difference between Lake Michigan-Huron and Lake Erie



- Determining how these changes are, or are not, reflected in Lake Michigan-Huron minus Lake Erie head difference plots based on recorded water levels.

The Study was then able to conduct an analysis to determine what portion, if any, of the reduction in the head difference between Lake Michigan-Huron and Lake Erie can be reasonably attributed to the apparent and physical effects of GIA.

Step 1. Absolute and Relative Vertical Velocities

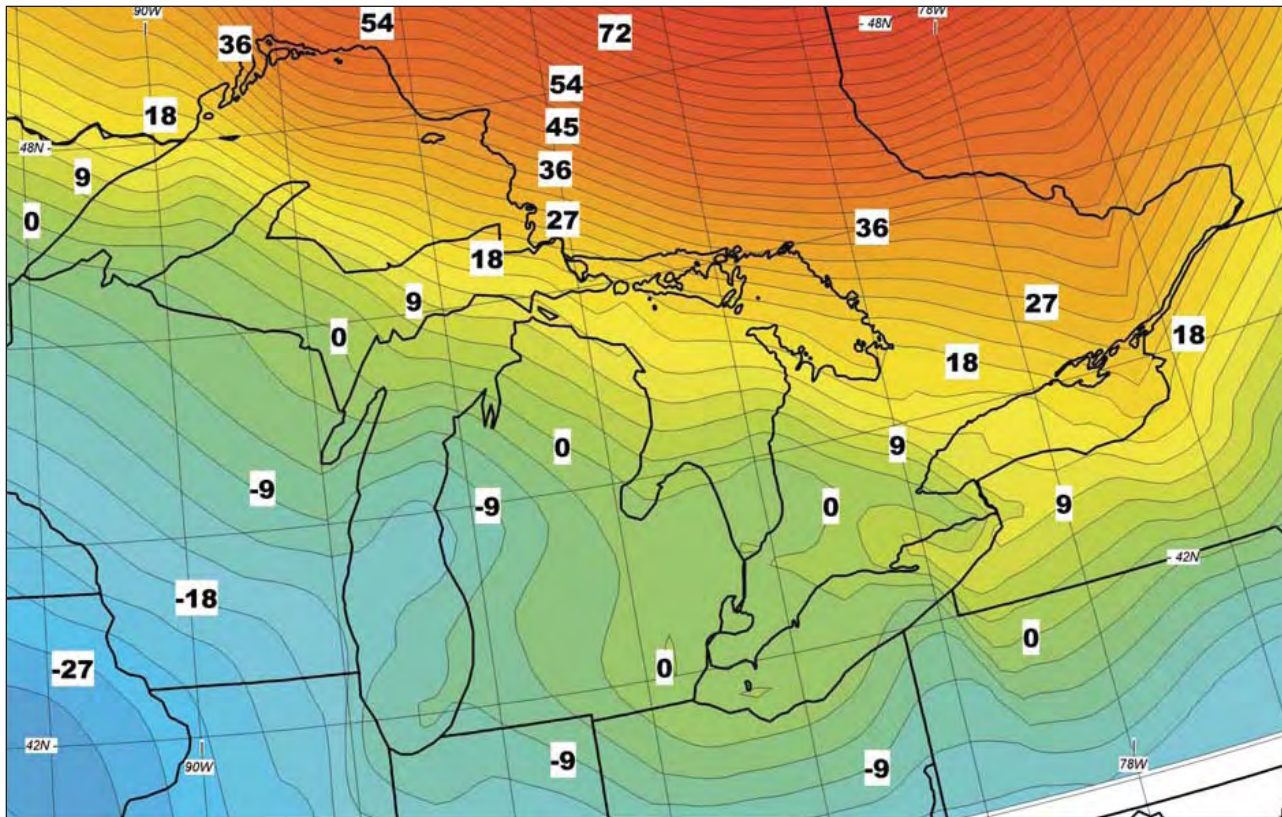
Vertical Movement over the Great Lakes Basin

Figure 6-3 illustrates recent estimates of the absolute vertical movement of the earth's crust over the whole Great Lakes region as determined by Mainville and Craymer (2005). The contours in this figure indicate that the northeastern part of the Great Lakes basin has been rising faster than the southwestern part. Based on the contours shown, it appears that the outlet of Lake Erie is rising at about 7 to 8 cm (2.8 to 3.1 in) per century relative to the

outlet of Lake Michigan-Huron, which appears to be stable. On the other hand, the contours in Figure 6-3 suggest there is little movement between the head of the St. Clair River on Lake Michigan-Huron and the outlet of the Detroit River on Lake Erie due to GIA.

It is important to note that the contours provided in Figure 6-3 are estimates, established by combining the absolute velocities from the ICE-3G global post-glacial rebound model (Tushingham and Peltier, 1991) together with lake gauge-derived relative velocities on each lake. Hence, one must exercise caution in using these vertical movement velocities at any one site or using them to determine the relative movement between sites on two different lakes. In addition, preliminary results from satellite-based GPS measurements (Henton *et al.*, 2006) suggest that much of the southern areas of the Great Lakes Basin are part of the subsiding glacial forebulge. It is possible that the outlet of Lake Erie is falling in absolute terms and relative to the outlet of Lake Michigan-Huron, which may itself be moving in an absolute sense.

Figure 6-3 Glacial Isostatic Adjustment in the Great Lakes Region
(Vertical velocity in centimetres [cm] per century)



Contour map of estimated vertical velocity derived from water level gauges over the Great Lakes and post-glacial rebound modelling.
Contour interval: 3 cm (1.2 in) per century.

Source: Mainville and Craymer (2005)

Therefore, based on available data, it cannot be said for certain whether the outlet of Lake Michigan-Huron is stable in an absolute sense. Nor can it be determined with certainty how, and at what rates, the two ends of Lake Erie are moving in an absolute sense relative to the whole earth or relative to the outlet of Lake Michigan-Huron.

The use of satellite-based GPS techniques is recognized as a highly effective and accurate technology for determining absolute and relative velocities of change in the level of the earth's crust. Continuously operating GPS stations have recently been established at Great Lakes water gauge sites in Canada by Natural Resources Canada's Geodetic Service Division in collaboration with the Ohio State University, and in the United States by the U.S. National Geodetic Survey. Combining the available data from these sites with other periodic GPS measurements is enabling the determination of an accurate and spatially coherent pattern of absolute crustal velocities that is consistent with the expected rates of GIA. The data available from this technology will allow researchers, over several years, to accurately establish the absolute rates of vertical movement at points throughout the Great Lakes region and precisely determine the rates of relative movement between points on each of the Great Lakes as well as Lake St. Clair (Henton *et al.*, 2006, Mainville and Craymer, 2005).

Relative Movement on an Individual Lake

The apparent relative vertical movement between two water level gauging stations on an individual lake can be precisely resolved from a long history of water gauge observations (*e.g.*, CCGLHHD, 1977, 2001; Mainville and Craymer, 2005). After recording water levels at two gauges for many years, their apparent relative vertical movement can be computed. The rate of apparent movement between each pair of stations can be determined through linear regression of the differences between water levels recorded at each station with respect to time. The rate of movement (vertical velocity) is equal to the slope of the linear regression trend line fitted to the plot of the differences each year over time.

Recent estimates of the vertical velocity at the water level gauging stations relative to each lake's outlet are provided in Mainville and Craymer (2005). Mainville and Craymer provide estimates of apparent vertical movement for each station based on the traditional paired-gauges linear regression method described above. However, owing to random errors in the water level data used, the rates obtained on a paired-gauges basis are not necessarily consistent among any three stations. For this reason, they also determined a

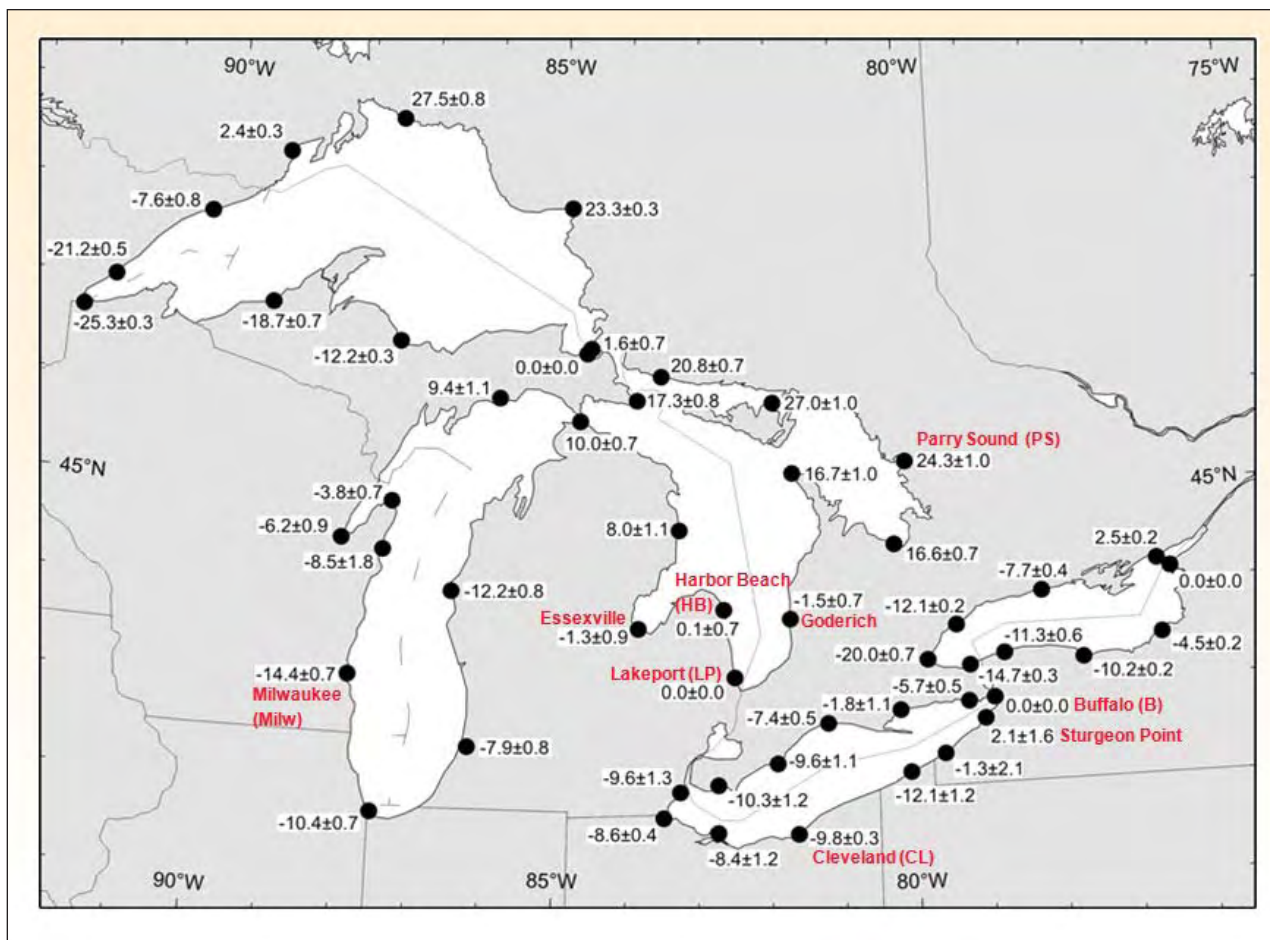
lake-wide adjusted velocity at each station to account for inconsistencies in the paired-gauges results due to site biases resulting from such factors as difference lengths of record and site-specific errors in water level data. These lake-adjusted vertical velocities are shown in Figure 6-4. A positive vertical velocity value indicates that this location is rising relative to the outlet of its lake, and thus the lake's water surface, over time. A negative value indicates that the site is falling (subsiding) relative to the lake's outlet.

The relative vertical velocities shown in Figure 6-4 for Lake Michigan-Huron indicate that the upper portion of the lake, including the Georgian Bay region, is rising, while the lower two-thirds of Lake Michigan is falling relative to the lake's outlet. For example, the velocities shown indicate that Parry Sound, ON (PS) is rising at a rate of about 24 cm (9.4 in) per century while Milwaukee, WI (Milw) is falling at about 14 cm (5.5 in) per century. Harbor Beach (HB) appears to be stable moving at about only 0.1 cm (0.04 in) per century relative to the lake's outlet, which is represented by Lakeport, MI (LP)—the lake level gauge located the closest to the Lake Michigan-Huron outlet. On Lake Erie, the negative velocities shown for all but one site, Sturgeon Point, NY located on the U.S. side near the eastern end of the lake, indicates that virtually all locations around Lake Erie are subsiding with respect to the lake's outlet at Buffalo, NY (B).

GIA affects land-to-water relationships around each of the Great Lakes as a result of differential relative crustal movement between points located on the same lake. For example, based on the rates of relative movement shown in Figure 6-4, between 1963 and 2006, the Parry Sound area rose approximately 10 cm (3.9 in) relative to the Lake Michigan-Huron outlet and the lakes surface, while Milwaukee subsided by about 6 cm (2.4 in) over the same period of time. On Lake Superior, most locations on the Canadian shoreline are rising with respect to that lake's outlet, while points along the U.S. shoreline are subsiding. On Lakes Erie and Ontario, most locations are subsiding with respect to their outlets and water surfaces.

Estimates of relative vertical velocity rates between gauge locations can be sensitive to the period of record, length of record and water level averaging period used. Care must be taken when using published relative vertical velocities for specific analysis purposes.

Figure 6-4 Estimates of Relative Vertical Crustal Velocity at Selected Sites in the Great Lakes (centimetres [cm] per century)



Note: Estimates of vertical crustal velocity and their standard error at water level gauge 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, Point Iroquois for Lake Superior, in cm per century.

Source: Mainville and Craymer (2005)

Step 2. The Impact of GIA on Water Levels

The Impact of Absolute Vertical Movement on Actual and Recorded Water Levels

The actual elevation of a lake's surface as a whole relative to mean sea level may be gradually rising or falling due to the absolute vertical movement up or down of the lake's outlet due to GIA. The lake's outlet is important because the outflow of a lake with a natural outlet depends in whole or in part on the depth of water at its outlet. If the outlets of two lakes are moving at different rates, the relative movement between the two outlets will cause the head difference between two lakes to either increase or decrease over time.

As noted in Chapter 2, however, the water levels throughout the Great Lakes are currently measured relative to IGLD 1985. IGLD is updated every 25 to 30 years to correct for differential movement of the earth's crust in the Great Lakes region and bring the elevations of the water level gauges up to date. To convert the historical water level data at a gauge from one vertical data datum to the next (e.g., IGLD 1955 to IGLD 1985), a constant value is added to the historical water level data at that gauge. For example, to convert the historical water levels at Lakeport and Buffalo from IGLD 1955 to IGLD 1985, their historical water level data referred to IGLD 1955 were increased by 0.202 m and 0.203 m (0.66 ft), respectively (CCGLHHD, 1995).

Based on these adjustments, an analysis might conclude that the absolute elevations of both Lakeport and Buffalo increased about 20 cm (7.9 in) from 1955 to 1985, and that there was virtually no change in the relative difference between their surfaces due to absolute movement over that time. However, IGLD update adjustments can reflect more than just the movement over the basin due to GIA (*e.g.*, local subsidence, measurement techniques). As such, it would be incorrect to draw either of these conclusions, particularly in light of the smaller rates of absolute vertical movement suggested in both Figure 6-3 and the preliminary results of the GPS work by Henton *et al.* (2006).

Between periodic updates, IGLD represents a fixed frame of reference being used to measure water levels in a moving environment. As a result, changes in the absolute elevation of each lake's surface and the relative head difference between lakes are accounted for in the adjustments applied to elevations of the controlling benchmark and the historical water level data recorded at each gauging station during each IGLD update. Therefore, changes in the actual elevation of a lake's surface due to the movement of its outlet as a result of GIA are not reflected in water levels recorded with respect to IGLD as they take place over time between IGLD updates (with the possible exception of related changes due to backwater effect or changes in discharge relationships).

The Impact of Relative Movement on Observed and Recorded Water Levels

An important factor in determining GIA effects is how the trends in relative movement on an individual lake, as shown in Figure 6-4, affect the land-to-water relationship around that lake, and, in turn, how this relationship is perceived by those observing water levels and how it is reflected in recorded water level data referred to IGLD at different gauge locations.

How water depths and apparent water levels change over time at any point along the shoreline on an individual lake due to GIA depends on the direction and rate of movement of that particular shoreline location relative to the lake's outlet. As before, Parry Sound and Milwaukee have been chosen here for discussion purposes.

At locations that are rising at a given rate over time relative to their lake's outlet, such as Parry Sound, water levels appear to be falling at an equal and opposite rate compared to those recorded at the outlet. Conversely, at sites that are subsiding relative to their lake's outlet, such as Milwaukee, water levels appear to be rising over time compared to those recorded at the lake's outlet. Observed water levels at Parry Sound and Milwaukee track up and down with levels at Lakeport reflecting the pattern of highs and lows experienced on Lake Michigan-Huron as a whole.

However, the *apparent* water levels at these sites also reflect the impact of relative movement between their locations and the Lake Michigan-Huron outlet. Therefore, water depths and water levels observed and recorded on IGLD at Parry Sound appear to be falling over time compared to those recorded at Lakeport and compared to local frames of references (*e.g.*, piers, docks, large rocks) for the same lake-wide average water level. At the same time, water depths as well as water levels observed and recorded at Milwaukee appear to be increasing over time.

In fact, the actual water levels at Parry Sound and Milwaukee are not falling nor rising over time relative to those at Lakeport as suggested by the recorded data and visual comparisons. This is because all three sites are located on Lake Michigan-Huron, which, as is the case for each of the Great Lakes, is considered to have a geopotentially equal (*i.e.*, level) water surface (CCGLHHD, 1995). Allowing for short-period fluctuations due to meteorological disturbances and local effects, the actual water level at all points on and around Michigan-Huron is at the same elevation above mean sea level.

The apparent downward and upward trends in water levels observed at Parry Sound and Milwaukee, respectively, and reflected in their recorded data compared to those recorded at Lakeport, are due to the change in the land-to-water relationship at these locations as the earth's crust at these locations rises or falls relative to the Michigan-Huron outlet over time. Although the rates of crustal tilting driven by GIA on each lake are not particularly large, the impact of the tilting steadily accumulates over time. Based on the example provided in Step 1, between 1963 and 2006 observed and recorded water levels at Parry Sound fell about 10 cm (3.9 in) relative to those recorded at Lakeport. At the same time, levels at Milwaukee increased by about 6 cm (2.4 in) over the same period of time. Given that the entire Georgian Bay area continues to rise relative to the outlet of Lake Michigan-Huron, depths along its shoreline will continue to decrease for any given lake level with time. On the other hand, the southern portion of Lake Michigan will get deeper for any given lake level. Similar circumstances are occurring on each of the Great Lakes as land-to-water relationships around each of the lakes change as a result of relative movement on each lake due to GIA.

Step 3. Determining the Head Difference between Lake Michigan-Huron and Lake Erie over Time

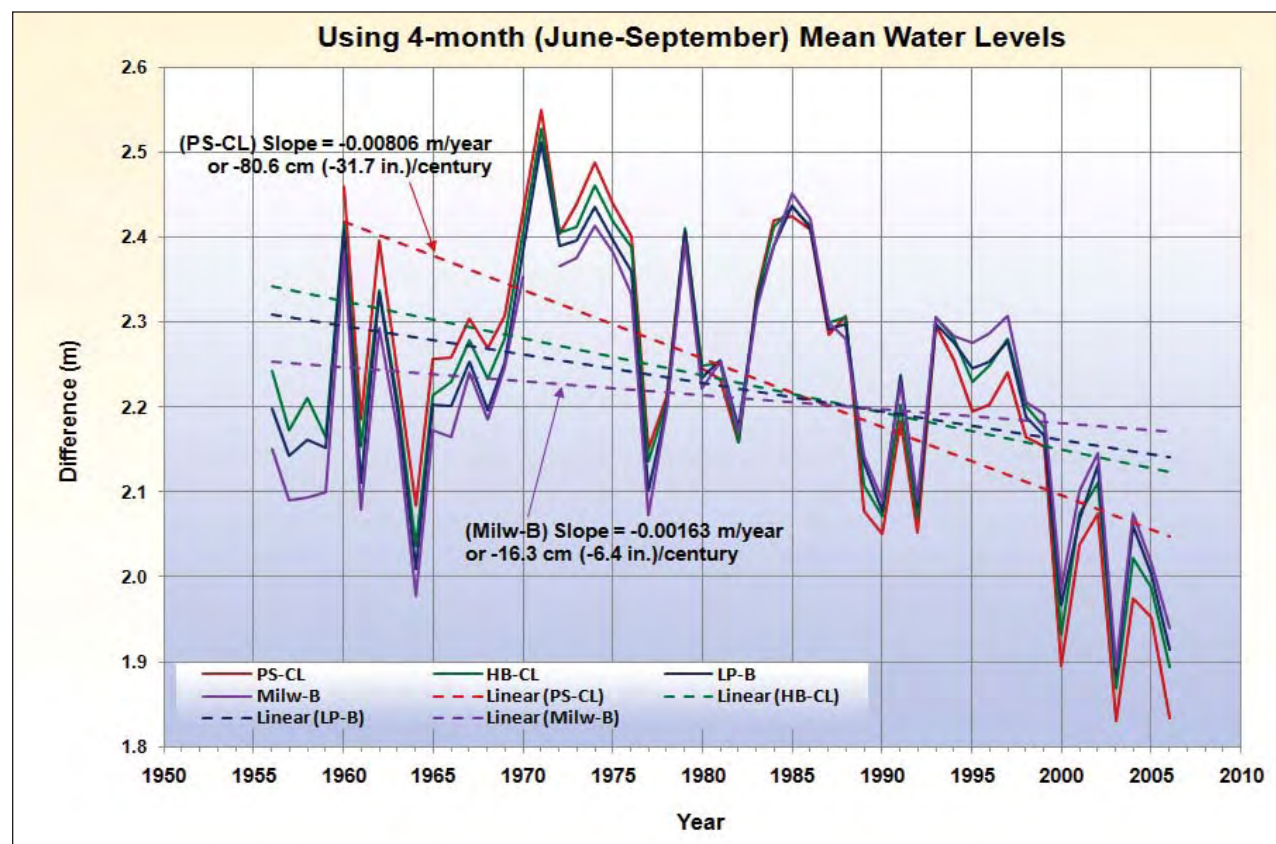
As noted earlier, the water levels recorded at Harbor Beach and Cleveland have been used in the past to determine the head difference between Lake Michigan-Huron and Lake Erie over time. Freeman (1926), however, determined that, "...so long as dependence in determining the difference in elevation between Lake Huron and Lake Erie is placed on comparisons of readings at the Harbor Beach gage with readings at the Cleveland gage and not on comparisons of actual water elevations in the two lakes measured close to the head of the St. Clair River and close to the foot of the Detroit River...", the tilting of the Great Lakes basin due to GIA over time "...would introduce a gradually increasing error in the apparent drop from lake to lake (making it appear too small in recent years)".

Freeman (1926) understood the impact of GIA on recorded water level data and noted the need to compare actual (*i.e.*, absolute) water elevations on Lake Michigan-Huron and

Lake Erie¹ to determine the head difference between the two lakes. However, actual elevations for water levels on Lake Michigan-Huron and Lake Erie are not available over time. As noted, the water levels of the Great Lakes are currently measured relative to IGLD. Recorded water level data referred to IGLD 1985 at a water level gauge reflect the elevation assigned to its controlling benchmark when IGLD 1985 was established and the impact of relative movement between the gauge's location and its lake's outlet over time.

Figure 6-5 highlights the need to consider the effects of GIA on recorded water levels when plotting and interpreting the apparent change in lake-to-lake head difference based on recorded water levels. It illustrates the apparent change in the head difference between Lake Michigan-Huron and Lake Erie over time, based on the differences between water levels recorded with respect to IGLD 1985 at four different "Lake Michigan-Huron minus Lake Erie" gauge pairs selected for demonstration purposes: Parry Sound minus Cleveland (PS-CL); Harbor Beach minus Cleveland (HB-CL); Lakeport minus Buffalo (LP-B); and Milwaukee minus Buffalo (Milw-B).

Figure 6-5 Apparent Head Difference between Lake Michigan-Huron and Lake Erie over Time
(Based on the differences between water levels recorded at different gauge pairs)



¹ Given that both Lake Michigan-Huron and Lake Erie are considered to have geopotentially equal (*i.e.*, level) water surfaces, the difference between absolute water level elevations at any locations on the two lakes would give the actual head difference between them.

Note that water level differences plotted in Figure 6-5 are based on the mean water levels recorded at each gauge location during the four-month period from June to September every year. This period is typically used for plotting differences between water levels recorded at Great Lakes gauges, because the surface of a lake is more likely to be calm during these months than during the stormy seasons of spring, fall and winter.

The differences between the head difference plots² and their linear regressions produced by the four gauge pairs demonstrate that the apparent change in the Lake Michigan-Huron to Lake Erie head difference over time, when based on recorded water level data, is a function of the gauges used.

The difference plots and their regression lines are also a function of the use of IGLD 1985 water level data as well as the period and length of record used. The year-to-year differences for all four pairs are similar during years close to 1985 (and their regression lines cross near 1985) because the water level differences are based on IGLD 1985 water levels, which were brought back into harmony (to a common average date) on each lake using water level adjustments based on 1982-1988 June to September water level data. (*i.e.*, they all refer to a common date of 1985). In addition, the slopes of the linear trend lines can be sensitive to the period of record and the length of record used to determine them. For example, the Parry Sound minus Cleveland (PS-CL) plot begins in 1960, not 1956 as is the case for the other three differences plots. As a result, its linear trend line is slightly steeper than it would be if 1956-1959 differences were available and could be included. Finally, it is clear that the change in fall over a given period of time is significantly affected by the start and end years selected, regardless of the gauge pair used. The actual year-to-year differences reflect all factors affecting the water levels on each lake and the head difference between them at any given point in time.

Figure 6-5 and the discussion leading up to it in Steps 1 through 3 demonstrate that analyses must consider the effect of GIA and the use of IGLD on recorded water level data if it is used to estimate changes in the head difference between two lakes over time. If the change in the Lake Michigan-Huron and Lake Erie head difference over time is estimated based on the difference between water levels recorded on IGLD, then the *apparent effect* of GIA on the estimated change in fall must be determined as well as the *physical effect* of GIA.

The next two sections detail the Study's approach to addressing these two aspects of GIA effects to identify what portion, if any, of the apparent reduction in head difference between Lake Michigan-Huron and Lake Erie (as shown in Figure 6-2 based on water levels recorded at Harbor Beach and Cleveland) can be reasonably attributed to the apparent and physical effect of GIA.

6.2 DETERMINING THE APPARENT EFFECT OF GIA

6.2.1 Data and Analysis

Following a review of the effects of GIA on recorded water level data, the Study concluded that, due to the impact of GIA on the land-to-water relationship around each lake and the use of IGLD, the fall relationship between Lake Michigan-Huron and Lake Erie should be based on the differences between water levels recorded at the lake gauges located closest to the outlet of each lake (Quinn and Southam, 2008). The closest gauge on Lake Michigan-Huron is at Lakeport and on Lake Erie at Buffalo. (This is not to say that Lakeport minus Buffalo represents the actual change in head difference between Lake Michigan-Huron and Lake Erie over time, but that they should be used in order to address the issues related to GIA.)

By comparing the change in head difference between levels recorded at Lakeport and Buffalo with the change in apparent head between Harbor Beach and Cleveland over the same period of time, it is possible to identify the portion of the change in head difference shown in Figure 6-2 that can be reasonably attributed to the apparent effect of GIA on water levels recorded at Harbor Beach and Cleveland.

Harbor Beach versus Lakeport

The +0.1 cm (+0.04 in) per century lake-wide adjusted velocity estimate shown for Harbor Beach (relative to Lakeport) in Figure 6-4 suggests that there is almost no relative movement between Harbor Beach and the Lake Michigan-Huron outlet. As such, it would seem possible to use water levels recorded at Harbor Beach almost as well as levels recorded at Lakeport to represent Lake Michigan-Huron's IGLD water level at its outlet.

2 Plots are the graphical representation of the head difference variation over time for a pair of water level gauges, usually on two different lakes.

However, consider Figure 6-6, which illustrates the linear trend line fitted to the paired-gauges plot of 1956-2006 Lakeport minus Harbor Beach (LP-HB) water level differences. The trend line's $+0.00032$ m ($+0.001$ ft) per year (or $+3.2$ cm [$+1.3$ in]) per century slope suggests that the Harbor Beach area is rising relative to Lakeport. This value is equal to the paired-gauges estimate of relative movement determined by Mainville and Craymer (2005) between these two locations based on 1955-2000 monthly mean water level data. The near-zero value provided in Figure 6-4 may be the result of the lake-wide adjustment process that sought to reconcile the apparent uplift at Harbor Beach relative to Lakeport with the apparent subsidence at both Essexville and Goderich, located nearby.

A key point for this analysis is that there has been a small but evident upward trend in the Lakeport minus Harbor Beach plot over the past 50 years. This trend indicates that there is a downward trend in the recorded water levels at Harbor Beach at an equal and opposite rate of about -3.2 cm (-1.3 in) per century compared to those recorded at Lakeport.

It is also possible that IGLD water levels recorded at Lakeport are falling relative to those that would be measured right at the outlet of Lake Michigan-Huron. However, given the small rate of apparent movement between Harbor Beach and Lakeport and Lakeport's close proximity to the outlet, it is assumed that the rate of decline of water levels at Lakeport due to upward vertical movement at Lakeport relative to the Lake Michigan-Huron outlet over time, if any, would be very small.

Cleveland versus Buffalo

The -9.8 cm (-3.9 in) per century lake-wide adjusted vertical velocity shown for Cleveland in Figure 6-4 indicates that the Cleveland area has been falling relative to the lake's outlet over time. In this case, the -7.0 cm (-2.8 in) per century slope of the 1956-2006 Buffalo minus Cleveland linear trend line in Figure 6-7 is less than the -9.8 cm (-3.9 in) per century value provided in Figure 6-4. The latter value, however, is based on the Buffalo minus Cleveland monthly water level differences available over the 1860-2000 period.

Figure 6-6 Rate of Change of Water Level Differences between Lakeport (LP) and Harbor Beach (HB): 1956-2006

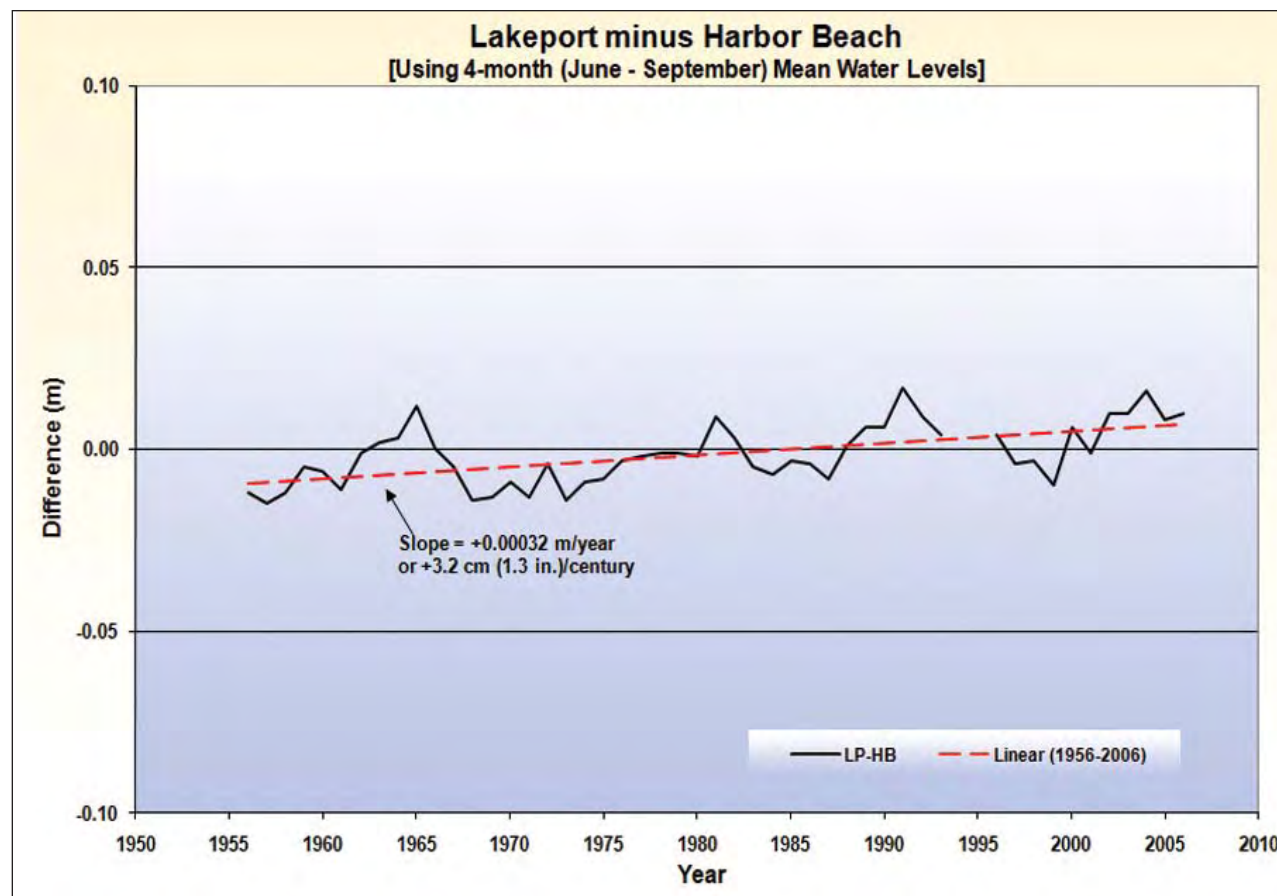
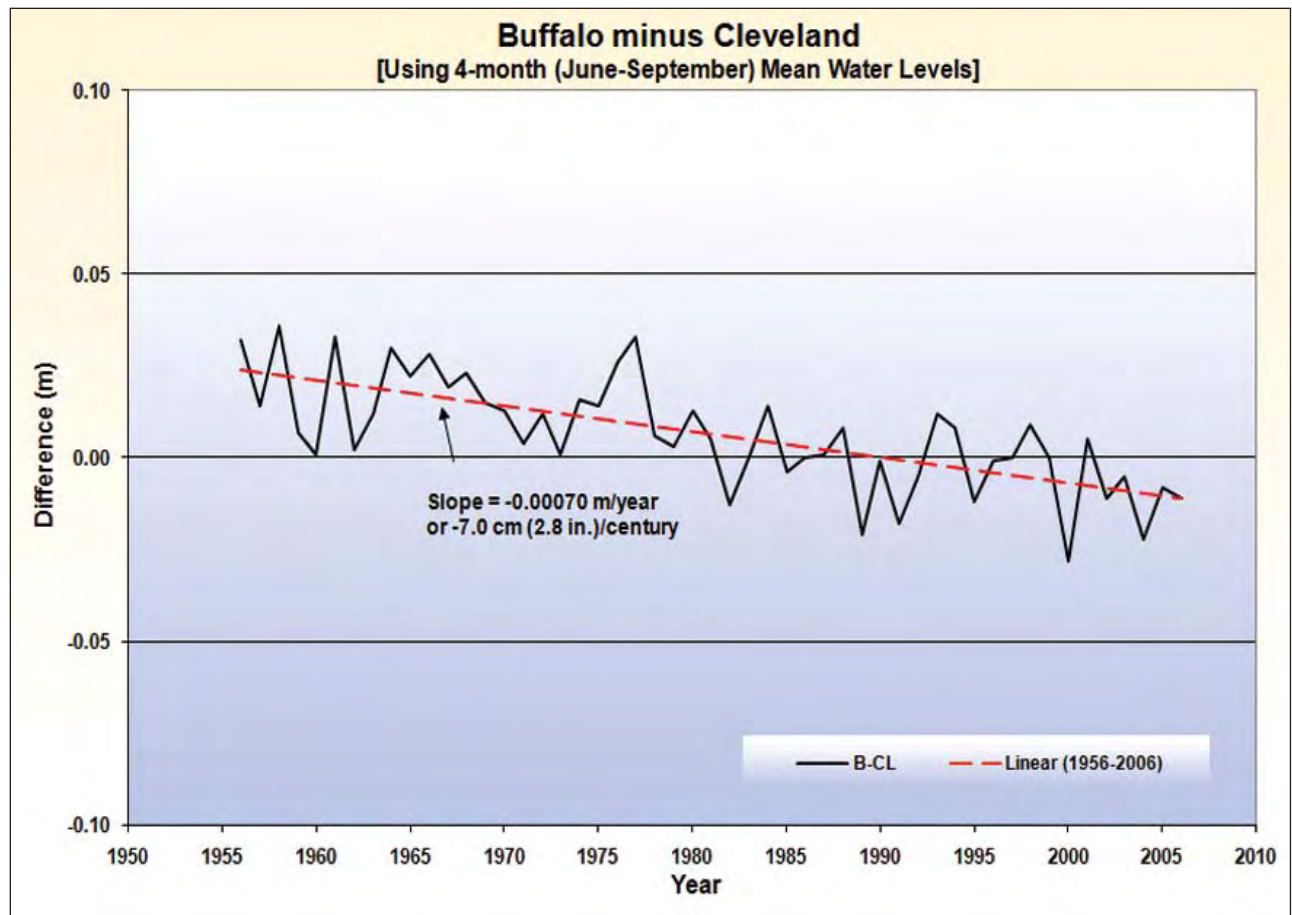


Figure 6-7 Rate of Change of Water Level Differences between Buffalo (B) and Cleveland (CL): 1956-2006



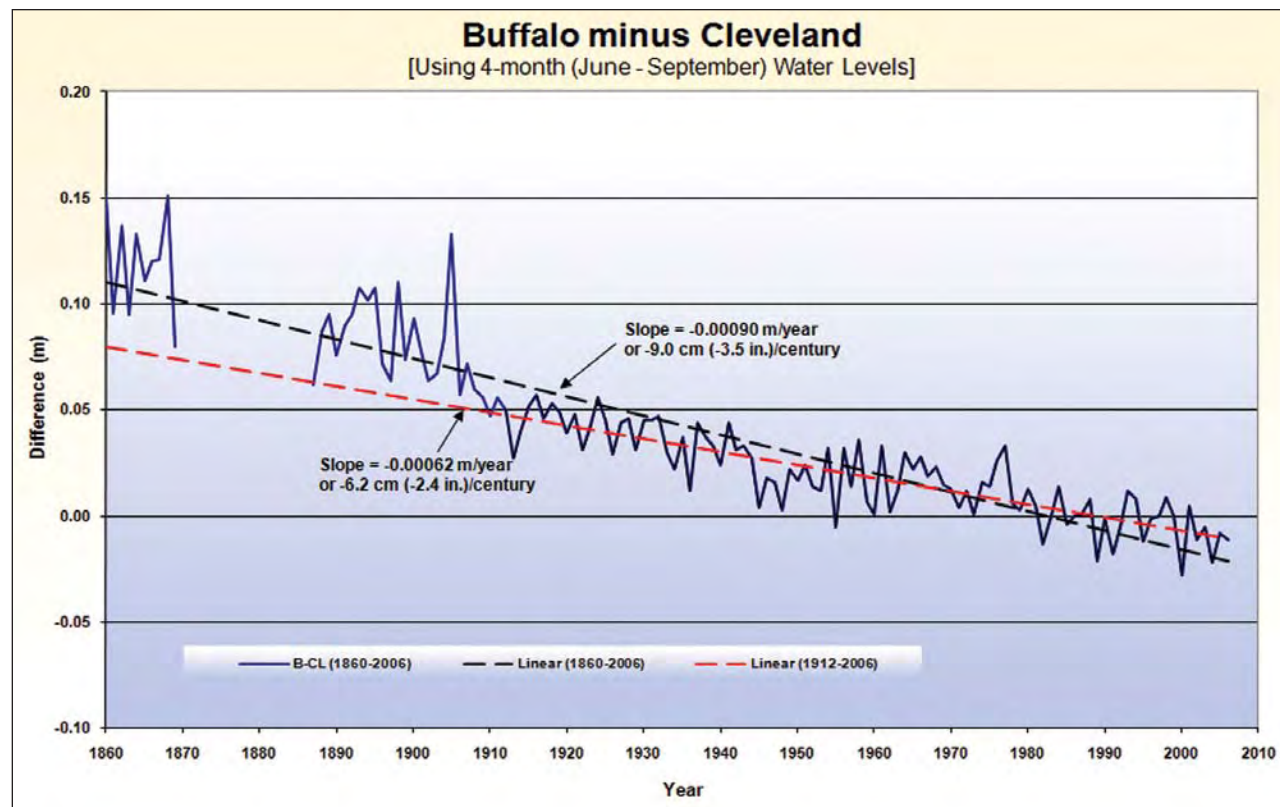
As indicated by the differences between the slopes of the three regression lines shown in Figures 6-7 and 6-8, the estimated rates of relative movement between gauge pairs can be sensitive to the period and/or length of record used for regression purposes. This is particularly true in the lower portion of the Great Lakes basin, where relative movement rates between sites are fairly low and trends in the water level difference plots can be somewhat step-like in nature, as shown in Figure 6-8. Of particular importance for this analysis is that water levels recorded at Cleveland have been increasing relative to those recorded at Buffalo at a rate of about 7 cm (2.8 in) per century in recent years and at least 6 to 9 cm (2.4 to 3.5 in) per century over the long-term.

General Impact on Apparent Lake Michigan-Huron Minus Lake Erie Head Difference Plot

Observed water levels at Harbor Beach and Cleveland track up and down with levels at Lakeport and Buffalo, respectively, reflecting the pattern of highs and lows experienced on Lake Michigan-Huron and Lake Erie over time. However, the IGLD recorded water levels at Harbor Beach and Cleveland also reflect the impact of relative movement between their locations and their lake's outlet.

Given that the Harbor Beach area is rising relative to the Lake Michigan-Huron outlet, water levels observed and recorded on IGLD at Harbor Beach appear to be falling over time compared to those recorded at Lakeport for the same lake level. On the other hand, because the Cleveland area is subsiding relative to the Lake Erie outlet, water levels observed and recorded on IGLD at Cleveland appear to be increasing compared to those at Buffalo over time. The apparent downward and upward trends in water levels observed at Harbor Beach and Cleveland and reflected in

Figure 6-8 Rate of Change of Water Level Differences between Buffalo (B) and Cleveland (CL): 1860-2006 and 1912-2006



their recorded data compared to those recorded at Lakeport and Buffalo, respectively, are due to the change in the land-to-water at these locations as the land there rises or falls relative to their lake's outlet over time due to GIA.

If water levels recorded at Harbor Beach and Cleveland are used to determine the change in Lake Michigan-Huron to Lake Erie differences over time, as in Figure 6-2, then the apparent reduction in Harbor Beach water levels and the apparent increase in Cleveland water levels that are occurring over time as these locations rise and fall, respectively, relative to the their lake's outlet will be misinterpreted as an actual reduction in head difference between Lake Michigan-Huron and Lake Erie. That is, given the relative vertical movement between Harbor Beach and Lakeport on Lake Michigan-Huron and Cleveland and Buffalo on Lake Erie, a portion of the decline shown in Figure 6-2 can be attributed to the apparent impact of GIA on recorded waters levels at Harbor Beach and Cleveland.

The portion of the apparent reduction in the head difference shown in Figure 6-2 over any given period of time due to the use of water levels recorded at Harbor Beach and Cleveland instead of those for Lakeport and Buffalo can be determined based on the difference between the slopes of the individual trend lines fitted to the Harbor Beach minus Cleveland (HB-CL) and the Lakeport minus Buffalo (LP-B) difference plots multiplied by the length of time of interest in years. That is,

$$\sum \Delta GIA_{\text{Apparent}} = (\text{Slope of (HB-CL)} - \text{Slope of (LP-B)}) \text{ m/year} * \text{Number of Years}$$

Alternately, the slope of a linear regression trend line fitted to the plot of the year-to-year difference between the Harbor Beach minus Cleveland and Lakeport minus Buffalo differences over time can be used. That is,

$$\sum \Delta GIA_{\text{Apparent}} = \text{Slope of ((HB-CL) - (LP-B)) m/year} * \text{Number of Years}$$

Similar relationships can be used to determine the apparent effect of GIA for any Lake Michigan-Huron minus Lake Erie gauge pair. If water levels recorded at Lakeport and Buffalo are used to determine the change in Lake Michigan-Huron to Lake Erie head difference over time, then $\sum \Delta GIA_{\text{Apparent}}$ will be equal to zero, or at least very close to it, recognizing the potential for some relative movement over time between Lakeport and the Lake Michigan-Huron outlet. This is because Lakeport and Buffalo represent their respective lake outlets.

Determining the Apparent Effect of GIA on the Harbor Beach Minus Cleveland Plot

Ideally, a comparison of the Harbor Beach minus Cleveland and Lakeport minus Buffalo differences based on recorded water level data over the entire 1860-2006 time period could be carried out to determine the portion of the reduction in the head difference shown in Figure 6-2 over both the short- and long-term that can be attributed to the apparent effect of GIA on Harbor Beach and Cleveland water levels.

However, monthly water level data are only available at Lakeport beginning in September 1955. Although published monthly data are readily available at Buffalo beginning in 1860, this data set contains limited data for 1860 to 1869 and no data from 1870 through to early 1887. In addition, a review of historical water level data by the Study also raised some concerns regarding the quality of the earlier data available at Harbor Beach, Cleveland and Buffalo (Quinn and Southam, 2008). For example, though published monthly mean water level data are available for the Harbor Beach gauge beginning in 1860, the Harbor Beach gauge did not begin operating until September 1874 (CCGLHHD, 1978). The published Harbor Beach data available prior to then were established using monthly levels recorded at the Milwaukee water level gauge transferred to Harbor Beach, accounting for the relative movement between the two locations. In addition, prior to February 1899, March 1901, and November 1903 the monthly mean water levels at Buffalo, Harbor Beach and Cleveland, respectively, were based on a limited number of staff gauge readings per month—typically just one or several readings a day (CCGLHHD, 1978, 1987). These early water levels at these stations are potentially subject to greater uncertainty than later data based on hourly readings from an analogue or digital recording gauge.

In response to these concerns about data gaps and reliability, the Study undertook two analyses:

- The first analysis used the September 1955 to December 2006 common period of recorded data at Lakeport, Buffalo, Harbor Beach and Cleveland. Given that recorded data are available for all but a few months during this time period, this approach provided the best comparisons between the Harbor Beach minus Cleveland and Lakeport minus Buffalo difference plots over the 1963-2006 period.
- For the second analysis, several 1860-2006 Lakeport minus Buffalo difference plots were generated based on both recorded and estimated Lakeport and Buffalo water level data (with the estimated data based on recorded water levels at Harbor Beach and Cleveland transferred to Lakeport and Buffalo by accounting for the impact of relative GIA over time). The results from this analysis were compared to the 80 cm (31.5 in) decline in head difference between Lake Michigan-Huron and Lake Erie determined by Baird from 1860 to 2003 (Baird, 2005). However, given the reliance of the long-term analysis on estimated as well as questionable early historical data, this analysis was more speculative in nature and its results much less certain than those for the analysis of short-term effects.

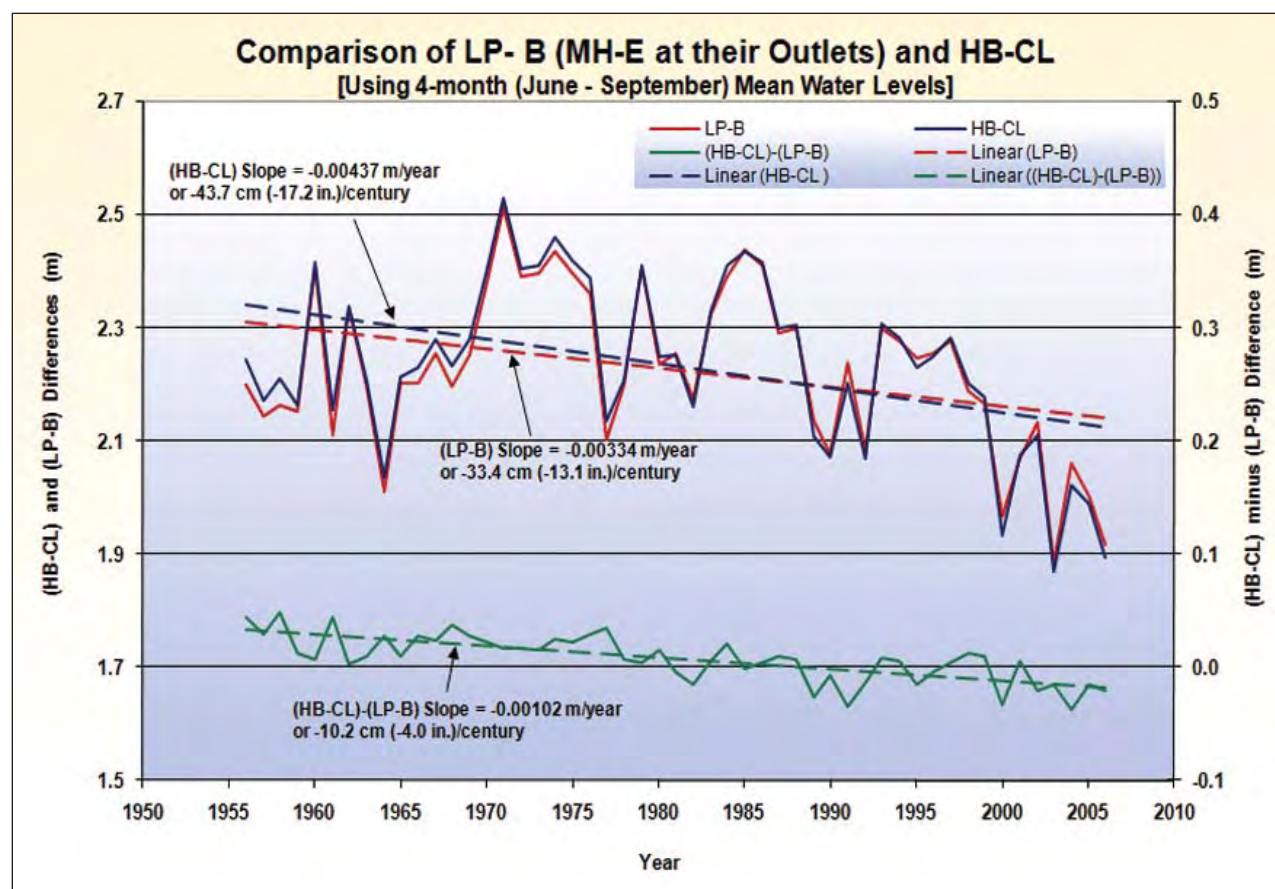
In both cases, the primary analyses were based on the differences between the four-month (June-September) mean water levels recorded at each location to limit the impact of seasonality on water level differences. However, equivalent difference plots were generated using annual and monthly water level data to help assess the sensitivity of results to the water level data averaging period used.

6.2.2 Results of the Short-term Analysis

Plots of the year-to-year differences between the four-month (June-September) mean levels recorded at Harbor Beach and Cleveland and Lakeport and Buffalo over the 1956-2006 time period are shown in Figure 6-9. The 1956-2006 differences are used instead of the 1963-2006 Study period of interest so as to include as long a record as possible for regression purposes.

The difference between the declines in the Harbor Beach minus Cleveland (HB-CL) and Lakeport minus Buffalo (LP-B) plots represents the portion of the reduction in the difference over time that can be attributed to the apparent effect of GIA on Harbor Beach minus Cleveland water levels.

Figure 6-9 Estimation of the Effect of Apparent GIA on Recorded Water Levels



Note: LP: Lakeport; B: Buffalo; HB: Harbor Beach; CL: Cleveland; MH: Lake Michigan-Huron; E: Lake Erie; It was necessary to estimate the four-month (June-September) mean water levels for 1994 and 1995 at Lakeport because of missing Lakeport data. The 1994 and 1995 levels were estimated based on water level transfers from Harbor Beach assuming the rate of apparent rate of relative movement between Lakeport and Harbor Beach shown in Figure 6-6.

The standard errors of the slopes of the linear trend lines fitted to the (HB-CL) and (LP-B) difference plots in Figure 6-9 are quite large. As a result, the linear trend lines are very poor estimators of either the Harbor Beach minus Cleveland or the Lakeport minus Buffalo differences in any given year. Also, as demonstrated previously, their slopes are also sensitive to the period of record used to determine them. Therefore, caution must be exercised in interpreting the slopes of the Harbor Beach minus Cleveland or the Lakeport minus Buffalo trend lines in the figure, *except* to help identify that portion of the fall in the Harbor Beach minus Cleveland plot that is due to the effects of GIA on recorded water levels over time, which is generally considered to be a linear process. Caution should also be exercised when determining apparent changes in the head difference between Lake Michigan-Huron and Lake Erie over a selected period of time based on the change in the differences between specific start and finish years. The

actual lake-to-lake difference in any given year reflects all factors affecting the water levels on each lake and the head difference between them at any given time.

The apparent reduction in the Lake Michigan-Huron to Lake Erie head difference over the 1963-2006 study period due to the use of Harbor Beach minus Cleveland pairing instead of Lakeport minus Buffalo (*i.e.*, the apparent effect of GIA on the Harbor Beach minus Cleveland fall over time) can be determined based on the difference between the slopes of the Harbor Beach minus Cleveland and Lakeport minus Buffalo trend lines multiplied by the number of years over the period of time in question. That is, for the 1963-2006 study period:

$$\begin{aligned} & (-0.00437 \text{ m/year} - (-0.00334 \text{ m/year})) * 43 \text{ years} \\ & = -0.00103 \text{ m/year} * 43 \text{ years,} \\ & = -0.044 \text{ m or } -4.4 \text{ cm } (-1.7 \text{ in}). \end{aligned}$$

However, the apparent effect of GIA on the reduction in HB-CL differences over time is more easily perceived by looking at the slope of the linear regression trend line fitted to the plot of the (HB-CL)-(LP-B) differences over time in Figure 6-9. The -0.00102 m (-0.0033 ft) per year slope of the trend line indicates that 0.00102 m (0.0033 ft) per year of the reduction in head difference determined based on Harbor Beach minus Cleveland is due to the apparent impact of GIA on water levels recorded on IGLD at these two locations. As expected, this value is virtually the same as the difference between the (HB-CL) and (LP-B) slopes determined above. The standard error of the slope of the (HB-CL)-(LP-B) trend line is 0.00013 m (0.0004 ft) per year, which is much smaller than those of the individual (HB-CL) and (LP-B) differences plots. Therefore, using the slope of the (HB-CL)-(LP-B) linear regression trend line and its standard error gives:

$$\begin{aligned} & (-0.00102 \text{ m/year} \pm 0.00013 \text{ m/year}) * 43 \text{ years} \\ & = -0.044 \text{ m} \pm 0.006 \text{ m, or} \\ & -4.4 \text{ cm} \pm 0.6 \text{ cm} (-1.7 \text{ in} \pm 0.2 \text{ in}) \text{ or} \\ & -3.8 \text{ to } -5.0 \text{ cm} (-1.5 \text{ to } 2.0 \text{ in}) \end{aligned}$$

Using (HB-CL)-(LP-B) differences based on annual or monthly water level data produces similar results.

Therefore, after rounding the results to the nearest centimetre, the Study concluded that about 4 to 5 cm (1.6 to 2 in) of the fall in the Harbor Beach minus Cleveland plot during the 43 years from 1963 to 2006 can be attributed to the apparent effect of GIA on water levels recorded at Harbor Beach and Cleveland. Furthermore, as indicated in Table 6-1, if the head difference between Lake Michigan-Huron and Lake Erie were based on the difference between the actual (or absolute) water levels of the two lakes (MH-E) or recorded water levels at Lakeport and Buffalo (LP-B), then the apparent effect of GIA on the change (Δ) over time would equal zero.

6.2.3 Results of the Long-term Analysis

The Study also analyzed the apparent long-term effects of GIA on the head difference between Lake Michigan-Huron and Lake Erie. Southam (2009), building on earlier work by Quinn and Southam (2008), estimated the head difference between Lake Michigan-Huron and Lake Erie over the 1860-2006 time period based on a combination of recorded and estimated annual, monthly and four-month (June-September) Lakeport and Buffalo water level data (with the estimated data based on recorded water levels at Harbor Beach and Cleveland, adjusted for the impact of GIA over time). As noted, however, this analysis may be more speculative in nature and its results less certain than those for the analysis of short-term effects.

To populate a complete set of four-month (June-September) water levels at Lakeport, the 1860-1955 water levels there were estimated based on recorded levels at Harbor Beach transferred to Lakeport assuming that the 1956-2006 rate of relative movement between in Harbor Beach and Lakeport of 3.2 cm (1.3 in) per century can be applied back in time to 1860. The annual and monthly data were estimated in a similar manner. (This is a significant, yet reasonable assumption to make for this analysis, given the trend in the plot of Lakeport minus Harbor Beach difference in Figure 6-6 and the persistent trends often seen in long-term comparisons for other gauge pairs.) The resulting 1860-2006 data set is referred to as Lakeport* (LP*) to clarify that it is based on a combination of recorded levels at Lakeport from 1956-2006 and estimated Lakeport levels based on water levels transferred from Harbor Beach to Lakeport for the 1860-1955 time period.

Table 6-1 Apparent Effect of GIA, 1963-2006
cm (in)

| On Δ (MH-E) (Actual water levels) | On Δ (LP-B) (Recorded levels) | On Δ (HB-CL) ² (Recorded levels) |
|---|---|---|
| 0.0 (0.0) | 0.0 (0.0) ¹ | -4.4 \pm 0.6 (1.7 \pm 0.2) |

Notes:

MH: Lake Michigan-Huron; E: Lake Erie; LP: Lakeport; B: Buffalo; HB: Harbor Beach; CL: Cleveland

1. Assuming no movement between LP and the MH outlet.

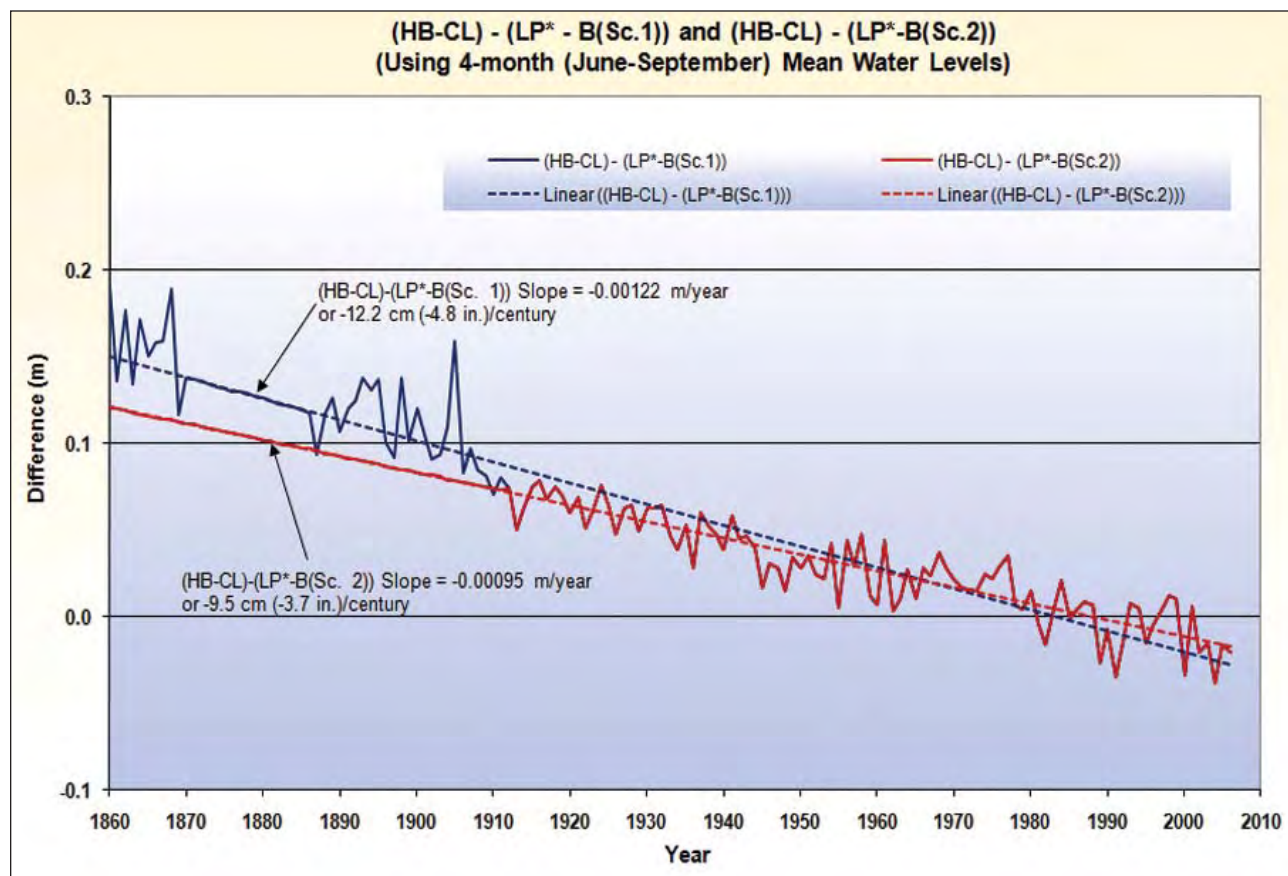
2. As used in Figure 6-2

To address data gaps and possible quality issues with the pre-1912 water levels at Buffalo, two 1860-2006 data sets were established. The first data set, Buffalo (Scenario 1) or B(Sc.1) for short, used recorded water level at Buffalo as available throughout the entire 1860-2006 time period and used estimated Buffalo levels based on water level transfers from Cleveland to fill in the missing data during the 1860-1887 time period. The water level transfers were based on the 1860-2006 rate of apparent rate of relative movement between Cleveland and Buffalo of -9.0 cm (-3.5 in) per century. The second data set, B(Sc.2), was based on recorded water levels at Buffalo from 1912-2006 and the recorded levels at Cleveland transferred to Buffalo for the entire 1860-1911 period, based on the 1912-2006 rate of apparent rate of relative movement between Cleveland and Buffalo of -6.2 cm (-2.4 in) per century. Again, annual and monthly mean levels were estimated in similar manner.

The resulting reductions in the LP*-B(Sc.1) and LP*-B(Sc.2) head differences over the 143-year time period (1860-2003) were about 57 cm (22.4 in) and 61 cm (24.0 in), respectively (based on the slope of the linear regression trend line fitted to their plots of four-month [June to September] water level differences). These estimate are 23 and 19 cm (9.1 and 7.5 in) less than the 80 cm (31.5 in) reduction in the Harbor Beach minus Cleveland head differences noted by Baird (2005), based on the fall in the linear trend line fitted to the plot of their 1860-2003 monthly differences.

Based on the slopes of the (HB-CL)-(LP*-B(Sc.1)) and the (HB-CL)-(LP*-B(Sc.2)) plots provided in Figure 6-10, about 17 cm (6.7 in) of the approximately 23 cm (9 in) difference between the reduction in 1860-2003 lake-to-lake head difference based on HB-CL and LP*-B(Sc.1) and about 14 cm (5.5 in) of the estimated 19 cm (7.5 in) difference between the HB-CL and LP*-B(Sc.2) is the result of using Lakeport minus Buffalo instead of Harbor Beach minus Cleveland to determine the lake-to-lake head difference. In other words, depending on the long-term rate of relative movement assumed between Cleveland and

Figure 6-10 Analysis of Long-term Effects of GIA: Summary of Scenarios



Notes: LP*: Using the 1956-2006 LP-HB linear regression equation to extend LP data back to 1860
 B(Sc.1): Using the 1860-2006 B-CL linear regression equation to fill in missing B data during the 1860-1887 period
 B(Sc.2): Using the 1912-2006 B-CL linear regression equation to estimate the 1860-1911 Buffalo data
 (HB-CL)-(LP*-B(Sc.1)) and (HB-CL)-(LP*-B(Sc.2)) are the same for 1912-2006.

Buffalo, about 14 to 17 cm (5.5 to 6.7 in) of the 80 cm (31.5 in) reduction in the 1860-2003 Harbor Beach minus Cleveland plot based on monthly water level data is due to the apparent effect of GIA on water levels recorded at Harbor Beach and Cleveland.

Comparisons between difference plots based on annual, monthly and four-month (June to September) water levels indicated that nearly 2 cm (0.8 in) of either the 19 or 23 cm (7.5 or 9.1 in) differences can be attributed to the use of the four-month (June-September) mean levels instead of monthly water levels to determine the 1860-2003 linear estimate of change in Harbor Beach minus Cleveland and Lakeport* minus Buffalo (Scenarios 1 and 2) head differences over time. Although monthly water level data usually dampen the effect of short-period water level fluctuations, seasonal trends in wind patterns are reflected in the monthly and annual mean water level data at gauges on Lake Erie and in estimates of any Lake Michigan-Huron to Lake Erie head differences based on these data. Finally, the remaining portion of the 19 or 23 cm (7.5 or 9.1 in) differences might be due to the level of rounding precision used to calculate and report the 1860 and 2003 water levels and their differences based on the relationships for the linear trend lines used for analysis purposes to represents long-term trends.

It must be noted, however, that the need to estimate the early Lakeport and Buffalo water level information based on water level transfers from Harbor Beach and Cleveland, combined with concerns regarding the quality of these data, limits the Study's confidence in the early Lakeport* minus Buffalo (Scenarios 1 and 2) and Harbor Beach minus Cleveland differences. Therefore, the estimates of the long-term reductions in the head difference between Lake Michigan-Huron and Lake Erie and findings based on the comparisons of the differences between them cannot be considered definitive. However, it is reasonable to conclude that approximately 14 cm (the smaller of the 14 cm and 17 cm estimates noted above) of the 80 cm (5.5 of the 31.5 in) decline from 1860 to 2003 in Figure 6-2 can be attributed to the apparent effect of GIA on water levels recorded at Harbor Beach and Cleveland.

6.3 DETERMINING THE PHYSICAL EFFECT OF GIA

6.3.1 Data and Analysis

The Study investigated the potential physical effect of GIA on the head difference between Lake Michigan-Huron and Lake Erie over time as reflected in the water level difference plots.

The physical effect of GIA results from the impact of absolute and relative vertical movement of key locations on and between Lake Michigan-Huron and Lake Erie on the actual water levels of the two lakes. The effect includes potential changes in the actual level of either lake due to vertical movement of their outlets over time, as well as any associated impacts due to backwater effects, where a portion of a change in Lake Erie's actual water level is transferred to Lake Michigan-Huron, and a change in the outflow relationship of Lake Michigan-Huron is due to a change in the slope of the bed of the St. Clair-Detroit River system. The potential impacts of relative movement of the basin of each lake and/or changes on the volume of the lakes over time or levels at their outlets are also included in the analysis. The physical effect of GIA impacts the actual water level of a lake as a whole, and thus will affect the slope of any Lake Michigan-Huron minus Lake Erie head difference plots based on recorded water levels equally.

As described in Section 6.1.3, the actual elevation of a lake's surface as a whole relative to mean sea level may be gradually rising or falling due to the absolute vertical movement up or down of its outlet due to GIA. Although absolute vertical movement due to GIA may be either increasing or decreasing the relative vertical difference between the actual water levels of Lake Michigan-Huron and Lake Erie over time, this physical change due to GIA will not be reflected in the slope of a head difference plot based on their recorded IGLD water level data. Great Lakes water levels are referenced to IGLD, which is updated periodically. Changes in the relative elevations between gauging sites on either lake are reflected in the adjustments applied to their benchmark elevations and their recorded water levels during each IGLD update. Given that the adjustment applied to the historical water levels at each gauge is a single value, this affects the difference between water levels at the two gauges equally over their common period of record. As a result, their year-to-year differences will change, but the slope of their differences plot will remain the same.

However, relative movement between key locations on the two lakes due to GIA may result in a related backwater effect or change in the outflow relationship of Lake Michigan-Huron. These effects would be reflected in the recorded water levels of the lakes as they occur over time and as such affect the slopes of their difference plots.

The Study used the extended Telemac-2D model (Faure, 2009) to estimate the combined impact of these two related physical effects. An appropriate range of relative movement between the outlets of the two lakes and between Fort Gratiot at the head of the St. Clair River and Bar Point at the foot of the Detroit River was assumed.

To capture the current level of uncertainty that exists with respect to the absolute movement in the Great Lakes region, and hence the relative movement between the outlets of Lake Michigan-Huron and Lake Erie, the Study used an objective estimate of the range of vertical movement of Buffalo with respect to Fort Gratiot based on published values. A lower bound of -5 cm (-2.0 in) per century based on the outputs from a number of recent global post-glacial rebound models and an upper bound of +8 cm (3.1 in) per century from Figure 6-3, were selected. The preliminary GPS information available was not considered due to problems with velocity estimates at some of the U.S. sites in the lower portion of the basin. It was also necessary to specify a range of possible movement rates between Fort Gratiot and Bar Point consistent with the range of movement assumed for Buffalo relative to Fort Gratiot. For this purpose, it was assumed that the western end of Lake Erie is subsiding at a rate of 10 cm (3.9 in) per century relative to Buffalo as suggested in Figure 6-4. Finally, Lakeport was assumed to be stable relative to Fort Gratiot. Both these sites were also assumed to be stable in absolute terms for the modelling exercise.

Table 6-2 provides three possible Fort Gratiot/Lakeport, Buffalo and Bar Point vertical movement scenarios based on these assumptions. Note that even if there were no relative movement between the outlets of the two lakes there would still be about a 10 cm (3.9 in) per century increase in the slope of the bed of the St. Clair-Detroit River system over its length as the western end of Lake Erie subsides relative to the outlets of both lakes.

Three relative movement scenarios were simulated using the extended Telemac-2D model (Scenarios 1, 2 and 3, in 6.3.2, below). For these model runs, the elevation of the model's nodes at Fort Gratiot, Lakeport, Buffalo and Bar Point were adjusted based on the movement rates shown in Table 6-2 assumed over a 50-year time period. Therefore, Buffalo and Bar Point were moved vertically by +4 cm and -1 cm (+1.6 and -0.4 in), 0 cm and -5 cm (0 and -2.0 in), and -2.5 cm and -7.5 cm (-1.0 and -3.0 in), respectively, while Fort Gratiot and Lakeport were held stable. The elevations of the nodal points in between Fort Gratiot and Bar Point were adjusted linearly as required to account for the assumed changes in slope of the bed of the St. Clair and Detroit Rivers. The corresponding changes in depth at Lakeport for the three scenarios were +1.2, -1.4, and -3.0 cm (+0.5, -0.6, and -1.2 in), respectively.

Six additional movement scenarios, in which either Buffalo or Bar Point was moved independently while the remaining sites were held stable, were modelled in order to help interpret the combined movement scenario results. Comparisons between the results of the three combined and six independent Buffalo and Bar Point movement simulations indicated that the impact of the three combined Buffalo and Bar Point movement simulations can (within reason) be scaled up or down linearly to estimate their impact over a different time period based on the length of the selected time period relative to the 50-year modelling period. Therefore, for the 1963-2006 time period, the estimated impact for each of the three combined Buffalo and Bar Point movement scenarios modelled would be equal to 43 years/50 years (or 86% of the 50-year simulation results).

Table 6-2 Assumed Rates of Vertical Movement at Fort Gratiot (and Lakeport), Buffalo and Bar Point
cm (in) per century

| Fort Gratiot/Lakeport | Buffalo | Bar Point |
|-----------------------|----------|------------|
| 0 | +8 (3.1) | -2 (-0.8) |
| 0 | 0 | -10 (-3.9) |
| 0 | -5 (-2) | -15 (-5.9) |

Table 6-3 Results of the Analysis of Physical Effect of GIA: Summary of Scenarios
Estimates of the Combined Impact of Backwater and Change in St. Clair-Detroit River Bed Slope due to GIA on Lake Michigan-Huron Water Levels

| Assumed Vertical Movement at FG, B & BP per 50 years cm (in) | Modelled ¹ Estimate of Change in MH Level per 50 years cm (in) | Vertical Movement at FG, B & BP, 1963-2006 cm (in) | Scaled ² Estimate of Change in MH Level, 1963-2006 cm (in) | Estimate of Change in MH-E Head Difference, 1963-2006 cm (in) |
|---|--|---|--|--|
| Scenario 1 0, +4, -1 (0, +1.6, -0.4) | +1.2 (+0.5) | 0.0, +3.4, -0.9 (0, +1.3, -0.4) | +1.0 (+0.4) | +1.0 (+0.4) |
| Scenario 2 0, 0, -5 (0, 0, -2) | -1.4 (-0.6) | 0.0, 0.0, -4.3 (0, 0, -1.7) | -1.2 (-0.5) | -1.2 (-0.5) |
| Scenario 3 0, -2.5, -7.5 (0, -1, -3) | -3.0 (-1.2) | 0.0, -2.2, -6.5 (0, -0.9, -2.6) | -2.6 (-1) | -2.6 (-1) |

Note: MH: Lake Michigan-Huron; E: Lake Erie; FG: Fort Gratiot; B: Buffalo; BP: Bar Point

1. Using the extended Telemac-2D model

2. Assumed equal to 86% of 50-year modelled estimate.

6.3.2 Results of the Analysis of the Physical Effect of GIA

The adjusted model results of the three scenarios are summarized in Table 6-3 and below. Estimated impacts are provided for the 1963-2006 time period only, as it is not considered reasonable to scale the modelled results for the 50-year movement scenarios up to 143 years to cover the full 1860-2006 period.

Scenario 1: Lake Erie Outlet Rising Relative to Outlet of Lake Michigan-Huron

If the outlet of Lake Erie is rising at a rate of 8 cm (3.1 in) per century relative to the outlet of Lake Michigan-Huron due to GIA, then over the 1963-2006 time period, the actual water level of Lake Erie would increase by 3.4 cm (1.3 in) as its outlet rises by that much. This would result in a reduction in the actual head difference between Lake Michigan-Huron and Lake Erie by this amount. The 3.4 cm (1.3 in) increase would not be reflected in the slope of a head difference plot, because this increase in the actual level on Lake Erie is not reflected in the water levels recorded at Lake Erie gauges as it occurs over time. As noted, the increase is captured in the water level adjustments applied to historical water level data as part of the IGLD update process.

However, due to the resulting combination of backwater effect and a change in the slope of bed of the St. Clair-Detroit River system, the actual level of Lake Michigan-Huron as a whole is estimated to increase by 1.0 cm (0.4 in). This increase would be reflected in the water levels recorded at its gauges. Therefore, for this movement scenario GIA actually offsets 1.0 cm (0.4 in) of the reduction in head difference between the two lakes based on recorded water levels over the 1963-2006 time period.

Scenario 2: Lake Erie Outlet Stable Relative to Outlet of Lake Michigan-Huron

If the outlet of Lake Erie is not moving relative to the outlet of Lake Michigan-Huron due to GIA, then the actual water level of Lake Erie would not change relative to that of Lake Michigan-Huron due to GIA over time. There would be no change in actual head difference between Lake Michigan-Huron and Lake Erie due to movement of the Lake Erie outlet; however, due to the resulting change in the slope of the bed of the St. Clair-Detroit River system, the actual level of Lake Michigan-Huron as a whole is estimated to fall by 1.2 cm (0.5 in), which would be reflected in the levels recorded at its gauges.

Therefore, for this movement scenario, there is an equivalent reduction in the head difference between the two lakes, which contributes to, or accounts for 1.2 cm (0.5 in) of the 1963-2006 reduction in head difference in any water level difference plot for Lake Michigan-Huron and Lake Erie.

Scenario 3: Lake Erie Outlet Falling Relative to Outlet of Lake Michigan-Huron

If the outlet of Lake Erie is falling at a rate of 5 cm (2.0 in) per century relative to the outlet of Lake Michigan-Huron due to GIA, then over the 1963-2006 time period, the actual water level of Lake Erie would decrease by 2.2 cm (0.9 in) as its outlet falls by that much. This would result in an increase in the actual head difference between Lake Michigan-Huron and Lake Erie by this amount. The change would not be reflected in the head difference plot, because this decrease in the actual level on Lake Erie is not reflected in the water levels recorded at Lake Erie gauges as it occurs over time. However, due to the resulting combination of backwater effect and change in the slope of the bed of the St. Clair-Detroit River system, the actual level of Lake Michigan-Huron as a whole is estimated to fall by 2.6 cm (1 in), which would be reflected in the levels recorded at its gauges.

Therefore, for this movement scenario, GIA actually contributes 2.6 cm (1 in) to the 1963-2006 reduction in head difference between Lake Michigan-Huron and Lake Erie based on recorded levels.

In summary, the results suggest that the combined impact for the effect of backwater and change in the slope of the bed of the St. Clair River-Detroit River system due to GIA *could* be offsetting up to 1.0 cm (0.4 in), or contributing as much as 2.6 cm (1 in) of the apparent reduction in head difference between Lake Michigan-Huron and Lake Erie over the 1963-2003 time period.

6.3.3 GIA Effects on Water Balance and Net Basin Supply Calculations

Finally, due to differential crustal movement, portions of each of the Great Lakes are either rebounding or subsiding relative to their outlets. As a result, each of the lakes is potentially storing or decanting a certain amount of water over time due to the tilting of their lake basins. The Study undertook an analysis to determine whether this physical effect of GIA on water balance and net basin supply (NBS) calculations was significant (Bruxer and Southam, 2008a). The results of this effort indicate that storage change as a result of GIA in the Great Lakes is negligible for water balance and net basin supply (NBS) calculation purposes.

In addition, the tilting of either the Lake Michigan-Huron or Lake Erie basins due to GIA would not affect the difference in water level elevations between the two lakes unless the rate of vertical movement at points around either lake relative to their outlets were to change enough

to affect the rate at which they are storing or decanting water over time, thus affecting their outflow and the levels at their outlets. If this were the case, then the resulting effect on the lake-to-lake head difference could be either an increase or a decrease, depending on the changes that were experienced.

A review of relative movement trends between water level gauge locations on Lake Michigan-Huron and Lake Erie and their outlet indicated that the effect of the differential tilting over their basin on the depth at their outlet is very small (Bruxer and Southam, 2008b). There are features in the water level differences plots for several Lake Michigan-Huron and Lake Erie gauge pairs that might reflect changes in rates of relative movement between some gauges and the outlet of each lake. However, none of the changes is significant enough to have an effect on the head difference over time. Therefore, the potential effect of a change in the tilting pattern of the Lake Michigan-Huron and/or Lake Erie basins on their lake-to-lake difference is negligible over both the short- and long-term as considered here.

6.4 CONCLUSIONS OF GIA ANALYSIS

To address the impact of GIA on the land-to-water relationship around each lake and the use of IGLD, the fall relationship between Lake Michigan-Huron and Lake Erie should be based on the differences between water levels recorded at the lake gauges located closest to the outlet of each lake. The closest gauges are the Lakeport, MI and Buffalo, NY gauges on Lake Michigan-Huron and Lake Erie, respectively.

For the 1963 to 2006 period, the apparent effect of GIA accounts for (after rounding) about 4 to 5 cm (1.6 to 2 in) of the approximately 23 cm (9 in) reduction in head in the Harbor Beach minus Cleveland plot based on the linear regression trend line relationship. The apparent effect of GIA on the change in head difference over time can only be reasonably estimated over the long-term using estimates of historical water level data assuming long-term rates of relative movement.

Of the approximately 80 cm (31.5 in) drop in the lake-to-lake fall from 1860-2003 noted by Baird (2005) based on the linear regression trend line (Figure 6-2), the Study determined that about 14 cm (7.5 in) can reasonably be attributed to the apparent effect of GIA on the recorded water levels at Harbor Beach on Lake Michigan-Huron and Cleveland on Lake Erie. Another 5 cm (2 in) might be explained by differences in computation methods (e.g., the level of rounding precision applied and the water level averaging period used).

Analyses are currently limited to estimating the relative movement between key locations on Lake Michigan-Huron and Lake Erie to determine the physical effect of GIA. The results of a limited hydraulic modelling effort based on an objective range of relative movement due to GIA between the outlets of Lake Michigan-Huron and Lake Erie and between the outlet of Lake Michigan-Huron and the inlet of Lake Erie suggest that over the 1963-2003 time period the combined impact for the effect of backwater and change in slope could be offsetting up to 1.0 cm (0.4 in), or contributing as much as 2.6 cm (1.0 in) of the apparent reduction in head difference between Lake Michigan-Huron and Lake Erie based on water level differences.

6.5 KEY POINTS

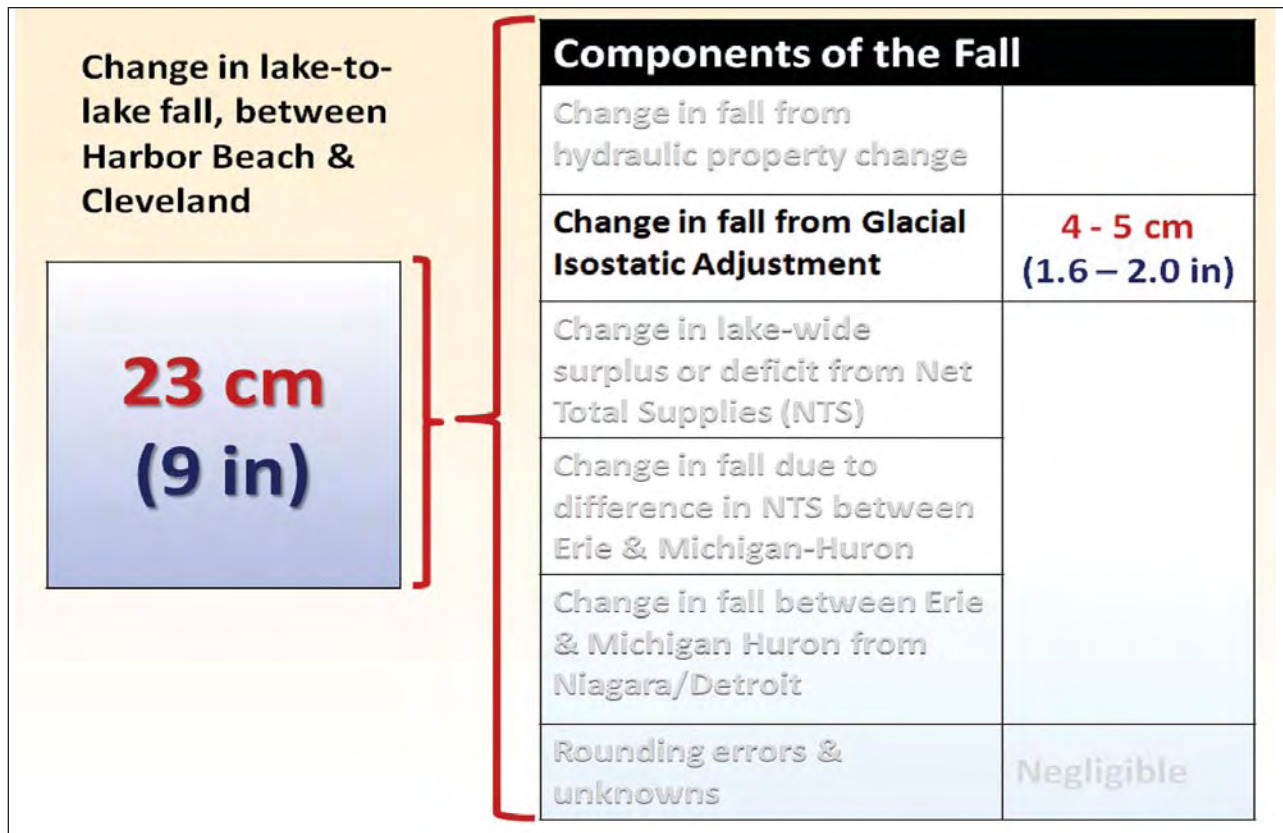
With respect to the primary science question regarding the effects of GIA, the following significant points can be made on the basis of the analyses summarized in this Chapter:


- ▶ The earth's crust continues to move today, at varying rates throughout the Great Lakes region, as it recovers from its deformation during the last glacial era. Given that differential vertical movement of the earth's crust due to GIA affects land-to-water relationships

around each of the Great Lakes, as well as the elevation differences and hydraulic relationships between them, GIA is another factor that needs to be considered when determining changes in head difference between Lake Michigan-Huron and Lake Erie over time.

- ▶ There are two different types of GIA effects to consider:
 - The *apparent* effect on water levels resulting from the change in the land-to-water relationship around each lake due to the “tilting” of the earth's crust; and
 - The *physical* effect of GIA due to the impact of movement of the earth's crust on the absolute water levels of the two lakes (i.e., their actual surface elevation at any given time relative to mean sea level).
- ▶ The Study identified that the apparent effect of GIA accounts for about 4 to 5 cm (1.6 to 2 in) of the approximately 23 cm (9 in) decline in the head difference between Lake Michigan-Huron and Lake Erie between 1963 and 2006 (Figure 6-11).

Figure 6-11 Study Findings: What factors are responsible for the change in lake-to-lake fall?



- 
- ▶ The Study identified important challenges with respect to data availability and reliability. For example, due to limitations in current knowledge regarding absolute movement between key locations on each lake, it is not yet possible to accurately determine changes in the actual water levels on each lake over time and in turn, the physical effect of GIA on the head difference between Lake Michigan-Huron and Lake Erie over time. Efforts using satellite-based GPS techniques are underway that will enable researchers, over several years, to accurately establish the absolute rates of vertical movement at points throughout the Great Lakes region and therefore more precisely determine the rates of relative movement between points on each of the Great Lakes.
 - ▶ GIA effects will need to be better understood to support future management decisions on Lake Superior regulation. For example, public concerns about declining or rising water levels on shorelines, and declines in water levels in the upper Great Lakes as a result of climate change will be exacerbated by the effects of GIA.
 - ▶ The Study's approach to analyzing the effects of GIA on the upper Great Lakes basin with respect to the head difference between Lake Michigan-Huron and Erie was reviewed by experts in Canada and the United States familiar with both GIA and its impact on actual and recorded water levels. These experts confirmed the validity of the Study's methodology and analysis.

CHAPTER 7

UPPER GREAT LAKES BASIN HYDROCLIMATIC PATTERNS AND TRENDS

Chapter 7 examines the hydroclimatology of the upper Great Lakes. It determines how the various hydrological factors affect water supplies and Great Lakes water levels, focusing on the role of climate as a contributing factor in the change in fall between Lake Michigan-Huron and Lake Erie.

The Chapter also looks ahead to describe briefly the Study's ongoing efforts to improve understanding of hydroclimatic conditions and trends in the upper Great Lakes basin. Many of the hydroclimatic monitoring and modelling projects undertaken in support of the St. Clair River report are continuing and will be important components of the second part of the Study, which is examining Lake Superior regulation. These projects primarily are addressing current uncertainties in the estimates of net basin supplies (NBS). The goal is to improve NBS estimates so that the Great Lakes' water budget can be monitored more accurately to identify the impacts of climate change.

7.1 INTRODUCTION

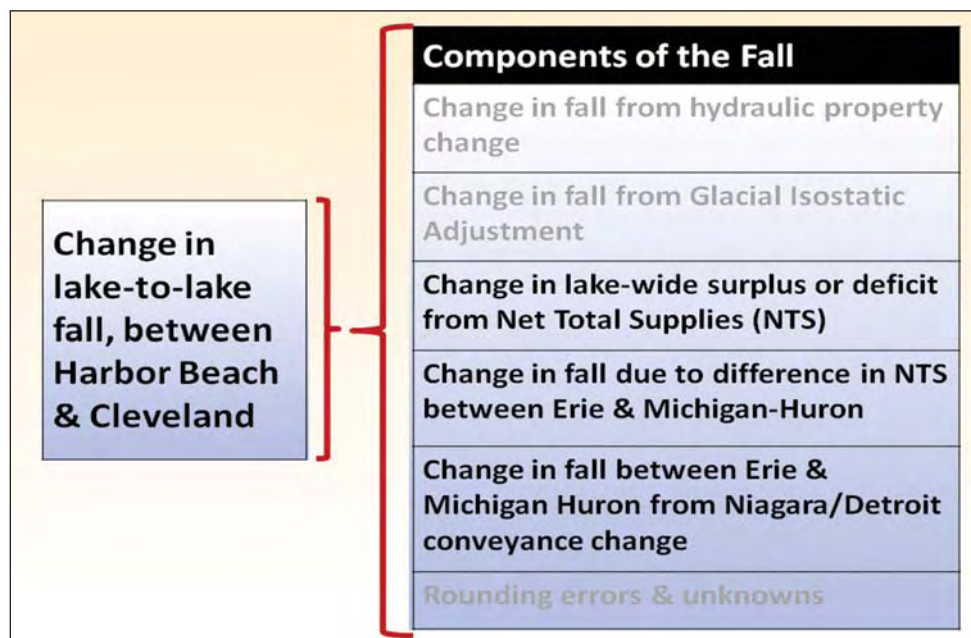
7.1.1 Science Question

The water levels of the Great Lakes are determined not only by the conveyance of their connecting channels, but also in large part by the climatic conditions and patterns in the basin (Figure 7-1).

The key science question addressed by the hydroclimatology perspective of this the Study is:

How has climate affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?

Figure 7-1 Study Approach: What factors are responsible for the change in lake-to-lake fall?



The Study investigated this science question through an integrated approach that focused on comparative statistical hydrological data analyses and modelling studies. The hydroclimatic modelling strategy focused on overlake precipitation, basin runoff and lake evaporation as the major contributors to the NBS (Lee and Pietroniro, 2008). The strategy was developed following an assessment of the literature and in consultation with experts, and was independently peer-reviewed.

The water level relationship between the lakes varies over time. Consequently, the hydroclimatic projects undertaken in the Study addressed the post-dredging period of 1962-2005, with a closer focus on the period from 1996 to 2005. The latter period is of interest due to the accelerated decline in the water level relationship experienced during those years (see Figure 2-7 in Chapter 2). Some of the projects use longer periods of record where needed to identify underlying long-term climate trends or to provide a historical context.

The analyses undertaken used the best available information and methodology. However, the Study will be continuing to collect information and improve the methodologies, which will result in improved estimates and assessments of NBS for the next part of the Study, addressing Lake Superior Regulation.

7.1.2 Assessing Uncertainty in the Water Balance of the Lakes

Addressing the key science question required a thorough understanding of the water balance of the Great Lakes. A water balance is an accounting of all water entering and leaving a given lake. As noted in Chapter 2, NBS can be calculated using two methods: component and residual.

Component Method

The component method determines NBS directly from its component contributions, (*i.e.*, overlake precipitation, lake evaporation, groundwater and basin runoff). The mathematical equation for this method is:

$$NBS = P + R - E + G \quad (1)$$

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.

All terms are expressed in m³/s-months (ft³/s-months) (or other time periods).

The groundwater flux was not considered further in the analyses, given its relatively small effect on the water balance and the fact that it is well within the uncertainty of the major components.

Residual Method

The residual method determines NBS indirectly by accounting for the inflow to the lake, its outflow, and net change in storage or water level, for a period using the following equation:

$$NBS = O - I + \Delta S - \Delta ST + D_o - D_i + C_{use} \quad (2)$$

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 m³/s-months (ft³/s-months) (or other time periods).

Consumptive uses, like the groundwater component, have relatively small effects on the water balance and are also well within the uncertainty of the major components. Thus, these uses are not considered further here.

Researchers have quantified Great Lakes water balances for many decades. However, uncertainties in estimates of the major components of the water balance in such a large system can vary dramatically, leading to significant uncertainty in the overall water balance. In the past, many different analyses were based on limited databases, which may have introduced various biases into previous computations. These large uncertainties make it challenging to quantify changes in the various water balance components.

Addressing these uncertainties and upgrading the approaches, data and models used for analysis were key elements of the hydroclimatic projects of the Study. Statistical techniques used in the Study to assess uncertainty included:

- *comparative analysis*, which compares two or more sets of data, generally developed independently of one another;
- *Monte Carlo simulation*, a statistical technique in which an uncertain value is calculated repeatedly using randomly selected “what-if” scenarios for each calculation. Parameter values in the model are replaced with approximated numbers to see how uncertainty affects the results; and
- *bootstrapping*, the technique of estimating statistical properties by measuring those properties when sampling from an approximating distribution. This can be achieved by re-sampling (with replacement) from the original dataset.

The statistical technique most applicable to each of the hydroclimatic projects was used and is briefly described in the following sections.

7.1.3 Overview of Study Approach

The hydroclimatic perspective of the Study consisted of three key assessments: a comparative analysis of the water balance estimates; an understanding of the role of climate in the change in fall; and monitoring and modelling of NBS.

Comparative Analysis of Water Balance Estimates

The Study first undertook an assessment of the contemporary estimates of the water balance (see Section 7.2), including a consideration of their uncertainty and methodological approaches. This step included identifying and updating existing residual and component NBS estimates used in the current management strategies by both the U.S. and Canada. The U.S. Army Corps of Engineers (USACE) and Environment Canada routinely compute the residual supplies. The component supplies are computed by the Great Lakes Environmental Research Laboratory (GLERL) of the U.S. National Oceanic and Atmospheric Administration (NOAA).

For estimating the residual supplies, the tasks included: adjusting the Niagara River flows for updates to stage-discharge relationships; correcting beginning-of-month lake elevations for gauge changes; correcting for glacial isostatic adjustment (GIA); and addressing system mass balance.

For estimating the component supplies, tasks included inspection and correction of computational errors and inclusion of all available hydrometeorological observations.

A comparative analysis of the residual and component NBS was undertaken concurrently to understand better where differences in the data occurred and the causes of these differences. Multiple revisions of the datasets were undertaken during the Study period. The analyses reported in the Study are based on the final data sets dated March 2009 for the residual supplies and April 2009 for the component supplies.

The comparative analysis also included statistical studies on the water balance data to explore trends (a gradual rate of increase or decrease over a period of time), shifts (an abrupt increase or decrease at a point in time) and change-points (the point in time when a change in trend or shift occurs in the data). These results were then inspected to determine whether they were artifacts of the data or reflected true physical phenomena such as a change in conveyance or climate patterns.

Understanding the Role of Climate on the Change in Fall

For the next assessment, the Study undertook extensive analyses to understand the role of climate versus conveyance in the change in fall (see Section 7.3). A water balance assessment was performed to identify how changes in water supply surpluses and deficits have contributed to the change in fall. This was followed by deterministic modelling and bootstrap statistical techniques to quantify the contributions of change in conveyance and change in climate to the change in fall.

Monitoring and Modelling of NBS

The third assessment of the hydroclimatic analyses of the Study was the investigation and development of new monitoring and modelling approaches to estimating the major components of the NBS – overlake precipitation, basin runoff and lake evaporation (see Section 7.4). New computational and sensing technologies offer the opportunity to improve upon current operational methods for computing NBS. The new computational technologies support current numerical weather and climate models that use data assimilation techniques to derive the components of the water balance. These independent models complement the existing quasi-operational modelling system developed by GLERL, and are being used to assess and pinpoint potential deficiencies in modelling approaches and further refine the water balance estimates.

These models include: the National Center for Environmental Prediction Climate Data Assimilation System reanalysis (NCEP CDAS); Environment Canada's Numerical Weather and Data Assimilation System (ECNWDAS); the Canadian Regional Climate Model (CRCM); and GLERL's new Coupled Hydrosphere-Atmosphere Research Model (CHARM). In addition, new sensing technology such as polarized, Doppler radars and eddy co-variance towers are being used to provide better estimates of precipitation and lake evaporation.

Figure 7-2 illustrates the data available for NBS and its components. Note the different lengths of time for which the data series are available. At the time of this report, the residual NBS data have the longest record, from 1900 through 2006. The GLERL component supplies are available from 1948 through 2005, while the new modelling and monitoring techniques have much shorter records for comparison. At the conclusion of the next part of the Study, addressing Lake Superior regulation, data through 2009 are expected to be available for all but the regional climate modelling techniques. The latter should be available through 2008.

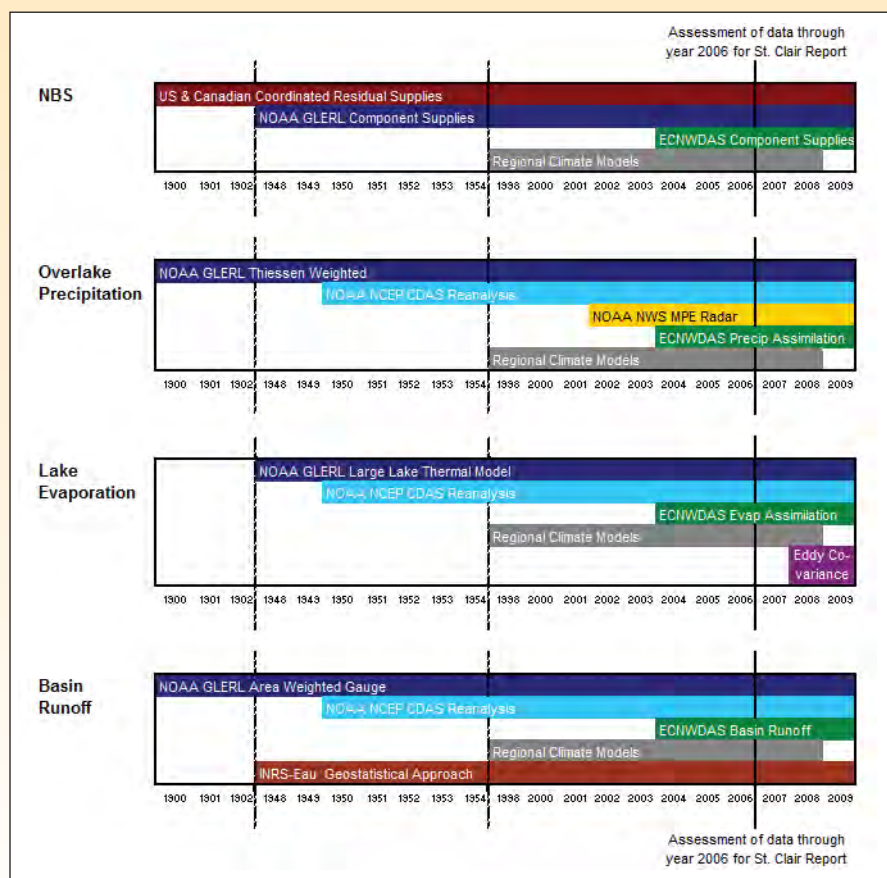
7.2 COMPARATIVE AND STATISTICAL HYDROCLIMATIC DATA ANALYSES

7.2.1 Comparative Analysis of Water Balance Data

The comparative analysis of pertinent Great Lakes water balance data was undertaken primarily through a series of applied research projects (Quinn, 2008a-e). Given that water supplies to the Great Lakes can be computed by the two independent methods (residual and component), these analyses provided the opportunity to identify differences between the two methods for insights into both climate and channel conveyance changes. The Study also investigated the uncertainty inherent in the data and made recommendations on improvements to the computational procedures.

Ideally, the two independent methods should arrive at the same NBS estimates. However, the analysis found that the residual NBS computations for Lake Michigan-Huron began deviating from those of the GLERL component NBS about 1970 (Quinn, 2008a). A second shift appears to have occurred shortly after 1985 in the residual NBS.

Figure 7-2 Timelines of NBS and Components Data Availability



The 1970 shift may be attributable to an apparent change in the lake level gauge at Thessalon, ON that affected the change-in-storage computations (Quinn and Southam, 2008). The 1985 shift likely is attributable to issues related to difficulties with estimated flows for the St. Clair River and possibly the Detroit River that both appeared about 1985 (Quinn, 2008b). Further, the analysis identified problems with an inconsistent water balance between the St. Clair River and Detroit River due to the interagency flow coordination procedure (Quinn, 2008c), as well as potential changes in the channel conveyance in the St. Clair River that appears to have occurred between 1971 and 1989 (Quinn, 2008d). With respect to changes in conveyance, findings reported by Quinn (2008 a-e) identified three possible significant events that could have resulted in erosion of the river bed: the 1973-1974 high lake levels; the 1984 ice jam; and the 1985-1986 record high lake levels. Quinn based his findings on changes in NBS and St. Clair River gauge relationships coincident with these notable events.

The Study also found issues with the Lake Erie residual NBS computation, not only due to problems associated with the St. Clair and Detroit River inflows, but also due to problems associated with Niagara River outflows and change-in-storage computations (Quinn, 2008e).

In response to these findings and other considerations, the Study revised data for the residual NBS. Specifically, the following changes to the residual NBS estimates were made:

- NBS data were recomputed, based on metric levels, flows and diversions;
- actual month lengths were used to convert changes in storage in cubic metres per second (m^3/s);
- outflow data from Lake Erie were revised by separating the Niagara River flow and the Welland Canal diversion, and estimating Niagara flows from 1961 to present, based on better gauged estimates of the outflow from the Maid of the Mist pool; and
- Lake Erie beginning-of-month and change-in-storage data were revised using Cleveland water level gauge data instead of Fairport water level gauge data from 1992 to present.

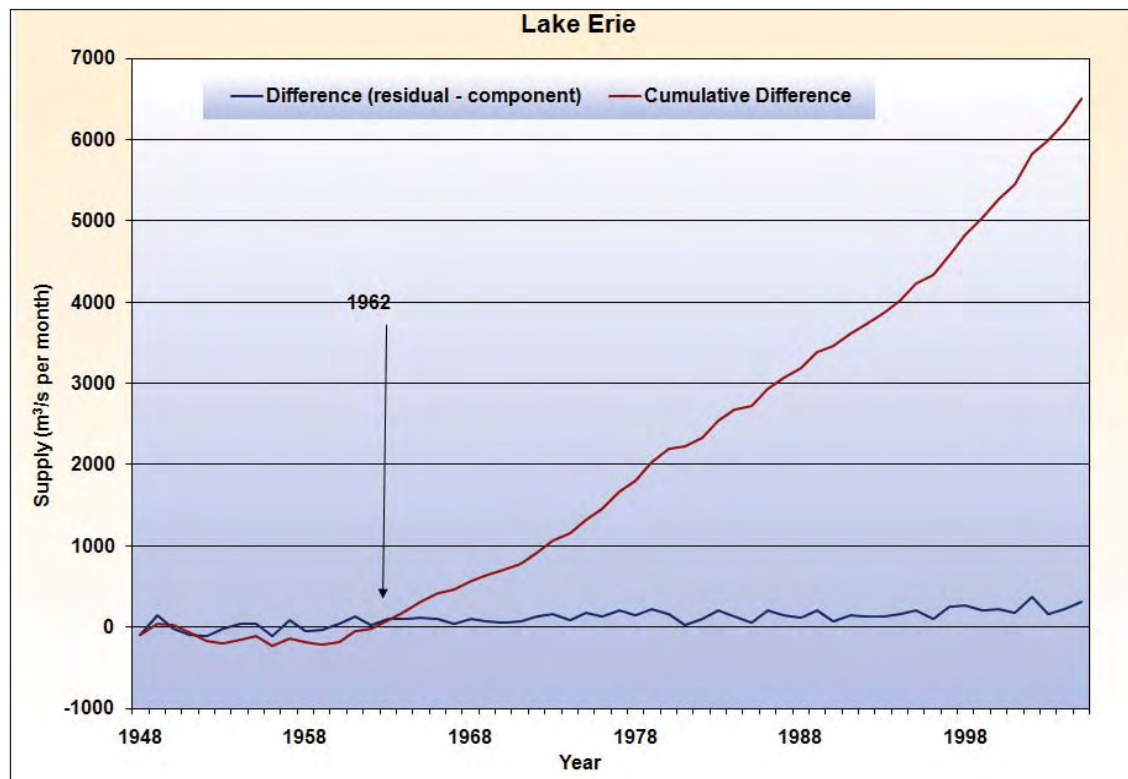
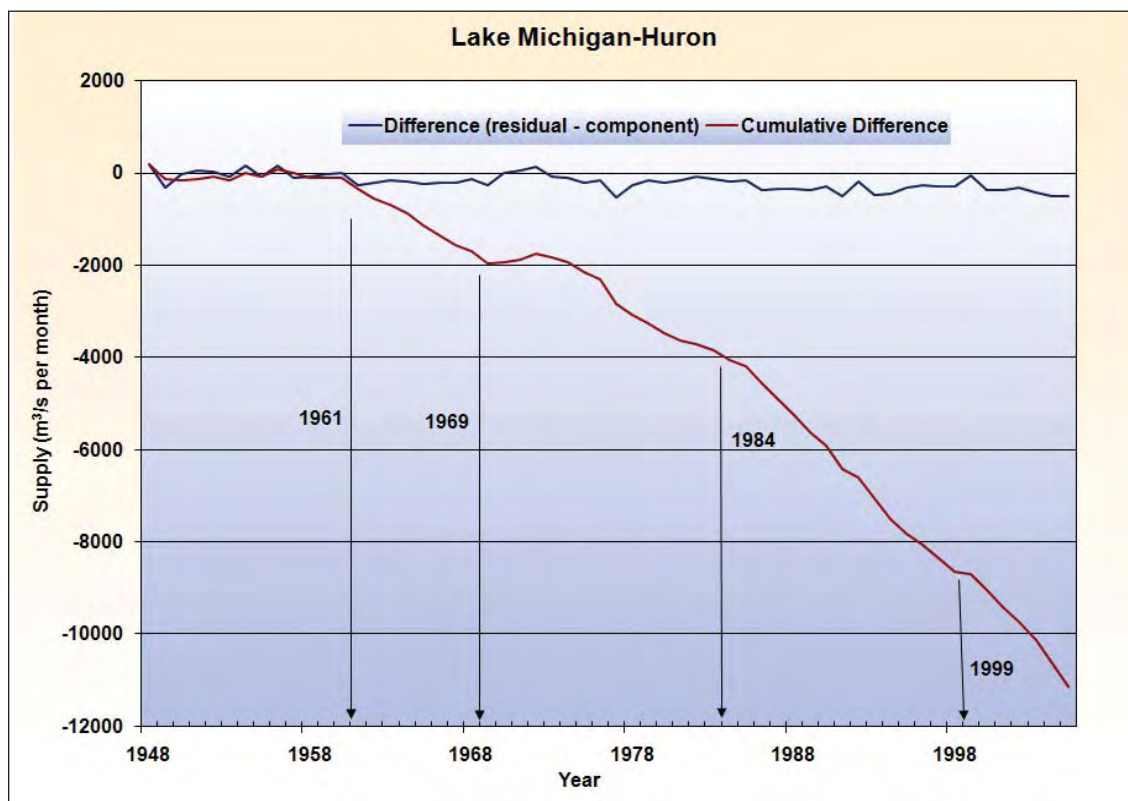
Finally, previous St. Clair River and Detroit River flow estimates are being revised in light of changes in conveyance reported by the Study. This work is being conducted under the auspices of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. This Committee is a bi-national inter-agency working group that coordinates Great Lakes data shared between the United States and Canada for management of the lakes. The task of revising the St. Clair and Detroit River flows is pending completion of the St. Clair River part of the Study in order to use the best estimates of conveyance change.

The Study demonstrated that earlier versions of GLERL component NBS datasets also contained significant errors (Quinn 2008a-e). Quinn identified several computational errors in the basin runoff estimates, as well as several anomalies in the lake evaporation estimates for 2001-2006. Both issues were subsequently addressed by GLERL.

The Study also noted that declines in the streamflow and precipitation gauging networks have introduced large uncertainties in the component NBS that contribute to the differences found between the two computational methods (DeMarchi *et al.*, 2009).

Annual differences in the GLERL component and residual NBS (residual minus component) for Lake Michigan-Huron and Lake Erie are plotted in Figure 7-3. Cumulative differences are also plotted and show consistent differences between these methods for each of the lakes. It would be expected that both annual and cumulative differences between NBS estimation methods would oscillate around zero. However, for Lake Michigan-Huron, the component method is consistently higher than the residual method beginning in 1961, while the opposite is true for Lake Erie. There could be several reasons for the differences between the estimates of NBS including incorrect estimates of St. Clair River flows (affecting the residual supply estimates) and incorrect estimates of lake evaporation (affecting the component supplies). Changes in slope on the cumulative curve in Figure 7-3 are also identified and highlight the deviation. The dates of these changes correspond to the significant events identified by Quinn (2008 a-e). Given that both NBS values are based on estimates (residual NBS based on flow estimates and lake level measurements; component NBS based on estimated water balance components), it is not possible to determine which is more correct. Regardless, the difference represents an average of only about $275 \text{ m}^3/\text{s}$ ($9,712 \text{ ft}^3/\text{s}$) per month, or about 5 percent of the monthly mean St. Clair River flow of $5,150 \text{ m}^3/\text{s}$ ($189,200 \text{ ft}^3/\text{s}$) for 1962 to 2005.

Figure 7-3 Differences in Annual Average Monthly NBS (m^3/s) for Lake Michigan-Huron and Lake Erie since 1948



Note: Differences are calculated as residual minus component NBS values.

7.2.2 Statistical Analyses of Hydroclimatic Data

The Study undertook extensive statistical analyses of the hydrological and climate data to identify climate trends, change-points and other statistical anomalies to discern their relationship to the change in lake level relationship between Lake Michigan-Huron and Lake Erie (Ouarda *et al.*, 2009). Statistical analysis was applied to each lake's monthly and annual water supplies and lake levels, water balance components (overlake precipitation, basin runoff, and lake evaporation), connecting channel flows, air and water temperature, change in storage and the change in fall between Lake Michigan-Huron and Lake Erie. Although the focus of this Study is the post-dredging period of 1962-2005, the period of record statistically evaluated was 1948-2005 for most data. When available, a longer period of record was used, primarily for lake levels and channel flows. This was done to assess the data for underlying, long-term climate trends as well as trends and variability on decadal time scales. Only component NBS estimates were used, because of the noted problems with the St. Clair River flow estimates. Also reported here is an assessment of lake ice cover and its relationship to lake evaporation for the period of available record, 1973-2008 (Assel, 2009).

For trend detection, two statistical tests were used: the original Mann-Kendall (MK) nonparametric test (Mann, 1945; Kendall, 1975); and the Trend Free Pre-whitening modified Mann Kendall (TFPW_MK) nonparametric test (Yue *et al.*, 2002). The latter test prevents the autocorrelation evident in most Great Lakes hydrological data from influencing the long-term trend assessment and was used in this analysis. For the change-point analysis, the Bayesian method (Seidou and Ouarda, 2007) was used.

NBS

Results of the statistical analysis showed no long-term climate trends in annual NBS to Lake Superior and Lake Michigan-Huron over the period of record 1948-2005 (see Table 7-1). Lake Erie does exhibit a weak increasing annual trend and a stronger seasonal trend in the fall months. These results were supported by no increasing long-term trends found in watershed runoff, overlake precipitation, lake evaporation and air temperature. The exception was Lake Superior, where an upward trend in maximum air temperature was found. It is important to understand that an absence of trend does not imply that there are no observed changes in temperature or water balance components. Rather, this indicates that there is no statistically significant increase or decrease in many of these variables over and above the observed natural variations seen during the 1948-2005 period.

Change-point analysis of NBS revealed no pronounced trends (increasing or decreasing) throughout the record on shorter (decadal) timescales (Figure 7-4). No change-point was detected for Lake Michigan-Huron NBS, with only a statistically insignificant rising trend from 1948 to 2005 (Figure 7-4a). No change-point was detected for Lake Erie NBS, though it exhibited a weak (10 percent significance level), rising trend over this period (Figure 7-4b).

Table 7-1 Annual Trend Detection Results for the Great Lakes Component NBS, 1948-2005 (Modified Mann-Kendall Test)

| Lake | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Annual |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| Superior | 0 | 0 | 0 | 0 | 0 | 0 | 0 | ▽ | 0 | 0 | 0 | 0 | 0 |
| Michigan-Huron | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | △ | 0 | 0 |
| Erie | 0 | 0 | 0 | 0 | 0 | 0 | 0 | △ | △ | 0 | △ | 0 | △ |

Key to Table 7-1, Table 7-2

0 : Acceptance of the null hypothesis (no trend)

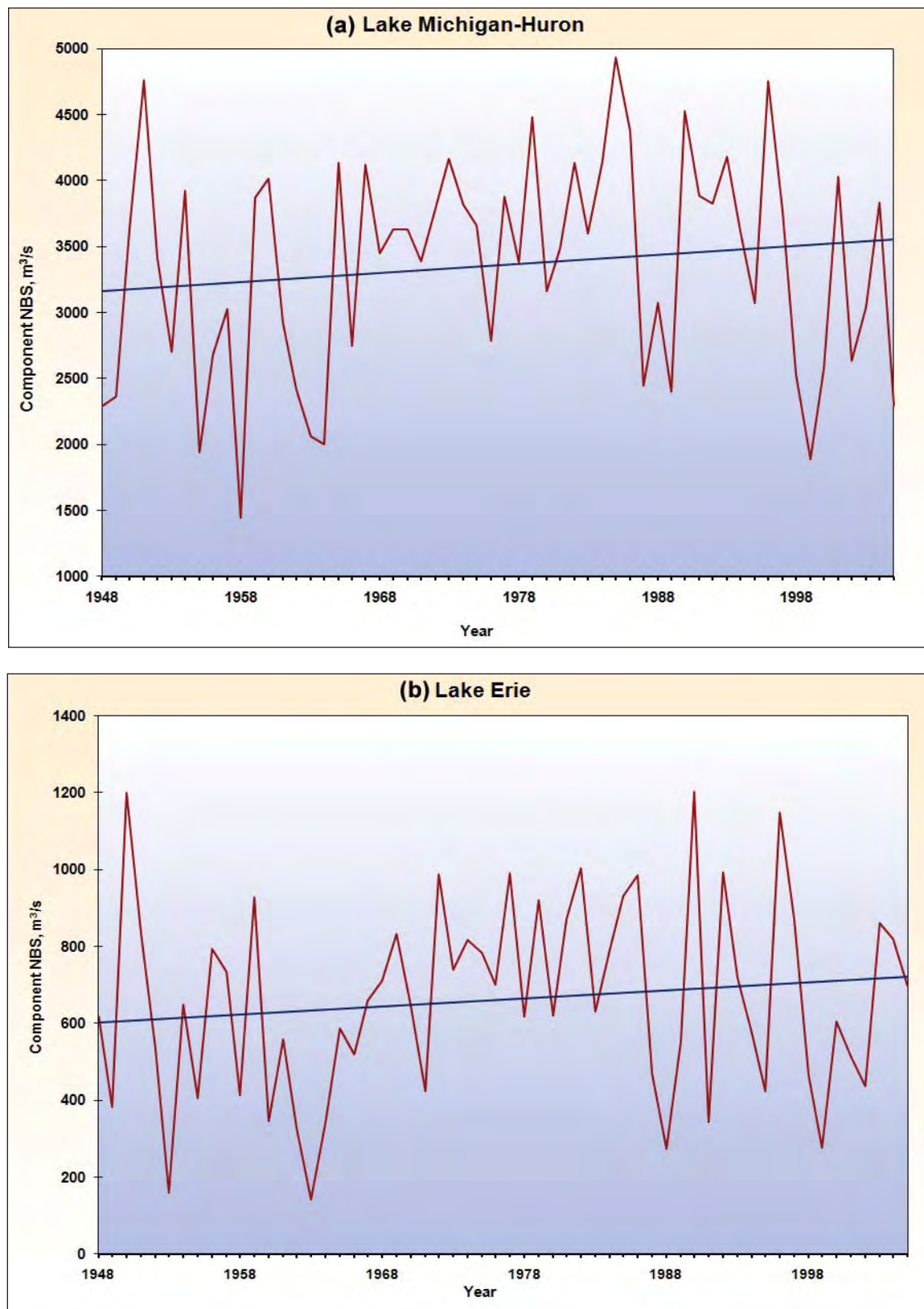
△ : Upward trend significant at 5 percent significance level

△ : Upward trend significant at 10 percent significance level

▽ : Downward trend significant at 5 percent significance level

▽ : Downward trend significant at 10 percent significance level

Figure 7-4 Change-Point Analysis of Annual NBS



Lake Levels

Annual lake levels for 1918-2007 were statistically analyzed for trends and change-points, focusing on the correlated variables of air temperature and overland precipitation. By considering these variables, change-points due to climate were removed using autocovariate statistical methods, leaving those related to the hydraulics of the system or other factors related to measuring water levels. The analysis showed that Lake Superior and Lake Michigan-Huron annual water levels exhibited no significant trends when analyzed over the period of record, whereas Lake Erie showed weak upward trends in annual water levels over the period of record (Table 7-2). Lake Erie has experienced significant upward trends for all monthly water level time series, indicating a change in its seasonal pattern of lake levels.

The results obtained from the Bayesian change-point detection method showed that there were two change-points in 1970 and 1989 for Lake Michigan-Huron water levels (Figure 7-5a) and a single change-point in Lakes St. Clair and Erie water levels in 1969 (Figure 7-5b). No change-point was detected in Lake Superior water levels. With respect to Lake Michigan-Huron, the change-points in 1970 and 1989 are consistent with findings of changes in 1969 and 1984 from Quinn's comparative analysis (Quinn, 2008a-e) and the conveyance changes reported in Chapter 5.

A common change-point in 1972 was set for all lakes, as a compromise for detected change-points for different lakes. Monthly and annual time series were tested for trends before and after the determined change-point. Table 7-3 highlights the results of the annual analysis and shows a significant downward trend for annual water levels after 1972 in Lake Superior, Lake Michigan-Huron and Lake Erie.

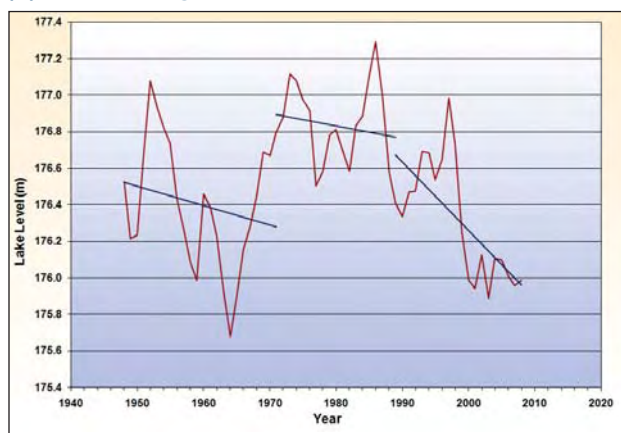
Table 7-2 Trend Detection Results for Water Levels in the Great Lakes
(Modified Mann-Kendall Test, 1918-2007)

| Lake | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Annual |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| Superior | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Michigan-Huron | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Erie | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ | Δ |

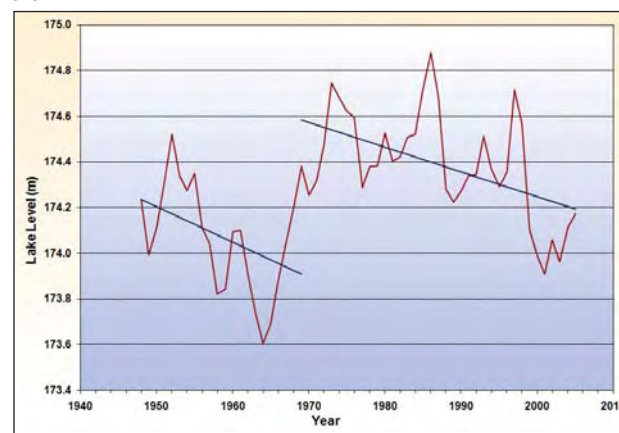
Note: See Table 7-1 for key to symbols.

Figure 7-5 Change-Point and Trend Analysis for Water Levels

(a) Lake Michigan-Huron



(b) Lake Erie



Note the change-points for Lake Michigan-Huron in 1970 and 1989 and for Lake Erie in 1969.

Connecting Channel Flows

The initial statistical analysis of the connecting channel flows for the period of record (1900-2006), adjusted for serial correlation, revealed no long-term trend in the flows for the St. Marys, St. Clair and Detroit Rivers. Subsequently, computational issues in the coordinated flows were recognized (see Chapter 5). Once the issue of any conveyance change has been resolved, then new coordinated flows for the St. Clair River will be recalculated. When these are completed, the trend analysis will be re-done on this new time-series. This will be done in the second part of the Study, addressing Lake Superior regulation.

Change in Fall

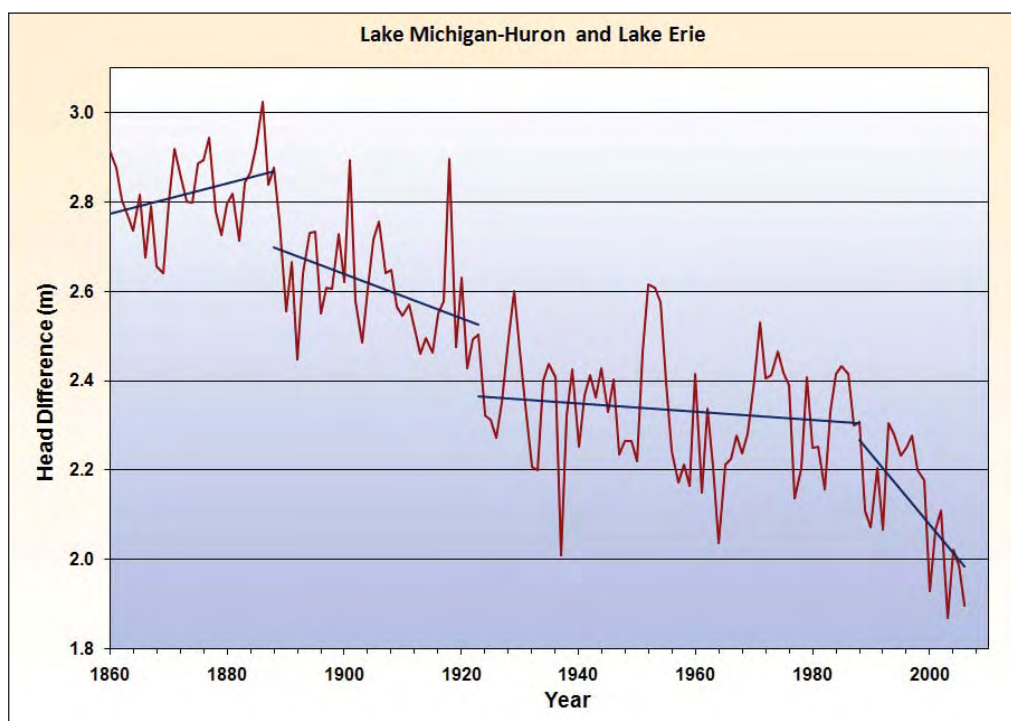
The Study conducted a statistical analysis of the change in fall between Lake Michigan-Huron and Lake Erie (1860-2006). Change-points were found in 1888, 1923, and 1988. After each breakpoint, downward shifts with downward trends were exhibited, with the trend post-1988 being noticeably steeper than the prior periods (Figure 7-6). The change-points in 1888 and 1923 are correlated with major human activities. For example, in 1888, the Edison Sault hydropower diversion station was completed in the St. Marys River; in 1920 and 1921, the St. Clair River channel was dredged to 6.4 m (21 ft). Quinn (2009) shows the earlier change-points are due to known anthropogenic factors, while Quinn and others (see Section 7.3) show that the post-1988 trend is due primarily to climate.

Table 7-3 Comparison of Trends in Annual Water Levels for Different Record Periods (Modified Mann-Kendall Test)

| Period Lake | 1918-2007 | 1918-1972 | 1973-2007 |
|----------------|-----------|-----------|-----------|
| Superior | 0 | 0 | ▽ |
| Michigan-Huron | 0 | 0 | ▽ |
| Erie | △ | △ | ▽ |

Note: See Table 7-1 for key to symbols.

Figure 7-6 Change-Points in the Fall between Lake Michigan-Huron and Lake Erie (1888, 1923 and 1988)



Lake Ice Cover

A significant change in the extent of ice cover conditions, occurring during the winter months, affects evaporation rates and, in turn, lake levels. To understand this relationship better, the Study undertook a number of statistical analyses of ice cover parameters to identify ice cover trends that may contribute to the recent change in fall between Lake Michigan-Huron and Lake Erie water levels (Assel, 2009).

The data used for this analysis consisted of daily lake-averaged ice concentration for winters 1973 to 2005 abstracted from Assel (2003, 2005). In addition, daily lake-averaged ice concentration for winters 2006 through 2008 were developed from data abstracted from the National Ice Center and the Canadian Ice Service. Additional data used for this analysis included the GLERL monthly lake evaporation and overlake air temperature data and monthly average Great Lakes water levels.

Statistical relationships between ice cover and water levels and ice cover and lake evaporation were derived through linear regression. Linear regression also was used to identify trends in lake-averaged ice cover over the 36 winters studied (1973-2008). The Mann-Kendall analysis was not applied in this case, because data on lake ice cover were not available to Ouarda *et al.* (2009) at the time of their analysis. Further work for the second phase of the Study on Lake Superior regulation will explore this issue.

Figure 7-7 illustrates the seasonal average ice cover for this period. The first five plots illustrate: seasonal average ice cover (blue line); a five-year centered running average (red line); and a linear regression of the five-year running average for Lakes Erie, St. Clair, Huron, Michigan and Superior. The last plot compares linear trends. Note that the greatest rate of decline is for Lake Superior. The five-year moving average is also shown.

Key findings of the analyses are:

- Regression analyses of the monthly, seasonal average, and seasonal maximum ice cover resulted in all lakes having decreasing trends over the 36-winter period.
- Three of the four lowest annual maximum ice covers occurred during the last 11 (1998-2008) of the 36 winters under study for Lakes Superior, Michigan, Huron, and Erie.

To evaluate the significance of ice cover changes on water levels, the Lake Michigan-Huron minus Lake Erie water levels for the months of January, February and March were correlated with average monthly ice covers for Lake Erie and Lake Huron over these three months. The regression analysis showed that ice cover has a positive correlation with the difference in lake levels.

The Study also investigated the statistical relationship between ice cover and lake evaporation. The resulting ice cover-evaporation analysis showed that the declining ice cover was negatively correlated with lake evaporation in January, February and March for both Lake Erie and Lake Huron. This supports the findings that monthly evaporation increased with decreasing ice cover concentration.

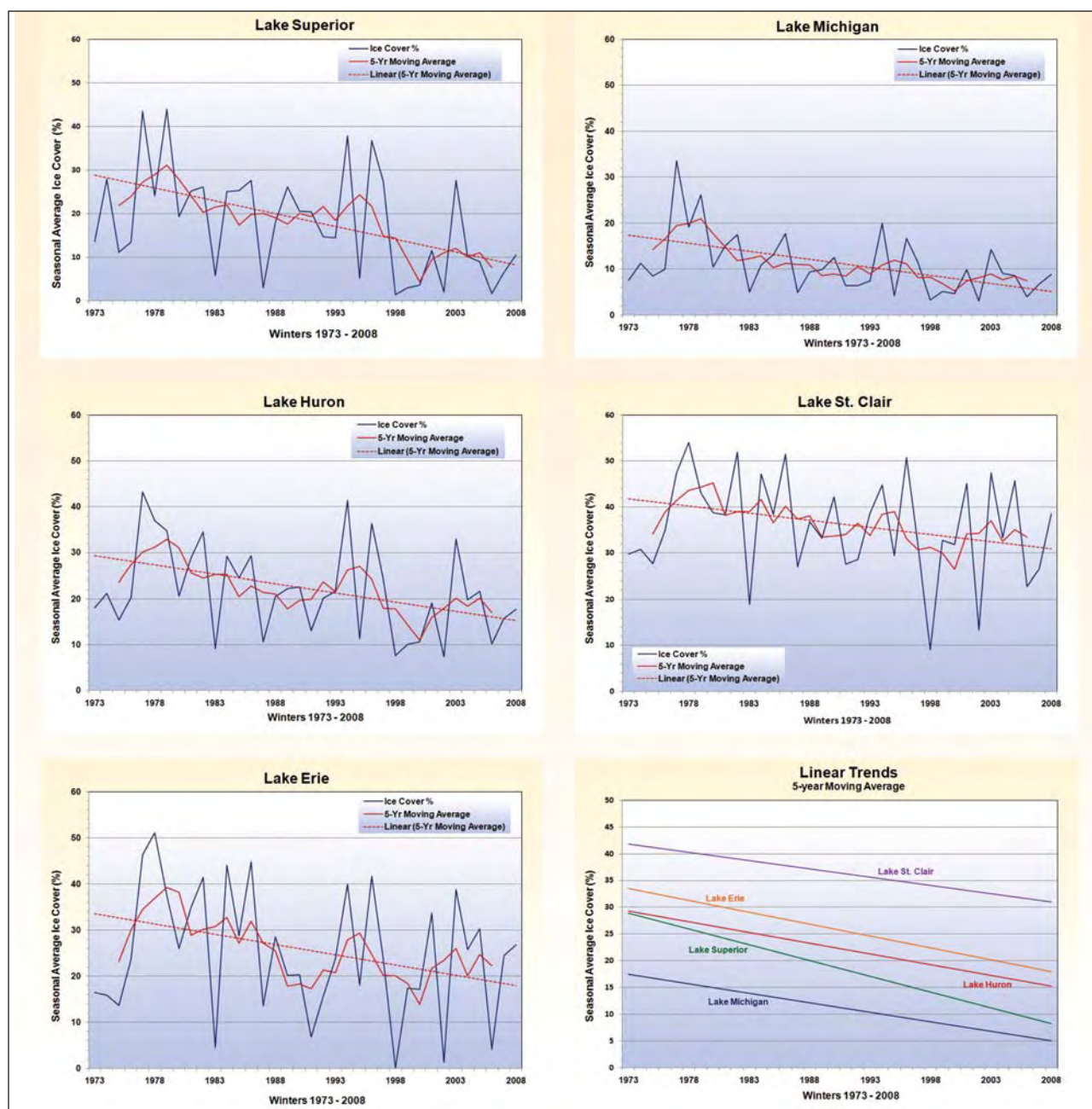
The Study also investigated a comparison of annual and monthly average air temperatures over the past 36 years with the change in fall. The analyses revealed that the annual and monthly average winter air temperature, with the exception of January, is not significantly correlated with the change in fall.

This trend appears to be explained partially by Desail *et al.* (2009), who note that for Lake Superior, mean surface water temperatures have warmed faster than air temperature. They maintain that this is because decreasing ice cover has led to increased heat input into the lake. They further note that coincident increasing lake and winter air temperatures have resulted in the temperature gradient between air and water being reduced, destabilizing the atmospheric surface layer above the lake and resulting in higher overlake winds. This leads to higher evaporation rates. It would appear that longer ice-free periods along with increased evaporation rates are influencing recent lake levels. Observation studies, reported in Section 7.4.1, are being conducted under the second part of the Study to understand further this phenomenon.

Summary

It is difficult to draw overall conclusions based on these statistical analyses, as they cannot identify the causative factors in trends and change-points. Further analysis is required to attribute recent changes in the lakes more comprehensively. However, of particular note is the post-1972 lake-level trend analysis (based on an assumed common change-point) that highlighted significant decreasing trends in upper lakes water levels following the record high water levels of the 1980s. Further analysis of the water balance components, including deviations from long-term means, analysis of total lake water supplies, and deterministic and stochastic numerical experiments, are described below to understand better the reasons for this trend.

Figure 7-7 Seasonal Ice Cover (1973-2008)



7.3 EFFECTS OF CLIMATE AND ANTHROPOGENIC CHANGES ON LAKE LEVELS

7.3.1 Water Balance Assessment

For further insights into climate effects on water levels, the Study conducted a basic water balance assessment for Lake Michigan-Huron and Lake Erie using the corrected monthly water supply values (see Section 7.2.1). These data included beginning-of-month lake levels, connecting channel flows (uncorrected for the St. Clair River) and

GLERL component estimates for overlake precipitation, basin runoff and lake evaporation. These data were divided into both five-year segments and annual averages.

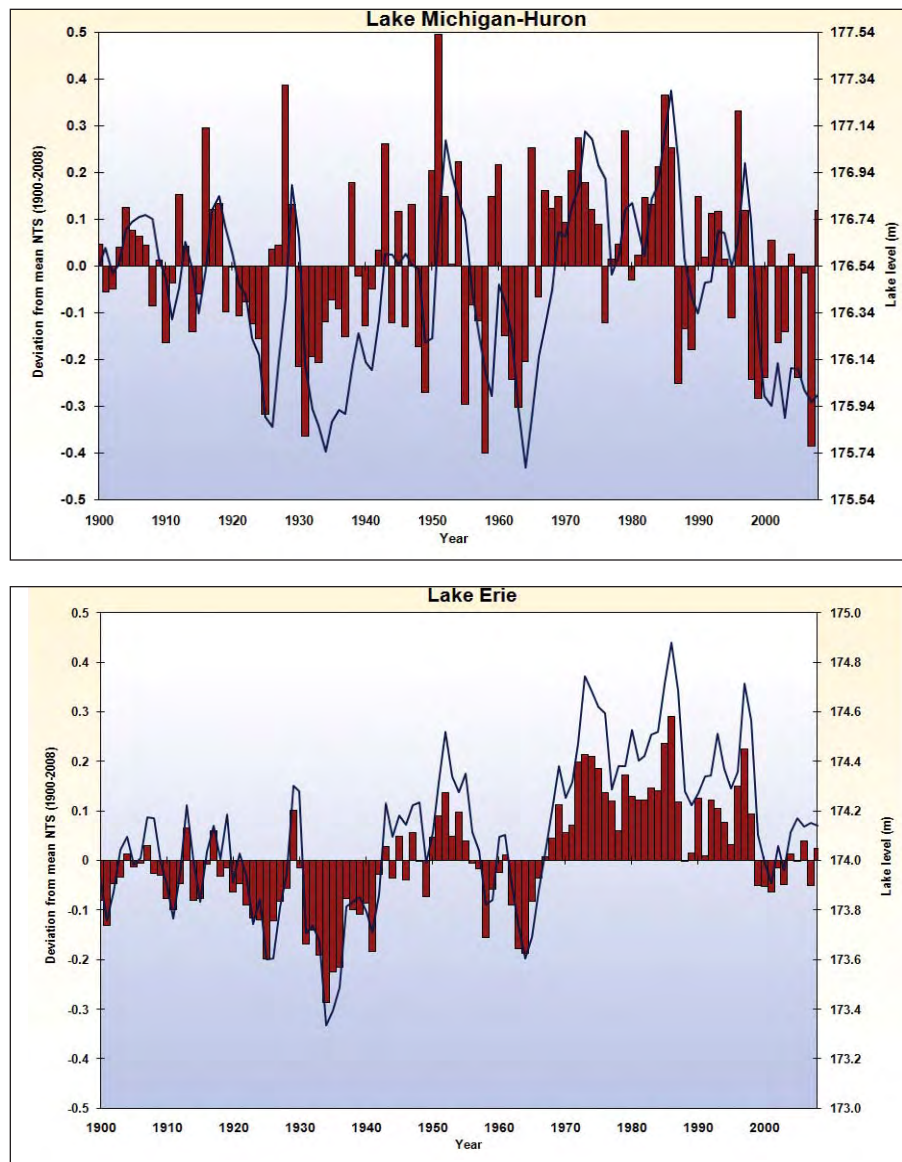
As part of this analysis, Net Total Supply (NTS) was estimated for both Lake Michigan-Huron and Lake Erie. The NTS is the total input into each lake, computed by adding the interconnecting channel flow to the NBS estimate. In the case of Lake Michigan-Huron, St. Marys River monthly flows are added to the NBS estimates (both residual and component). Similarly for Lake Erie, Detroit River flow estimates are added to the Lake Erie NBS monthly estimates.

To understand the historical context, available data for 1900-2005 were used in assessing deviations in NBS and NTS for Lake Michigan-Huron and Lake Erie. Deviations from the mean are expressed as the percent difference between the 1900-2005 mean NBS and NTS estimates and the estimated values for that given year. Figure 7-8 shows total deviations from 1900 to 2005 (as a percentage of the mean) for both Lake Michigan-Huron and Lake Erie. The plots show marked deviations in recent years for Lake Michigan-Huron and corresponding low water levels. Similar lake level declines and deviations are noted earlier in the measurement period, including the deviations and low lake levels noted throughout the 1930s.

Water levels in Lake Erie have recovered in recent years, and are similar to what they were in 1900. As of April 2009, water levels on Lake Michigan-Huron had recovered to just below historically average levels.

As mentioned, both residual and component estimates represented the total inflow into Lake Michigan-Huron and Lake Erie. As noted in Figure 7-8, there appears to be a prolonged period of negative deviations (*i.e.*, water supply deficits) from the mean for NTS within the last ten years, since about 1998. This coincides with a period of prolonged drought that occurred in western North America. Supplies into Lake Erie are shown to be less variable and result in more stable lake levels.

Figure 7-8 Annual Residual NTS Deviations from the Mean for Lake Michigan-Huron and Lake Erie (1900-2005)



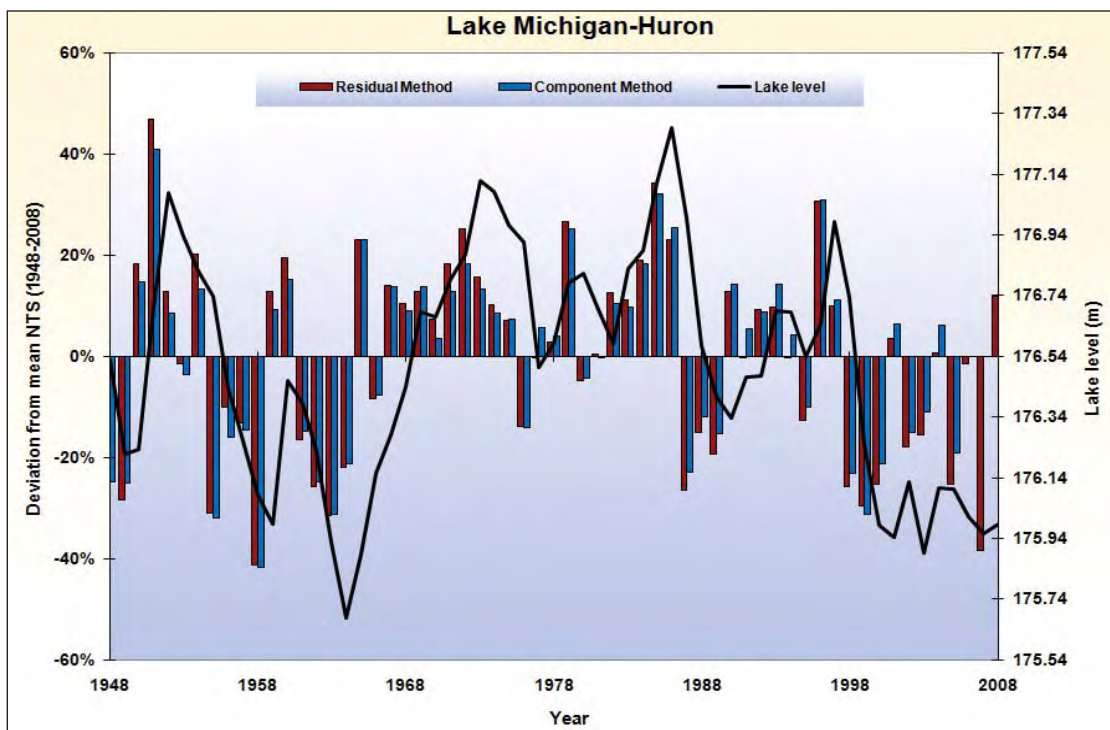
Note: Mainly negative NTS deviations observed from 1998 to 2005 for Lake Michigan-Huron. Lake level (metres; blue lines) are plotted on the right hand axis.

Inherent in the residual NBS and NTS estimates noted above are any biases or errors in flow or lake level estimates that are used to calculate the residual supplies. As discussed and shown earlier in Figure 7-3, two independent methods for estimating NBS have been available since 1948. Although minor differences in NTS using either component or residual estimates for Lake Michigan-Huron can be observed, the overall supply into the lake shows a long period of negative (deficit) supplies compared to the long-term mean, with a resulting decline in lake levels. This does not imply that the lake level decline is completely attributable to hydroclimatic factors. However, it does support independent observations and computations that these deficits are a major contributing factor to lake level declines. As discussed in the following sections, these factors do explain a large proportion of the observed changes. Figure 7-9 highlights the NTS estimates using both component and residual estimates for Lake Michigan-Huron. The findings indicate that both residual and component methods are synchronous with lake level fluctuations.

To examine further the context of recent changes, five-year average estimates of water balance components from 1948 to 2005 (Figure 7-10) indicated that for the last two five-year periods, there has been a substantial decrease in the Lake Michigan-Huron NTS (residual NBS plus the St. Marys River inflow), with a decrease of about 20 percent based on the 60-year mean (1948-2008). This resulted in a significant negative water balance for the lake over that period, with an average decrease in change in storage of about 400 m³/s (14,126 ft³/s). This equates to an average increase in the rate of decline of about 1 cm (0.4 in) a month relative to average over this decade.

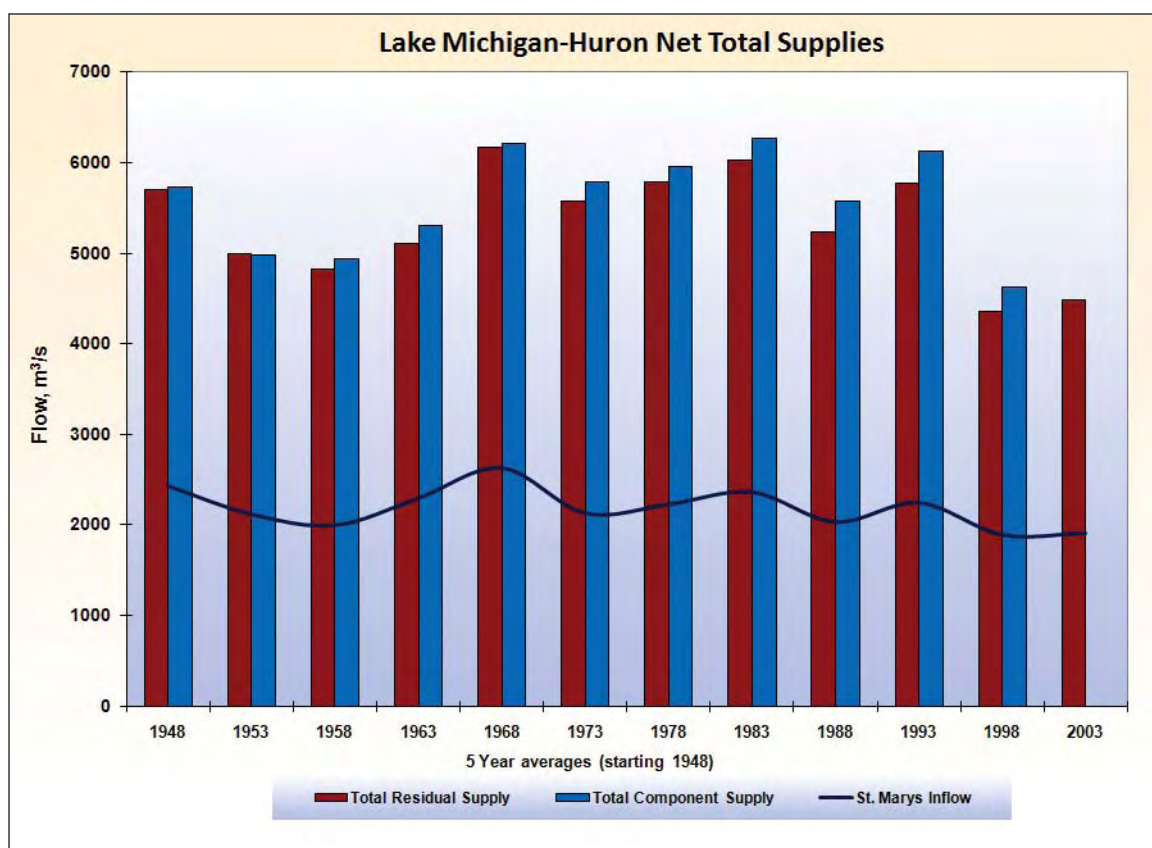
There is some question regarding the reliability of residual NBS due to the uncertainty in St. Clair River outflows. However, it is reasonable to conclude that there is a relatively strong climate signal present in explaining the deviations in Lake Michigan-Huron water levels given that that 10-year average St. Marys River inflows (a significant portion of the NTS) are reliable and that St. Marys River inflows alone into Lake Michigan-Huron have decreased by about 13 percent over the last 10 years when compared

**Figure 7-9 Annual NTS for Lake Michigan-Huron
1948-2005 for Component Supplies
1948-2008 for Residual Supplies**
(expressed as average monthly flow in m³/s)



Note: Both component (light gray bars) and residual NTS estimates (St. Marys River flow + NBS; blue bars) are shown. Changes in lake level (metres; black line) are plotted on the right axis.

Figure 7-10 Analysis of NTS for Lake Michigan-Huron



Note: Illustrates the upstream St. Marys River contribution along with component and residual estimates of NBS. The plot highlights significant deviations using either component or residual NBS estimates of total inflow into the lake. Component NBS values for 2006-2008 were not available at the time of this report's preparation, and as a result the component NBS average was not done for the 2003-2008 period.

to the 60-year average. Using either component or residual NBS estimates, it is clear from Figure 7-10 that NTS into Lake Michigan-Huron has decreased substantially within the last 10 years resulting in a marked change in lake level.

In summary:

- Declines in Lake Michigan-Huron levels correspond to declines in NTS computed with either the residual or component NBS;
- Lake Michigan-Huron NTS has decreased about 20 percent from the long-term mean over the 1995-2005 period; and
- The St. Marys River inflows to the lake have decreased 13 percent over the same period, indicating a strong climate signal in explaining the declining lake levels.

7.3.2 Assessment on the Impact of Historical Anthropogenic Changes

To provide an historical perspective on all the factors leading to the decline in fall between Lake Michigan-Huron and Lake Erie over the past 120 years, the Study examined the possibility of adjusting present water levels to simulate historical water levels for Lake Michigan-Huron and Lake Erie. These simulated water levels would be those that would have existed with the water supplies of the past under current channel conditions.

The resulting simulated water levels provided a baseline of historical water levels that can be compared directly to present water levels. They also provided an estimate of change in fall between the two lakes that would have occurred without any anthropogenic impacts (excluding climate change or conveyance changes not included in the analysis). The comparisons provided an indication of the impacts of measurements errors, GIA, channel changes in the St. Clair and Niagara Rivers, and major diversions into and out of the upper Great Lakes.

These impacts are described in detail by Quinn (2009). The major channel changes considered in this work are listed in Table 7-4.

The Lake Michigan-Huron water levels corrected for both channel changes and diversions are shown on Figure 7-11a. The long-term annual mean is reduced from 176.55 to 176.45 m (579.2 to 578.9 ft), a decrease of 10 cm (3.9 in). What is apparent is that Lake Michigan-Huron oscillates between high and low lake level regimes and that the long-term annual mean, based on the unadjusted recorded lake levels, is not representative of either regime or the long-term mean given the current hydraulic system configuration. The Lake Erie water levels corrected for both channel changes, GIA and diversions are shown on Figure 7-11b.

Using the two adjusted lake levels highlighted above, the difference in head between the two lakes can be estimated. The fall with all corrections made to both lakes is shown in Figure 7-12. The trend line has a small downward trend in fall with time. Figure 7-12 compares the recorded fall with the corrected fall. The figure demonstrates that the decline in the recorded fall, with the exception of the 1880s, is explained by the changes in the channels of the St. Clair and Niagara Rivers, the diversions into and out of

the basin, and the subsidence from GIA of the Cleveland gauge relative to the lake's outlet. The main fluctuations about the corrected mean fall are then the result of changing NBS, with the possible exception of erosion in the mid-1980s in the St. Clair River. This simulated fall curve shows that the fall, when corrected, has varied around a mean of about 2.2 m (7.2 ft) over the past 120 years with minimal trend. Including these effects highlights that the current observed fall estimates are well within the realm of past hydroclimatic conditions. Putting this in context, the next sections attribute the observed recent variations to climate and possible conveyance changes.

7.3.3 Climate versus Conveyance

The Study undertook a project to attribute climate versus conveyance in the change in fall for 1996 to 2005 (Tolson, 2009). A working assumption of the Study was that post-1971 changes in the St. Clair River channel conveyance as well as the natural variability of water supplies to each lake contributed to the change in fall during this period. Various analyses were conducted to determine how much each factor independently contributed to the decline. The focus of this study on the 1996-2005 period is based on the following considerations: component NBS data is

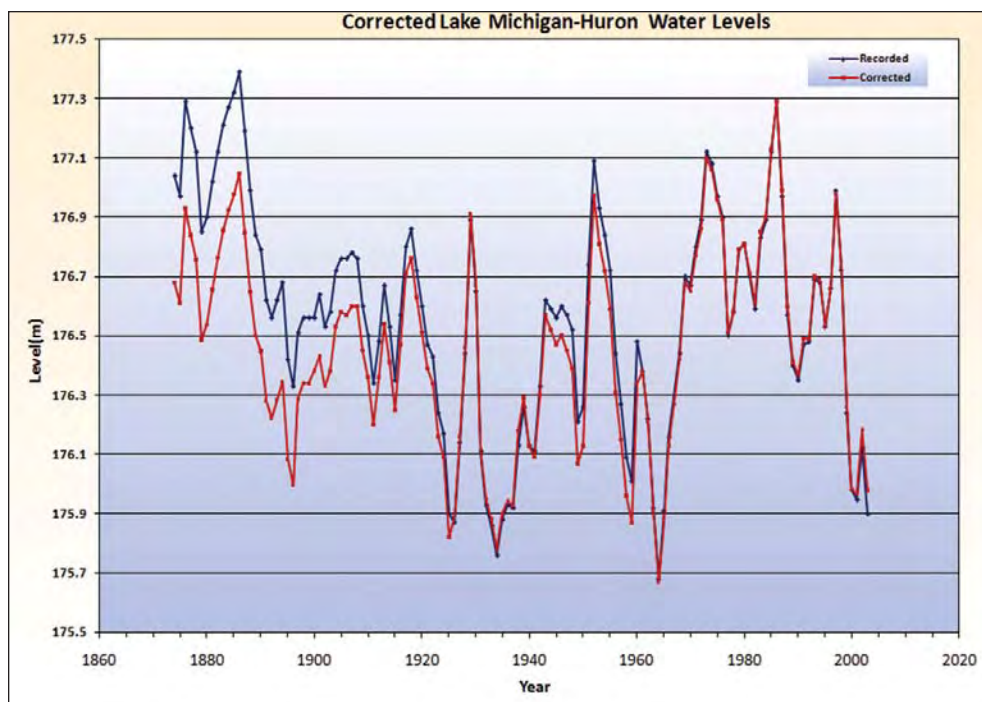
Table 7-4 Major Channel Changes in the St. Clair and Niagara Rivers Affecting Water Levels in Lake Michigan-Huron and Lake Erie

| Action in St. Clair River | Date | Impact on Michigan-Huron (m) |
|--|-----------|------------------------------|
| 16 ft navigation channel | 1874 | |
| 20 ft navigation channel | 1892 | -0.11 * |
| Shoal removal St. Clair Flats | 1906 | -0.01 |
| Sinking of steamers | 1900 | +0.03 |
| Sand and gravel mining | 1908-1925 | -0.09 |
| 25 ft navigation channel | 1935-1937 | -0.05 |
| 27 ft navigation channel | 1960-1962 | -0.13 |
| Action in St. Clair River | Date | Impact on Lake Erie |
| Construction of International Bridge | 1872 | +0.01 |
| Dredging by Niagara Falls Power Company | 1900 | ? |
| Dumping Upstream of First Cascade | 1916-1921 | +0.05 |
| Construction of Peace Bridge | 1925 | +0.03 |
| Change Upstream of Black Rock | 1930-1931 | +0.03 |
| Weir and Goat Island Dike | 1942 | +0.05 |
| Removal of Goat Island Dike | 1947 | -0.05 ** |
| Construction of CGIP Control Structure | 1954-56 | ? |
| U.S. Shore | 1961 | +0.00 |
| CGIP Wing Dikes and Intake Channel Constructed | 1954-56 | ? |
| Nicholl's Marine Lot Filled | 1971-1973 | +0.02 |

* Lower estimate for all dredging 1855-1906 (Southam, 1989); ** Assumed.

Figure 7-11 Simulated Historical Water Levels

(a) Lake Michigan-Huron



(b) Lake Erie

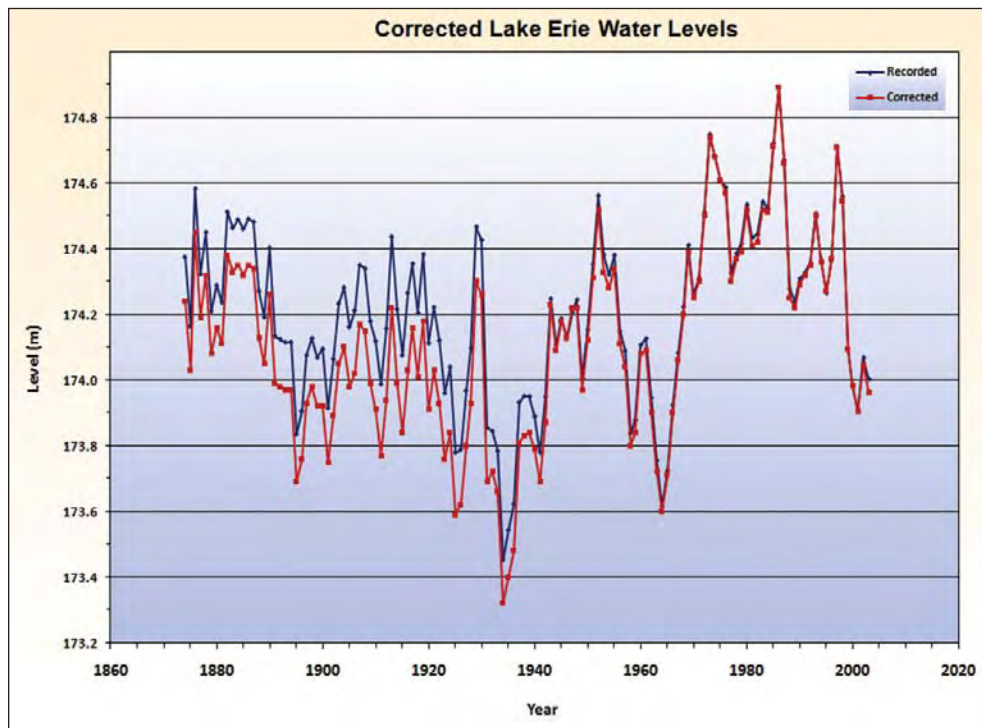
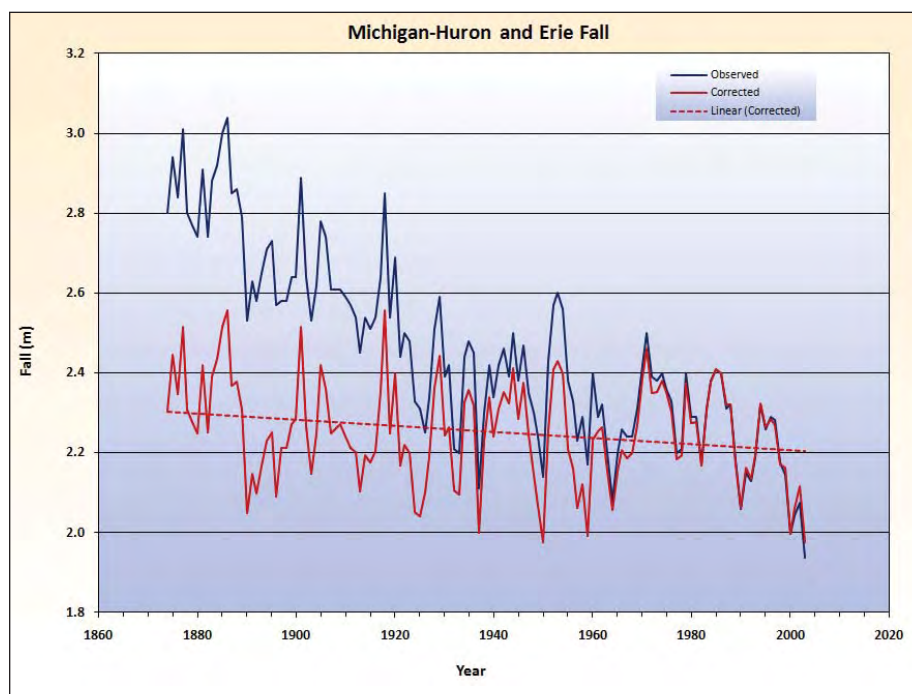


Figure 7-12 Fall Estimates between Lake Michigan-Huron and Lake Erie using Simulated and Recorded Lake Levels



only available through the end of 2005; the quantitative description of the current conveyance regime is based on a 1996 through 2006 data analysis; and there appears to be little trend in the head difference from 1963-1995 and as of 1995, the head difference is within a few centimetres of the 1963-1995 average.

The Coordinated Great Lakes Routing and Regulation Model (CGLRRM) was utilized to simulate lake levels (and thus the decline in head difference) for Lake Erie, Lake St. Clair and Lake Michigan-Huron in a suite of comparative modelling experiments.

CGLRRM is a hydrological routing model of the Great Lakes. It is comprised of continuity equations for each lake, solved using a second-order finite-difference technique (Quinn, 1978) with a numerical time step of one hour. It uses as inputs time series of NBS and diversions, as well as initial outflows and lake levels, for each lake. The model calculates discharge from each lake from an open water lake-to-lake stage-fall-discharge equation with regression-based coefficients. In the winter, flows in the connecting channels are naturally reduced by the presence of ice and in summer, by weed growth. Thus connecting channel apparent ice and weed retardation are also model inputs. Outputs of CGLRRM include monthly mean lake levels, beginning-of-month levels, and monthly flow rates for the connecting channels.

Deterministic Model Runs (Experiment 1)

The Study focused on building a robust and credible deterministic model of the Great Lakes system, through the following tasks:

1. Show that CGLRRM, based on component NBS, can replicate past lake levels.
2. Demonstrate that model predictions generate a head difference over time that tracks the observed head difference between Lake Michigan-Huron and Lake Erie.
3. Repeat steps 1 and 2 with different open water lake-to-lake stage-fall-discharge equations for St. Clair River flow for the 1963-1977 period and the 1996-2005 period such that two different conveyance regimes on the St. Clair were represented. The Study developed an empirical equation for the 1996-2005 period to specifically represent the current conveyance regime (Fay, personal communication, 2009).

The conveyance of the St. Clair River is represented in CGLRRM by a lake-to-lake stage-fall equation for open water between Lake Michigan-Huron and Lake St. Clair. Prior to this study, the equation for St. Clair River flow was taken to be Equation (3) from Fay and Noorbakhsh (2004):

$$Q=82.2((MH+SC)/2-166.98)^{1.87}(MH-SC)^{0.36} \quad (3)$$

Where: Q is the average monthly St. Clair River flow (m³/s); MH is the average monthly lake-wide average level for Lake Michigan-Huron (m); and SC is the average monthly lake-wide average level for Lake St. Clair (m).

The model is simulated with Equation (3) along with component NBS estimates from the GLERL, as described earlier. The simulated time series are compared to measured (coordinated) average monthly lake levels for the 1963-2005 period.

As described earlier, three potential causes for the disagreement between model simulated and measured lake levels are: errors in the component NBS estimates; changing St. Clair River channel conveyance over time; and apparent ice and weed retardation that are calculated based on the residual supplies. Therefore, to account for the changing St. Clair channel conveyance, a revised equation is taken to represent only the 1996-2006 period:

$$Q = 1450.92((MH+SC)/2-171)^{0.78472} (MH-SC)^{0.38388} \quad (4)$$

Where: Q is the average monthly St. Clair River flow (m³/s); MH is the average monthly lake-wide average level for Lake Michigan-Huron (m); and SC is the average monthly lake-wide average level for Lake St. Clair (m).

Results, plotted in Figure 7-13, show that with Equation (3), CGLRRM does not simulate the measured (coordinated) average monthly Lake Michigan-Huron lake levels very accurately as the prediction error grows with time. For example, after 2000, the model over-predicts Lake Michigan-Huron levels by an average of 0.20 m (0.7 ft). Simulated results with Equation (4) are a clear improvement in model prediction accuracy over Equation (3), with the remaining error attributed to the component NBS and apparent ice and weed retardation factors.

The next step focused on various deterministic modelling runs that varied one model input factor at a time and then compared the simulated decline in head differences. This step required the definition of various metrics that quantify the decline in head difference over time, focusing on the different equations for St. Clair River flow, such as switching the conveyance change on or off. Table 7-5 summarizes these metrics.

The Study then examined the analysis of conveyance change by comparing the baseline results, which use Equation (4), to those from Equation (3). The results, summarized in Table 7-6, indicate that conveyance was responsible for between 24 and 31 percent of the change in head difference between 1996 and 2005. Taking the

Table 7-5 Selected Baseline Simulated Metrics
Metrics approximate the change in head difference between Lake Michigan-Huron and Lake Erie observed for 1996-2005

| Metric Name | Period | Notes | Baseline metric value (head difference) = Initial – final average head difference (m) |
|--------------------|--------------------------|---|---|
| M _{1 ann} | 1997 ¹ - 2005 | Based on annual average head differences | 0.30 |
| M _{2 reg} | 1996 - 2005 | Calculated from linear regression of annual average head difference vs year | 0.28 |
| M _{3 3yr} | 1997 - 2004 | Based on 3-year moving average of annual average head differences | 0.24 |

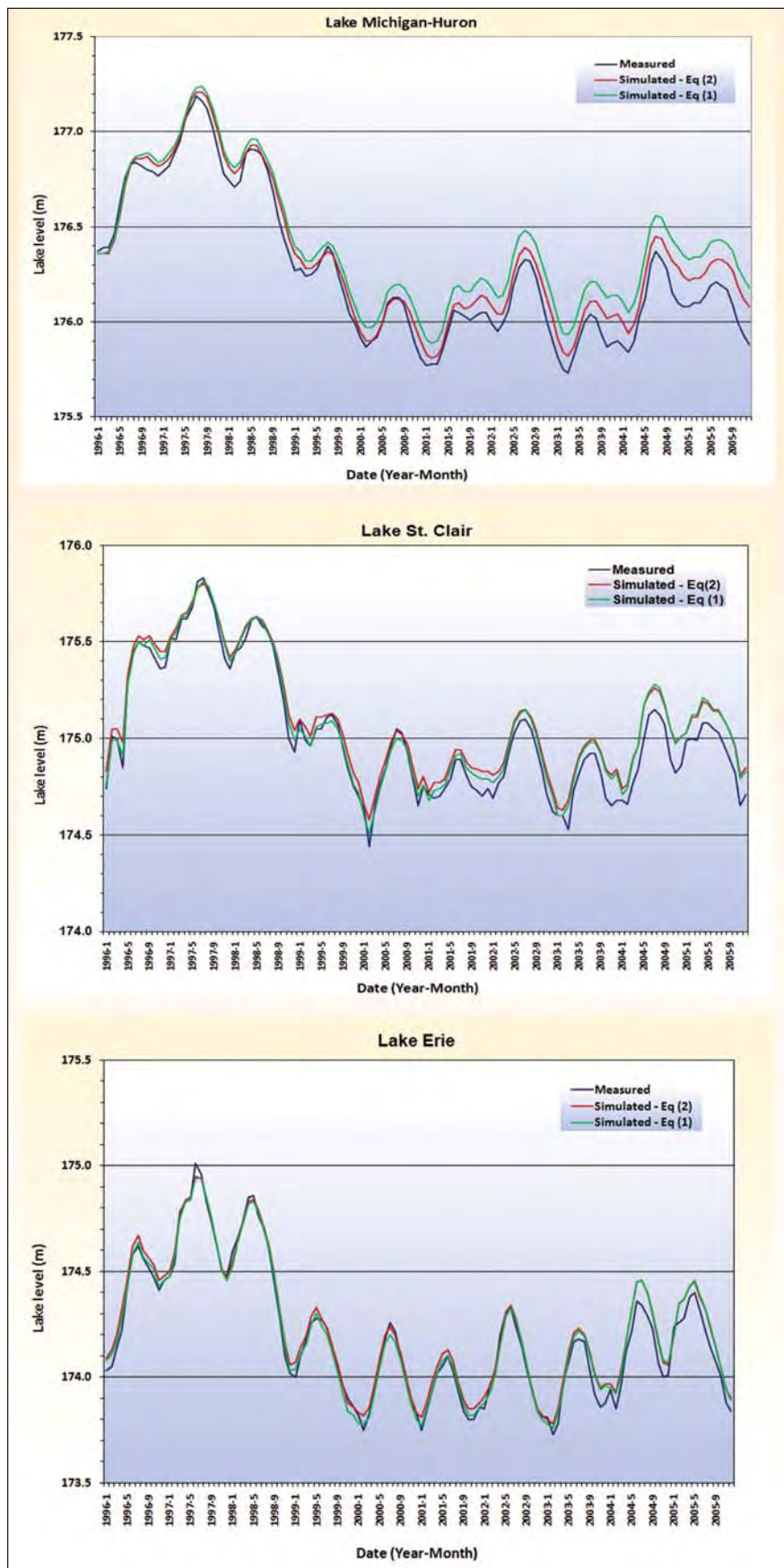
1: 1997 selected over 1996 as initial year because the difference between simulated M_{1 ann} is much closer to measured M_{1 ann}.

Table 7-6 Evaluation of Conveyance Change Effect on the Change in Head Difference using Simulated Metrics

| Metric Name | BASELINE Simulated change = Initial – Final average head difference (m) | Simulated change with Equation (3) = Initial – Final average head difference (m) | Percent of Change due to conveyance change ^a (brackets are percent attributed to other factors) |
|--------------------|--|--|--|
| M _{1 ann} | 0.30 | 0.23 | 24 (76) |
| M _{2 reg} | 0.28 | 0.19 | 31 (69) |
| M _{3 3yr} | 0.24 | 0.17 | 30 (70) |

a: Attribution percent column is calculated with more precision in head differences than appears in previous columns.

Figure 7-13 Summary of Results of Deterministic Model Runs



difference of the simulated change from the baseline in Table 7-6, the results show a change in fall ranging from 7 to 9 cm (2.8 to 3.5 in) due to conveyance changes. All other factors taken together, such as the change in climate patterns and GIA, have a more controlling influence on this change in head difference. The Study repeated the analysis for attributing relative cause of the decline to the change in head difference, substituting residual NBS for component NBS in the CGLRRM simulation. With residual NBS, the conveyance change was determined to be responsible for 21 to 22 percent of the simulated decline in head difference based on the three baseline metrics. Therefore, findings are consistent with both residual and component NBS. Figure 7-14 highlights the cumulative error in residual-minus-component NBS using the residual estimates shown in Figure 7-3 and the modified residual estimates calculated with the CGLRRM using Equation (4).

Stochastic Model Runs (Experiment 4)

The third step in building a deterministic model focused on assessing the relative contributions of both climate-era change (*i.e.*, NBS) change and conveyance change from a stochastic perspective that considers alternative sequences of NBS time series. Alternative sequences of NBS were

sampled using a moving blocks bootstrap approach (Efron and Tibshirani, 1993) and thus functioned to maintain the spatial correlation of NBS across all the lakes. Additional metrics for quantifying the decline in head difference over time were developed. The modelling experiments in this step involved isolating the effect of the 1996-2005 component NBS data and varying the equation for St. Clair River flow.

In analyzing the stochastic simulation experiments, two additional metrics for describing system behavior were identified and thus utilized in the results summarized in Table 7-7. Metric M_4 was defined as the number of years when the average annual head difference is less than or equal to the low value of 2.051 m (6.7 ft) for the measured data in 1990. Metric M_5 was defined as the number of years when the three-yr moving average of the annual head differences is less than or equal to the low value of 2.101 m (6.9 ft) for the measured data in 1991. These values were deemed to be low values on the basis of the 1963-1998 period (they are the lowest values in this 35-year period). Metrics M_4 and M_5 also were tabulated for the measured and simulated data in Table 7-7.

Figure 7-14 Comparison of 1996-2005 Cumulative NBS Differences (Residual – Component)

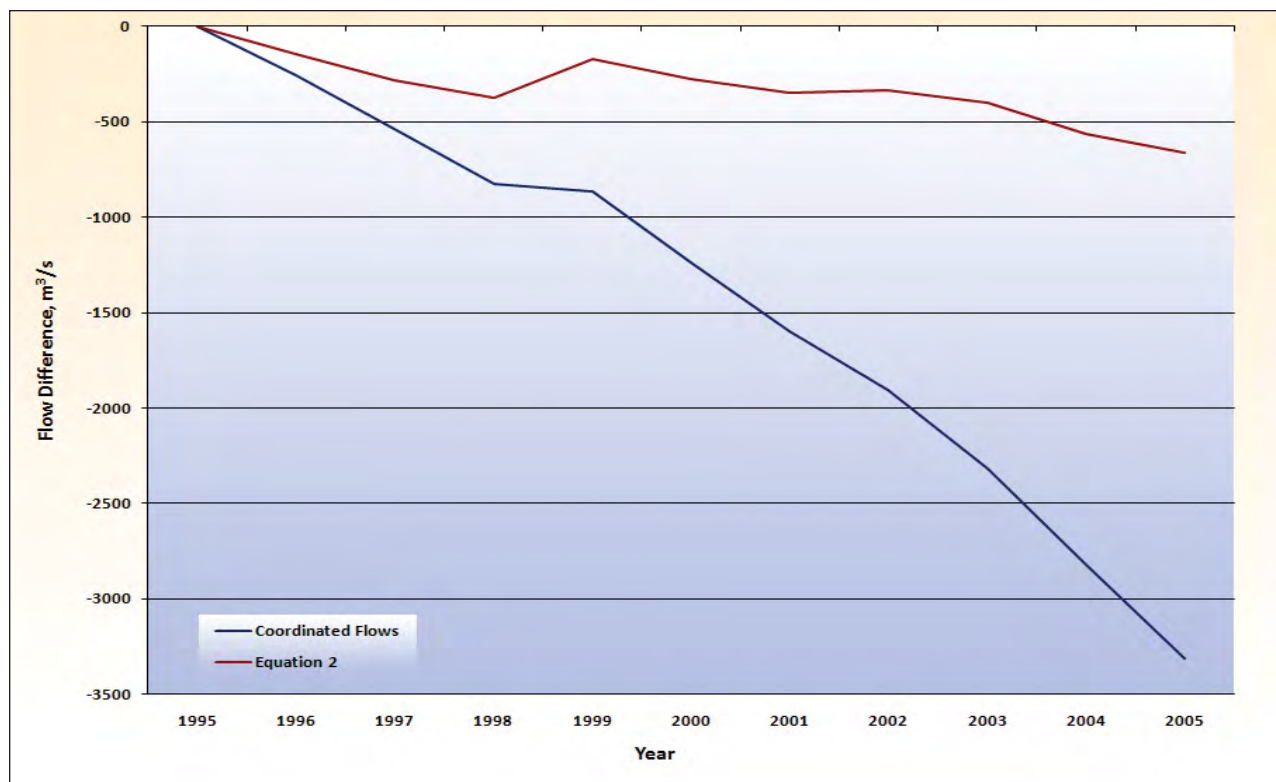


Table 7-7 Simulated Metrics for Assessing Change in Head Difference across Different Periods
(based on annual average lake levels)

| Metric Name | Period | Notes | Change in Measured Head Difference = Initial – Final average annual head difference over the period (m) | Baseline metrics for stochastic analyses of Change in Simulated Head Difference = Initial – Final average annual head difference over the period (m) |
|--------------------|--------------------------|---|---|--|
| M _{1 ann} | 1997 ¹ - 2005 | Based on annual average head differences | 0.35 | 0.37 (0.30) ² |
| M _{2 reg} | 1996 - 2005 | Calculated from linear regression of annual average head difference vs year | 0.35 | 0.35 (0.28) ^b |
| M _{3 3yr} | 1997 - 2004 | Based on 3-year moving average of annual average head differences | 0.29 | 0.29 (0.24) ^b |
| M ₄ | 1996 - 2005 | Count of years where annual average head difference below 1990 value of 2.051 m | 6 (count of years, not m) | 4 (count of years, not m) |
| M ₅ | 1996 - 2005 | Count of years where 3-year moving annual average head difference below 1991 value of 2.101 m | 6 (count of years, not m) | 5 (count of years, not m) |

Notes:

1: 1997 selected over 1996 as initial year because the difference between simulated M_{1 ann} is much closer to measured M_{1 ann}.

Brackets contain previous metric value for deterministic analyses as presented in Table 7-6.

In the stochastic experiments, the independent impacts of both the NBS (climate) and the conveyance change are controlled so that their relative importance could be assessed. The conveyance change for the St. Clair River is already assumed to be completely described by changing the equation for St. Clair River flow from Equation (3) to Equation (4). The NBS influence in these experiments is defined to be the 1996-2005 period of NBS values on the basis that values from the 1996-2005 period are notably smaller as described in Tolson (2009), than average Lake Michigan-Huron NBS values from the 1963-1995 period. For example, the difference in average NBS values between these two periods is a decrease of 0.12 m/yr (0.4 ft/yr) for Lake Michigan-Huron compared to a difference of only 0.03 m/yr (0.09 ft/yr) for Lake Erie. Therefore, the influence of the 1996-2005 NBS data can be removed by bootstrap sampling from past years not including this period (*i.e.*, sampling from years before 1996 only).

The bootstrap sampling period for all experiments in this section begins in 1963 to focus on the past NBS conditions observed since the last significant dredging of the St. Clair River, in 1962. Three bootstrap sampling experiments were conducted (Table 7-8):

- *Experiment 2a* sampled 10-year sets of input time series for CGLRRM from the 1963-2005 period and simulated St. Clair River flows with the current conveyance equation – Equation (4). This experiment then formed a baseline from which the impacts of conveyance and NBS were assessed by comparing with the other two experiments.
- *Experiment 2b* sampled 10-year sets of input time series for CGLRRM from the 1963-1995 period and simulated St. Clair River flows with the current conveyance equation – Equation (4). Thus, experiment 2b was the exact same as experiment 2a, except that the 1996-2005 period was not sampled from, thus isolating the effect of 1996-2005 NBS data.
- *Experiment 2c* sampled 10-year sets of inputs for CGLRRM from the 1963-2005 period and simulated St. Clair River flows with the conveyance equation for the 1960-1977 conveyance regime – Equation (3). Thus, experiment 2c was the exact same as experiment 2a, except that the conveyance equation was modified, thus isolating the effect of conveyance change.

The probabilities listed in Table 7-8 show similar relative results between experiments 2b and 2c. The very small probabilities (all less than 0.065) in Table 7-8 for experiments 2a and 2b, both of which simulate the conveyance change with Equation (4) suggest that, consistent with deterministic analyses in Tolson (2009), the sequence of NBS can play a strongly controlling role on the extreme behavior of the head difference. Furthermore, these low probabilities demonstrate that the sequence of actual climate or NBS for the 1996-2005 period was distinct. For example, only five of 1,000 (0.005) sets of 10-year input time series sampled from the 1963-1995 period yielded more extreme $M_{3 \text{ yr}}$ metric values than the baseline simulated results for the actual input time series observed from 1996 to 2005.

The impact of conveyance change in terms of a percentage of the baseline metric values can be determined based on the correlated sampling approach between experiments 2a and 2c (in which the same 1,000 input data sets were used). This approach allowed a paired comparison of the change in head difference metrics between experiments 2a and 2c. In addition, the majority of simulation results showed lake level behaviors that were not at all extreme statistically (extreme is defined as when the simulated metric value equals or exceeds the baseline metric value). This result suggests that the more refined conveyance change impact is focused only on those pairs of simulations when the result in experiment 2a was deemed to be extreme.

Considering $M_{1 \text{ ann}}$, 55 extreme behaviors were observed in experiment 2a. Conveyance change (comparing 55 pairs from experiments 2c with 2a) controlled an average of 13 percent (0.05 m [0.2 ft]) of the $M_{1 \text{ ann}}$ metric value (up to a maximum of 24 percent or 0.10 m [0.3 ft]).

Considering $M_{2 \text{ reg}}$, eight extreme behaviors were observed in experiment 2a. Conveyance change (comparing eight pairs from experiments 2c with 2a) controlled an average of 22 percent (0.09 m [0.3 ft]) of the $M_{2 \text{ reg}}$ metric value (up to a maximum of 34 percent or 0.12 m [0.4 ft]).

Considering $M_{3 \text{ yr}}$, 23 extreme behaviors were observed in experiment 2a. Conveyance change (comparing 23 pairs from experiments 2c with 2a) controlled an average of 17 percent (0.06 m [0.2 ft]) of the $M_{3 \text{ yr}}$ metric value (up to a maximum of 30 percent or 0.09 m [0.3 ft]).

These results demonstrate that the conveyance change effects across a range of extreme but plausible NBS inputs are fairly consistent with conveyance change controlling 13 to 22 percent on average, to a maximum of 34 percent of the decrease in head difference. These values are also in close agreement with the deterministic attribution percentages (24 to 31 percent) calculated in Table 7-6 on the basis of the actual 1996-2005 climate (NBS) inputs.

Summary of Results

CGLRRM simulation results reasonably approximated the observed past lake level behavior. Specifically, CGLRRM, based on component NBS, can reasonably replicate 1996-2005 lake levels (and head difference behavior) with an open water lake-to-lake stage-fall equation developed for the 1996-2006 period representing the post-1977 conveyance change. The deterministic modelling scenario analyses showed that the post-1977 conveyance change on the St. Clair River was estimated to cause between 24 and 31 percent of three different changes in head difference metrics considered. The metrics quantify the change in head difference for various periods and measures from 1996 to 2005. Other factors were attributed to be the cause of 69 to 76 percent of the metrics.

Table 7-8 Bootstrap Sampling Experiments: Summary of Probabilities

Probabilities that the simulated metric value is equal or more extreme than the baseline metric value for bootstrap experiment set 2 (conveyance regimes and NBS sampling periods varied). Each simulation length is 10 years and all simulations initialized to January 1, 1996 lake levels.

| Experiment (climate sampling period, conveyance equation) | $\text{Pr}(M_{1 \text{ ann}} \geq 0.373)$ | $\text{Pr}(M_{2 \text{ reg}} \geq 0.348)$ | $\text{Pr}(M_{3 \text{ yr}} \geq 0.293)$ | $\text{Pr}(M_4 \geq 4)$ | $\text{Pr}(M_5 \geq 5)$ |
|--|---|---|--|-------------------------|-------------------------|
| 2a (1963-2005, Equation 4) | 0.055 | 0.008 | 0.023 | 0.050 | 0.065 |
| 2b (1963-1995, Equation 4) | 0.020 | 0.001 | 0.005 | 0.011 | 0.017 |
| 2c (1963-2005, Equation 3) | 0.018 | 0.001 | 0.008 | 0.002 | 0.004 |

The stochastic modelling clearly indicated that system behavior resulting from the actual 1996-2005 NBS was distinct or extreme, compared to the distribution of possible 10-year NBS sequences sampled from the 1963-1995 period (1,000 samples). Moreover, multiple extreme but plausible 10-year NBS sequences were used to show that conveyance change on the St. Clair River controls 13 to 22 percent on average, to a maximum of 34 percent of the decline in head difference.

Considering all the findings, the post-1977 conveyance change on the St. Clair River was estimated to cause no more than one-third of the decline in head difference observed for the 1996-2005 period. Other factors, including changes in climatic patterns, controlled the remaining two-thirds or more of the decline in head difference.

7.3.4 Impacts of the Conveyance Change on Lake Michigan-Huron Levels

To assess the impacts of the St. Clair River conveyance change on Lake Michigan-Huron water levels, and the sensitivity of lake levels to the timing of the conveyance change, the Study modelled two likely scenarios. The first scenario assumed a conveyance change immediately following the April 1984 St. Clair River ice jam. The second scenario assumed a conveyance change in January 1993. A base case was established to compare the two scenarios. The base case and the two scenarios used the recorded Lake Superior outflows and NBS for Lakes Michigan-Huron, St. Clair and Erie from 1971 to 2005 derived by the component method. The period 1971 to 2005 was chosen to represent the full period of the post-conveyance change with the end date limited by the availability of the component NBS. The simulations were done using the CGLRRM as referenced in Section 7.3.3. In the base case, St. Clair River flows were computed using the rating curves based on Equation (3) (Section 7.3.3 Deterministic Model Runs), representing the hydraulics of the pre-conveyance change period. In the two scenarios, the updated rating equation for the St. Clair River, Equation (4) (Section 7.3.3 Deterministic Model Runs), was employed for computing river flows. In all cases, the same routing relationships were used to compute the flows in the Detroit and Niagara rivers. The starting water levels on January 1, 1971 for all cases were the same: 176.61 m (579.4 ft) for Lakes Michigan-Huron, 175.13 m (574.6 ft) on Lake St. Clair and 174.19 m (571.5 ft) on Lake Erie (all water levels referenced to IGLD, lake-wide averages) for a decline of 1.48 m (4.9 ft) across the St. Clair River. The base case and two scenarios produced the following results.

Base Case: Following routing of the NTS with the existing lake-to-lake equations, the computed Lake Michigan-Huron and Lake St. Clair levels on December 31, 2005 were 176.21 and 174.84 m (578.1 and 573.6 ft) respectively; the head difference being 1.37 m (4.5 ft).

Scenario 1: The same hydroclimatic regime and initial lake levels are used as the Base Case. A conveyance increase was assumed to have occurred immediately after the ice jam in April 1984. Following this date, the St. Clair rating equation was changed to reflect the new conveyance and the supplies routed through to 2005. In this scenario, the Lake Michigan-Huron and Lake St. Clair elevations at the end of simulation were 176.08 and 174.84 m (577.7 and 573.6 ft) respectively; the head difference being 1.24 m (4.1 ft). This reflects a decline of 13 cm (5.1 in) in the Lakes Michigan-Huron level due to the increased St Clair River conveyance (1.37 m to 1.24 m [4.5 to 4.1 ft]). Note that the levels of Lake St. Clair and Lake Erie end up at the same level as they did in the base case. The flows and levels simulated in Scenario 1 are compared to the Base Case in Figures 7-15 (flows) and 7-16 (levels). Note that by the end of the scenario, the Lake St. Clair level is about the same as it would have been without the change in conveyance, even though the Lake Michigan-Huron level is 13 cm (5.1 in) lower.

Scenario 2: The sensitivity of the timing of conveyance change was investigated in this scenario. The new equation was implemented starting in January 1993 and simulation carried out to the end of 2005. The resulting simulation yielded water levels of 176.08 and 174.84 m (577.7 and 573.6 ft) for Lake Michigan-Huron and Lake St. Clair respectively, exactly the same as in scenario 1, thus reflecting a decline of 13 cm (5.1 in) in the Lake Michigan-Huron level from the pre-conveyance change state.

These scenarios provide important information, including:

- an alternate estimate of the effect of the conveyance change on the lake level decline strictly as a result of the dynamic state of the lakes over a 35-year period;
- corroboration of the effect on levels of the conveyance change from hydraulic/sediment modelling (see Chapter 5);
- a better estimate of water volumes discharging from Lake Michigan-Huron; and
- an estimate of the effect on the quantity as a percentage of mean annual flow in the St. Clair River.

Figure 7-15 Impact of Conveyance Change in Lake Michigan-Huron Discharge

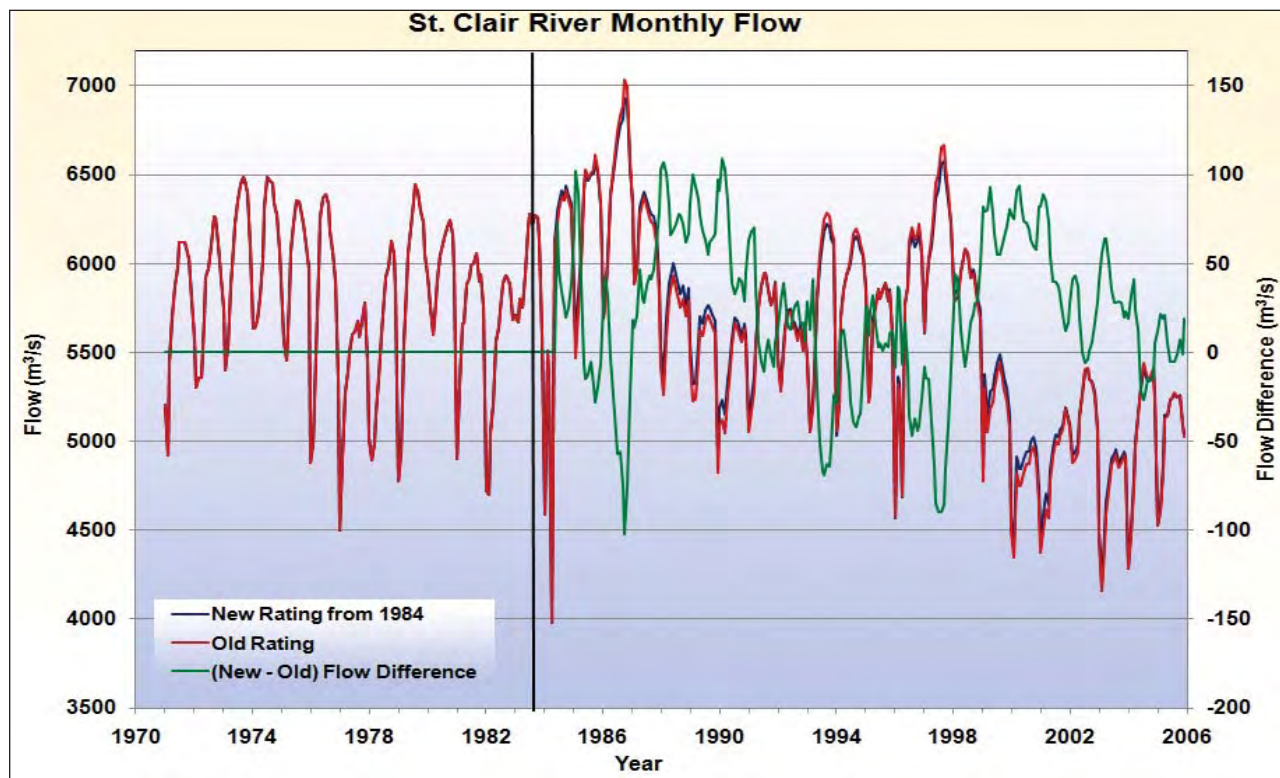
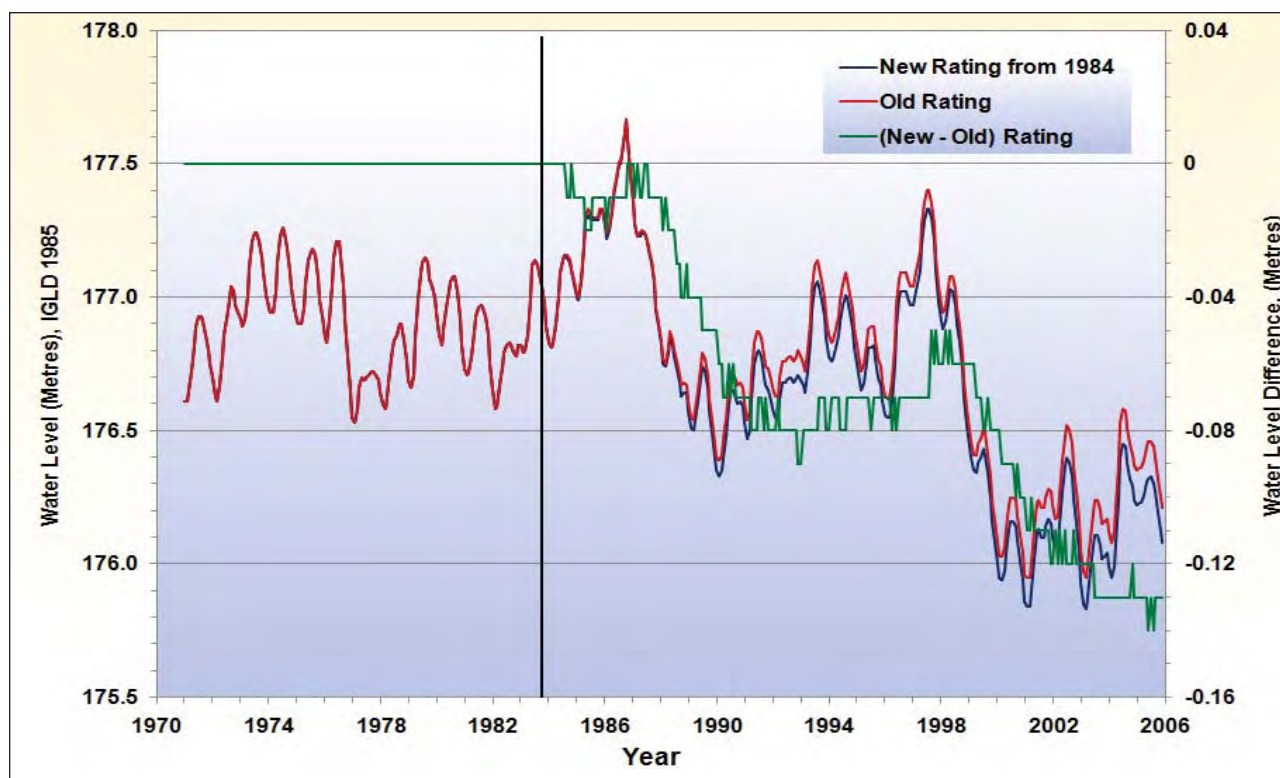


Figure 7-16 Impact of Conveyance Change in Lake Michigan-Huron Water Levels



It is interesting to note that the two scenarios resulted in exactly the same effects on lake levels at the end of the simulation. Without the assumed conveyance change in 1984, the simulated water levels by the end of 1992 would have been about 9 cm (3.5 in) higher. This higher lake level at the onset of the conveyance increase in the second scenario would have resulted in a large initial increase in the flow, but it would gradually converge to the same state as would have occurred had the change taken place in 1984. It also shows that if the conveyance change had occurred anytime within the 1984 to 1992 period, the same 13 cm (5.1 in) effect would have been seen by the end of 2005. Figure 7-17 shows the convergence in the difference of flows for the two scenarios. Similar convergence in lake levels between the two scenarios was also seen in the calculations.

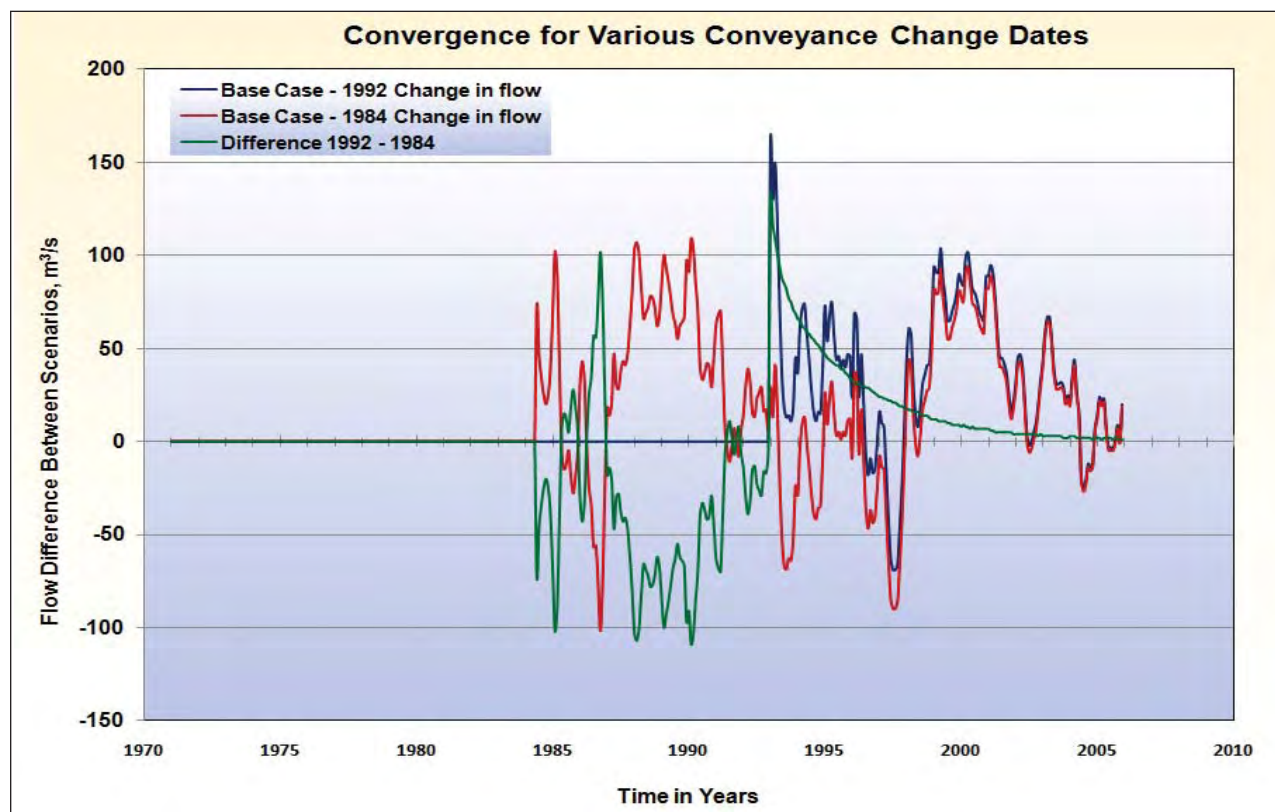
Also note the loss of water volume from Lake Michigan-Huron. The simulations suggest, as shown in Figure 7-15, the dynamic nature of the lakes and the behaviour of rating equations during high levels of Lakes Michigan-Huron, St. Clair and Erie. With the increased conveyance, there are periods when less water would have flowed out of Lake Michigan-Huron than would have occurred without the conveyance increase, due to lower levels of Lake Michigan-Huron in combination with downstream lake levels. If the

increased flows are aggregated over the entire 23-year period, the extra volume on a daily basis works out to be about 22 m³/s (788 ft³/s) or less than 0.4 percent of long-term average daily flow in the St. Clair River, which equates to the loss of about 13 cm (5.1 in) of water on Lakes Michigan-Huron.

7.3.5 A Focus on the 1996-2005 Period

The Study undertook an additional project to illustrate and quantify the contribution of the many possible factors that may have affected the change in fall between Lake Michigan-Huron and Lake Erie for 1962 to 2005, with a closer focus on the 1996 to 2005 period (Lee and Dahl, 2009). This latter period is of interest because of the accelerated decline in the change in fall and is consistent with the time period used by Tolson (2009) (Section 7.3.3). The period 1962 to 2005 was chosen to represent the full period from the time of the last navigation channel deepening. A series of lake level simulations were made to evaluate the contribution of NBS, the Lake Superior outflow, diversions, ice and weed retardation, and changes in conveyance.

Figure 7-17 Convergence of Discharge from Lake Michigan-Huron for Various Conveyance Change Periods



Base simulations for 1962 through 2005 and 1996 through 2005 were first conducted to represent long-term average hydrological conditions using the CGLRRM. The influence of each factor then was evaluated by repeating the base simulation with the observed values input to the simulation separately (Table 7-9). The simulations were started with actual 1962 and 1996 initial conditions, respectively, and assumed St. Clair River channel conveyances as represented by the Fay and Noorbakhsh (2004) stage-fall discharge relationship (*i.e.*, no conveyance change). The simulations were repeated for both residual and component NBS. The results were then compared to the recorded lake levels to verify the model's performance (Table 7-10).

Figure 7-18 illustrates the 1962 through 2005 simulation using residual NBS. The goodness of fit can be seen in comparing the observed lake levels to those simulated considering all factors (4d2). The dominant factor of Lake Michigan-Huron NBS is illustrated by comparing the observed lake levels to those simulated with just the Lake Michigan-Huron NBS added to the base case (2b).

Three additional simulations then looked at plausible scenarios regarding change in conveyance:

- a scaled change in conveyance beginning in 1971 and increasing to a new channel capacity by 1989 (3a);
- an abrupt change in conveyance beginning in 1984, coinciding with the record St. Clair River ice jam (3b); and
- an abrupt change in conveyance beginning in 1989, coincident with potential channel erosion following the high lake levels of 1986-1989 (3c).

The Fay and Noorbakhsh (2004) equation was adjusted to represent changes in conveyance of up to 150 m³/s (5,297 ft³/s), one of the estimates of the change in conveyance determined early in the Study.

**Table 7-9 Determining Factors Contributing to Conveyance Change, 1996-2005
Summary of Scenarios**

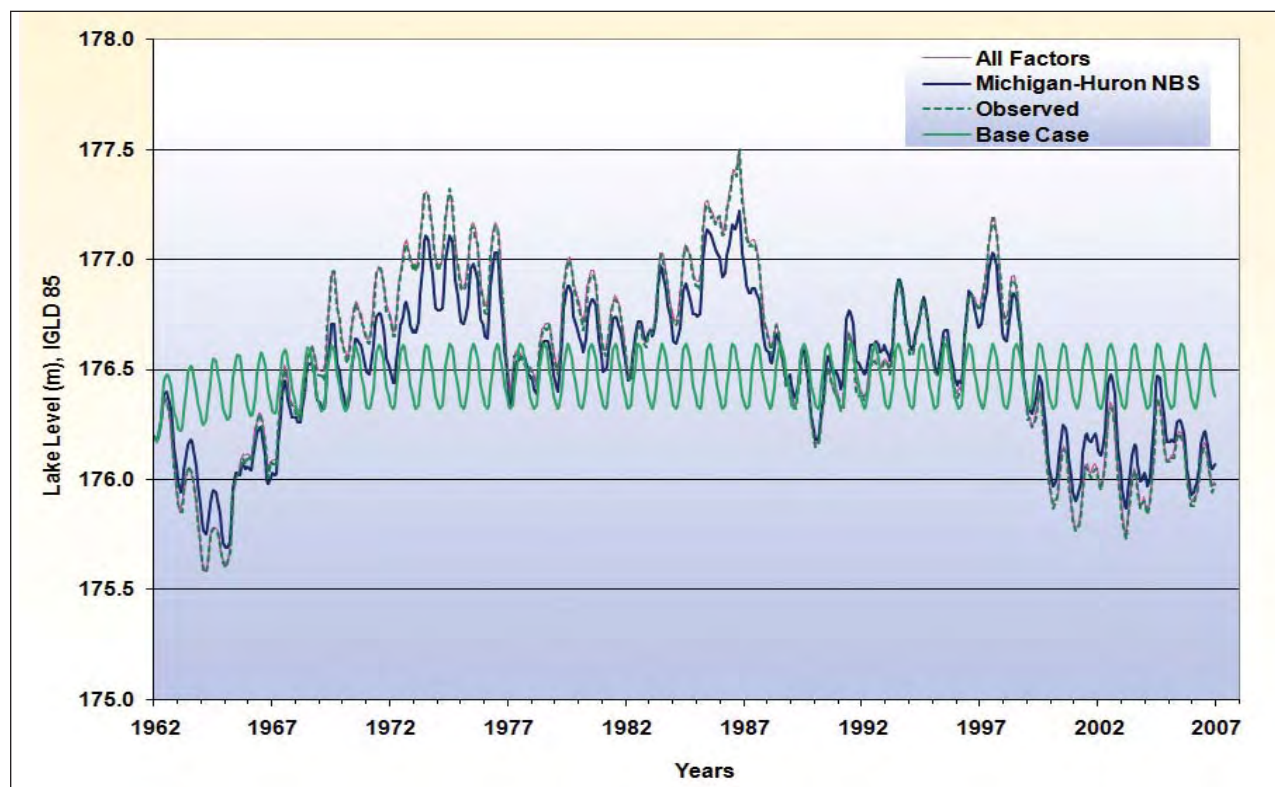
| Scenario | Description |
|----------|--|
| 1 | Base case (average NBS) |
| 2a | Base case with actual Lake Erie NBS |
| 2b | Base case with actual Lake Michigan-Huron NBS |
| 2c | Base case with actual Lake Superior outflows |
| 2d | Base case with actual diversions |
| 2e | Base case with actual (apparent) ice and weed retardation |
| 2f | Base case with actual Lake St. Clair NBS |
| 3a | Base case with an increased St. Clair River conveyance that varies from 0-150 m ³ /s (0 to 5,297 ft ³ /s) between 1971 and 1989, with a shift of 150 m ³ /s (5,297 ft ³ /s) from 1989-2006 |
| 3b | Base case with St. Clair River conveyance shifted by 150 m ³ /s (5,297 ft ³ /s) from 1989-2006 |
| 3c | Base case with St. Clair River conveyance shifted by 150 m ³ /s (5,297 ft ³ /s) from 1984-2006 |
| 4d2 | Base case with actual Lake Michigan-Huron, Lake St. Clair and Lake Erie NBS, actual Lake Superior outflows, actual diversions, and actual (apparent) ice and weed retardation |

Table 7-10 Model Verification Statistics for Lake Michigan-Huron Levels

| Fit Statistic | 1962-2005 | | 1996-2005 | |
|------------------|-----------------------|----------------------|-----------------------|----------------------|
| | Component Supplies | Residual Supplies | Component Supplies | Residual Supplies |
| R ² | 0.954 | 0.999 | 0.932 | 0.999 |
| RMSE (m) | 0.20 | 0.02 | 0.19 | 0.02 |
| Bias (m) | 0.18 | 0.01 | 0.16 | 0.01 |

Note: R² – coefficient of determination; RMSE – root mean square error; Bias – average monthly difference between the modelled and observed levels.

Figure 7-18 Simulated Lake Michigan-Huron Lake Levels Using Residual NBS



The change in fall between the lakes was then computed for each modelled scenario and for the observed lake levels. The percentage of the fall explained by each factor was then calculated (Table 7-11). The results included the following:

- For the 1962-2005 scenarios, the Lake Erie NBS accounted for 33 to 49 percent of the change in fall and the Lake Michigan-Huron NBS was responsible for 2 to 22 percent;
- In the 1996-2005 scenarios, Lake Michigan-Huron's supply accounted for 36 to 62 percent of the change in fall while the contribution of Lake Erie's supply declined to only 2 to 10 percent;
- Lake Superior outflows appear to have played a greater role in the change in fall for 1996-2005 than for 1962-2005;
- For 1962-2005, the outflow of Lake Superior accounted for 1 percent of the change in fall, but increased to 10 to 11 percent for 1996-2005;

- Summing the percentage contributions of NBS from all of the lakes and for Lake Superior outflow (Table 7-11), the total impact of climate on the change in fall accounted for 40 percent (component supplies) to 74 percent (residual supplies) for 1962-2005. For the period 1996-2005, the total impact of climate ranged from 58 percent (component supplies) to 76 percent (residual supplies);
- The change in St. Clair River conveyance accounted for 16 to 18 percent of the change in fall for 1962-2005 and 7 to 8 percent for 1996-2005;
- Diversions from Lake Michigan-Huron were relatively small and constant and had negligible effect on the change in fall; and
- Results for scenarios 3a-c were the same, showing that the sensitivity of the change in fall to the timing of the conveyance change is negligible by 2005.

An estimated 4 to 34 percent (1962-2005) and 5 to 24 percent (1996-2005) of the change in fall is attributed to other factors not explicitly accounted for in these simulations, including GIA, NBS uncertainties and model error. The lower estimates of the change in fall attributable to the change in conveyance compared to those of Tolson (2009) (Section 7.3.3) are likely due to the shift of 150 m³/s (5,297 ft³/s) being an underestimate of the conveyance change as compared to Equation (4).

Table 7-11 Attribution of the Change in Fall to Conveyance and Climate Factors

| | 1962-2005 | | | | 1996-2005 | | | |
|--|-----------------------|---------|----------------------|---------|-----------------------|---------|----------------------|---------|
| Factor (Scenario) | Component Supplies | | Residual Supplies | | Component Supplies | | Residual Supplies | |
| | meters | percent | meters | percent | meters | percent | meters | percent |
| Lake Erie NBS (2a) | 0.13 | 33 | 0.23 | 49 | 0.05 | 10 | 0.01 | 2 |
| Lake Michigan-Huron NBS (2b) | 0.01 | 2 | 0.10 | 22 | 0.17 | 36 | 0.25 | 62 |
| Lake Superior Outflow (2c) | 0.01 | 1 | 0.01 | 1 | 0.05 | 10 | 0.04 | 11 |
| Diversions (2d) | 0.00 | 1 | 0.00 | 0 | 0.01 | 2 | 0.00 | 0 |
| Apparent Ice and Weed Retardation (2e) | 0.03 | 6 | 0.02 | 5 | 0.04 | 9 | 0.04 | 10 |
| Lake St. Clair NBS (2f) | 0.02 | 4 | 0.01 | 2 | 0.01 | 2 | 0.00 | 1 |
| St. Clair River Conveyance Changes (3a-c) | 0.08 | 18 | 0.07 | 16 | 0.03 | 7 | 0.03 | 8 |
| Other (includes GIA, model and NBS error) | 0.14 | 34 | 0.02 | 4 | 0.11 | 24 | 0.02 | 5 |
| Total Contribution of Climate to the Change in Fall ¹ | | 40 | | 74 | | 58 | | 76 |
| Modeled Change in Fall (4d2) | 0.21 | | 0.40 | | 0.16 | | 0.36 | |
| Observed Change in Fall | 0.40 | | | | 0.36 | | | |

1 The total contribution of climate to the change in fall is the sum of the percentages for Lake Erie NBS, Lake Michigan-Huron NBS, Lake Superior outflow and Lake St. Clair NBS.

Note: Results were rounded to the nearest cm or whole percentage. The tables were created by comparing the change in fall for each scenario (2a-f & 3a) with the change in fall for the base case simulation (1). The contributions from the individual factors were summed and compared to the actual change in fall from the historical record. The difference between the sum of the individual factors and the actual change in fall is labeled "Other" and includes GIA and interaction effects from multiple factors. The magnitude of the change in fall was calculated by taking the absolute value. These magnitudes were summed and the percentage contribution to the total magnitude reported in the table.

These modelling exercises appear to support independent earlier work done by Quinn (2008b), which concluded that a conveyance change occurred in the St. Clair River in the mid-1980s, possibly due to the record high lake levels of 1986 and/or a major ice jam in 1984. The Quinn study concluded that the changes appear to have taken place in two reaches of the St. Clair River, the reach from Dry Dock to St. Clair Police gauges and the reach from the Mouth of Black River to Dunn Paper. (See Figure 5-3, in Chapter 5, for a map of the gauge locations on the St. Clair River.) The analysis concluded that it is possible that erosion has increased the conveyance in the river and resulted in the lowering of Lake Michigan-Huron by about 5 to 7 cm (2 to 2.6 in). The results of the Study's analysis described above are consistent with these conclusions.

7.3.6 Summary

In responding to the science question

How has climate affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?

the various projects in this section indicate that climate has played the dominant role during the period 1962-2005, while channel conveyance and glacial isostatic adjustment have had a smaller effect. A significant decline in net total water supplies to Lake Michigan-Huron but less so for Lake Erie over the past decade (1996-2005) has resulted in Lake Michigan-Huron's levels declining relative to Lake Erie's water levels (See Figure 7-8). Once the anthropogenic effects are removed from the historic (recorded) water levels, it can be seen that the change in fall between the two lakes is within the normal variability over the extended period of record (1860-2005) (See Figure 7-12) but distinct and extreme when considering just the

1963-1995 period. It is also shown that by 2005, the decline in Lake Michigan-Huron's water level would have converged regardless of when the conveyance change was initiated in the 1984 to 1992 period. Thus, the attribution of the various factors (climate and conveyance) is very dynamic and is dependent on the period of time over which the change in fall is measured. Also, the uncertainties in the channel conveyance and NBS have clouded our ability to attribute the causative factors with precision. As part of the next phase of the Study, addressing Lake Superior regulation, a final, comprehensive assessment and attribution of climate versus conveyance will be undertaken once adjusted St. Clair River flows are available, along with corrected lake NBS and coordinated St. Clair River stage-fall discharge relationships. The hydroclimatic projects reported in this section have revealed the need for more careful estimates and continual monitoring and analysis of Great Lakes water supplies and connecting channel flows.

The efforts of hydroclimate modelling supported earlier efforts in hydraulic modelling and described in Chapter 5 in explaining the change in conveyance of the St. Clair River and associated decline in water levels of Lake Michigan-Huron. These are summarized in Table 7-12.

7.4 IMPROVING COMPONENT NBS ESTIMATES

As noted in the introduction to this Chapter, efforts to examine the hydroclimatic conditions and trends in the upper Great Lakes basin are continuing into the second part of the Study, which is addressing the question of Lake Superior regulation. The focus of these ongoing hydroclimatic analyses is the investigation and development of new monitoring and modelling approaches to estimating the major components of the NBS – overlake precipitation, basin runoff and lake evaporation. The goal is to reduce current uncertainties in NBS estimates so that the Great Lakes' water budget can be monitored more accurately to identify the impacts of climate change.

This section provides an overview of the ongoing analyses. The work described here remains preliminary, for the most part, though early results are promising. The Study's final report on the Lake Superior regulation question, in 2012, will provide a comprehensive review of the results of this important work.

7.4.1 Understanding and Improving Observational Data Sets

The Study has several efforts underway to understand and improve observational datasets of lake evaporation, basin runoff and overlake precipitation. The efforts use new and innovative sensing technologies and include the development of more sophisticated computational techniques.

Lake Evaporation

Until recently, evaporation from Lake Superior could be estimated only as a residual of the long-term water or heat budgets or from meteorological data. The Study has a project underway to measure evaporation over Lake Superior and Lake Huron using an eddy co-variance system (Spence *et al.*, 2009). Data collection began in June 2008 on Lake Superior at Stannard Rock Lighthouse, and in September 2009, another system was set up on Spectacle Reef to derive evaporation estimates from Lake Huron (Figure 7-19).

Comparison of these direct measurements with evaporation estimates generated by models will identify strengths and weaknesses in each method of lake-wide evaporation estimation. Analysis performed to date has been promising and has already led to improved parameterization of one of the regional climate models. Continuing field observations of evaporation over multiple years is an important step to understanding and improving this observational dataset.

Basin Runoff

The Study assessed GLERL's methodology for basin runoff estimates (DeMarchi *et al.*, 2009). Uncertainty in the GLERL estimates of basin runoff has three sources:

1. errors in the United States Geological Survey and Water Survey of Canada estimates of discharge at gauge locations;
2. errors caused by extending the discharge per unit area measured at the most downstream gauges to an entire watershed; and
3. errors caused by applying the basin-wide average discharge per unit area in the gauged watersheds to the ungauged watershed in the lake basin.

Table 7-12 Summary of Maximum Conveyance Change Estimates from Hydroclimatic Modelling

| | |
|---|----------------|
| 1962-2005 (Section 7.3.5, component supplies) | 8 cm (3.1 in) |
| 1962-2005 (Section 7.3.5, residual supplies) | 7 cm (2.8 in) |
| 1971-2005 (Section 7.3.4, component supplies) | 13 cm (5.1 in) |
| 1996-2005 (Section 7.3.3, component supplies) | 7 cm (2.8 in) |

Figure 7-19 Evaporation Data Collection Locations



It is difficult to evaluate the total uncertainty in basin runoff estimates in analytical form because of the large number of error sources and the fact that error distributions may vary for different sources of error. As a critical first step to a comprehensive assessment of NBS uncertainty, the Study adopted a Monte Carlo analysis approach, in which the uncertainty of each error source is simulated by randomly generating an ensemble of alternative and equally likely discharges.

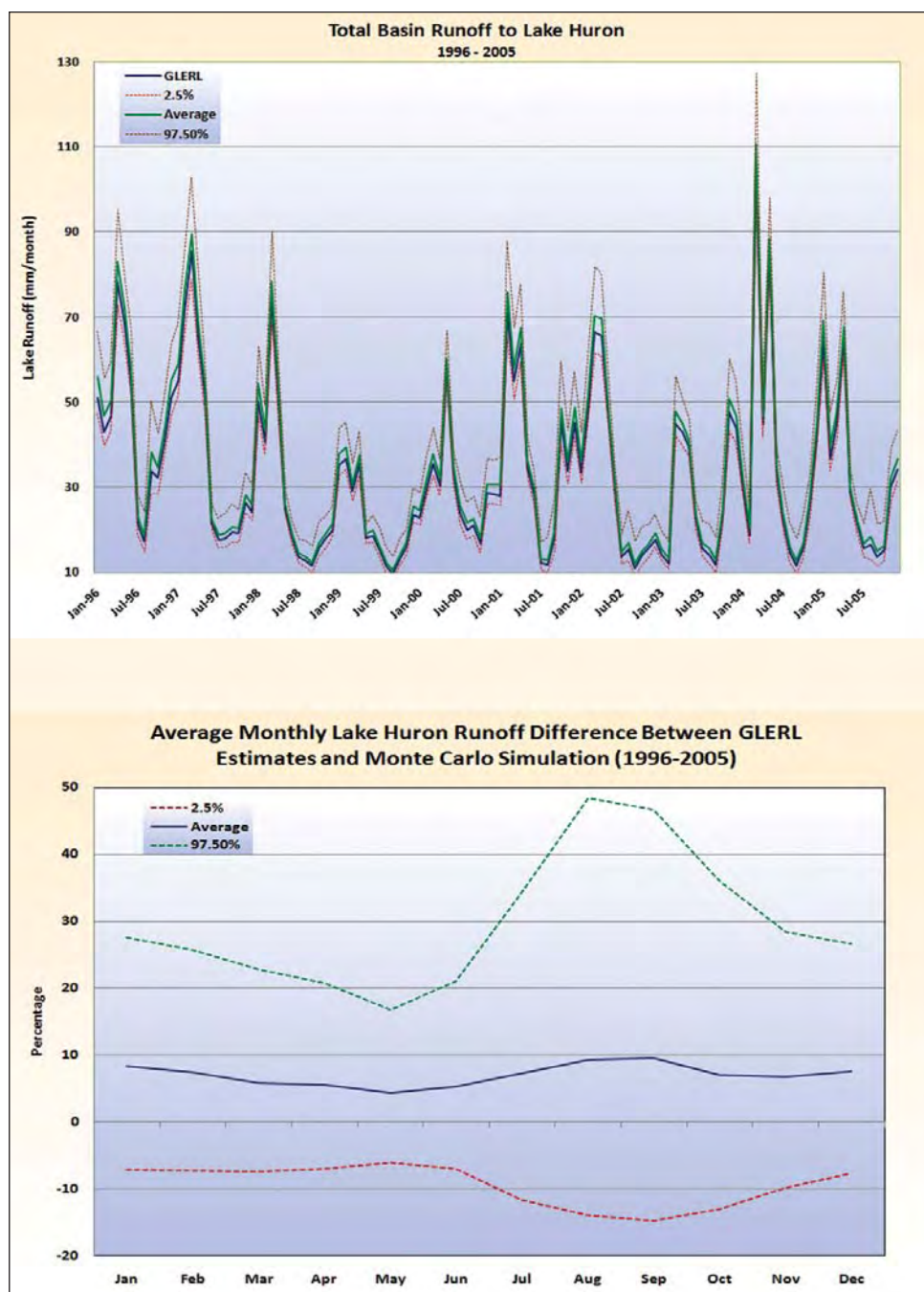
Monte Carlo simulation was performed with an ensemble size of 50,000 elements. Figure 7-20 shows an example of the analysis results. Figure 7-20a shows the GLERL nominal monthly runoff to Lake Huron for 1996-2005, the average of the Monte Carlo simulation and its 95 percent-confidence interval. Figure 7-20b shows that the average monthly relative error is higher in summer and early fall, when the intense and strongly localized convective storms

make the same-basin and inter-basin error higher; conversely, the relative error is lower in spring, when the more uniform snowmelt runoff affects most of the basin at the same time. The overall results for each of the lakes are shown in Table 7-13 (note that Georgian Bay is considered separately for this analysis). The results show that the Monte Carlo simulation monthly runoff is slightly higher than GLERL estimates, indicating that GLERL estimates may have a slight negative bias in the runoff estimate. It should be noted that these estimates of basin runoff error are conservative (larger perhaps than actual error) and that they should not be directly applied to estimates of NBS. As next steps, the Study will extend the uncertainty analysis to overlake precipitation (see below) and lake evaporation and obtain estimates of NBS uncertainty.

Table 7-13 Relative Differences of Basin Runoff Estimates between Monte Carlo Simulations and GLERL Estimates (1986-2005) (Percent)

| | Lake Erie | Lake St. Clair | Lake Huron | Georgian Bay | Lake Michigan | Lake Superior |
|-------------------------------------|-----------|----------------|------------|--------------|---------------|---------------|
| 2.5 Percent Lower Confidence Limit | -8.1 | -13.2 | -8.9 | -10.3 | -3.5 | -12.3 |
| Average | 2.6 | 6.7 | 6.6 | 6.1 | 6.8 | 5.7 |
| 97.5 Percent Upper Confidence Limit | 17.0 | 37.2 | 28.0 | 31.9 | 20.3 | 29.6 |

Figure 7-20 Total Basin Runoff to Lake Huron Estimation and Relative Uncertainty, for 1996-2005



Given the differences between the Monte Carlo simulation and GLERL estimates, the next part of the Study, addressing Lake Superior regulation, will be developing a new technique for prediction of streamflows at ungauged sites based on Regional Flow Duration Curves (RFDCs) and nonlinear spatial interpolation techniques (Ouarda *et al.*, 2009). This project will consist of two parts. The first will involve the reconstruction of daily historical streamflow time-series for all ungauged basins, using spatial interpolation techniques. Climatic and physiographic basin characteristics will be used to establish regional estimation models using a step-wise regression method. RFDCs at ungauged sites will be estimated using a regional parametric approach. The second part of this project will develop an optimal approach for predicting daily streamflows at ungauged sites using neighbourhood regionalization techniques. A comprehensive evaluation of existing approaches of regional RFDC estimation and a comparison of a spatial interpolation method with drainage area ratio methods will be performed. This project will lead to the development of a real-time streamflow prediction tool for ungauged basins within the Great Lakes basin, improving runoff estimates and ultimately NBS estimates.

Overlake Precipitation

The Study estimated the error in estimates of overlake precipitation for each Great Lake (DeMarchi *et al.*, 2009). Overlake precipitation estimates from the National Center for Environmental Prediction Multi-sensor Precipitation Estimates (MPE) Stage IV product were compared to values derived by GLERL's Thiessen interpolation method along with the MESH modelling estimates using the Canadian Precipitation Analysis (CaPA) (Fortin and Charpentier, 2008).

The analysis showed that MPE can correctly identify areas of high and low precipitation for most of Lake Ontario, Lake Erie, Lake St. Clair, Lake Michigan, and part of Lake Huron. However, before using it for long term quantitative assessments, its bias must be removed by merging it with daily gauge data. The approach taken in the Study was to compute the precipitation over the invalid MPE pixels as inverse square distance weighting interpolation of MPE* over valid pixels and gauge data. Given that the number of MPE pixels is much larger than the number of gauges (80,500 vs. 1,030), a simple interpolation of the nearest pixel or gauge would give a disproportionate weight to the MPE pixels. Thus, the precipitation over each invalid pixel, that we name IMPE*, is computed according to the following procedure: the region was subdivided into four quadrants centered on the pixel; the five nearest valid MPE pixels or precipitation gauges in each quadrant were identified; and inverse square distance weighting interpolation of the selected pixels and gauges was performed. Results from this procedure are shown in Figure 7-21.

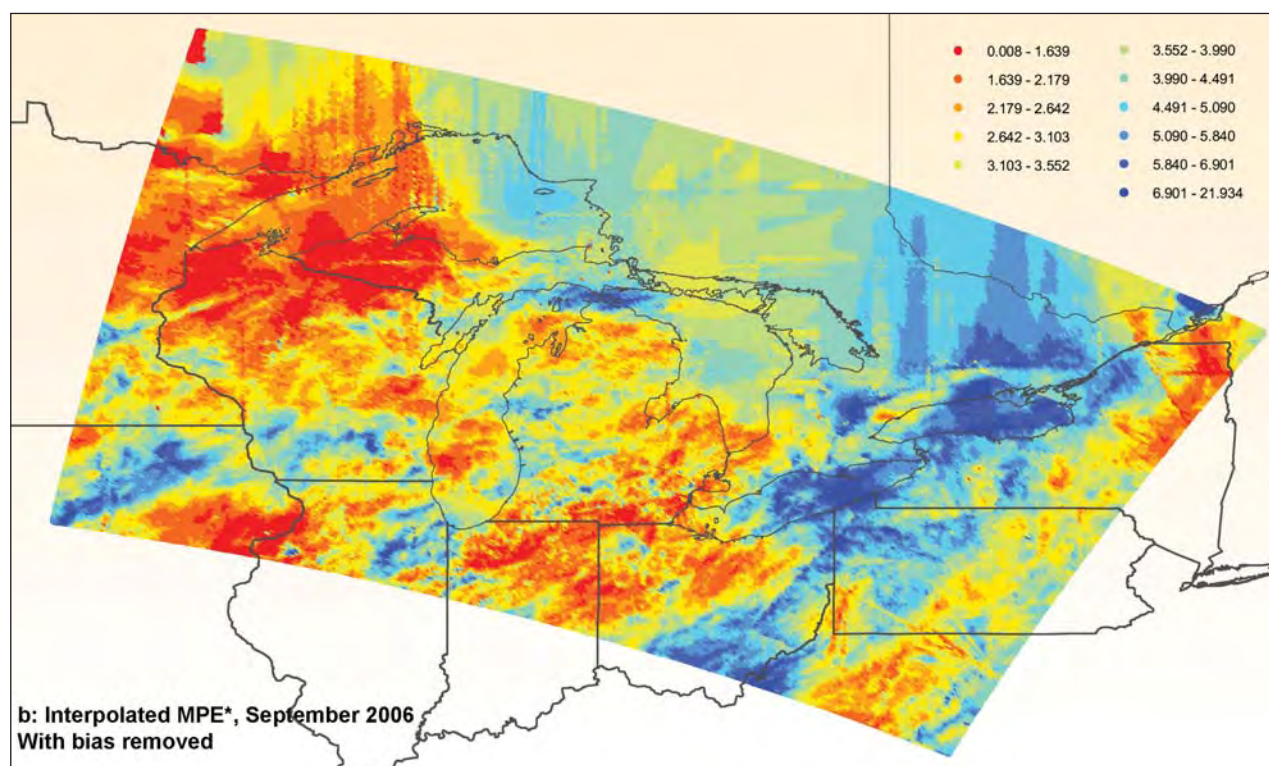
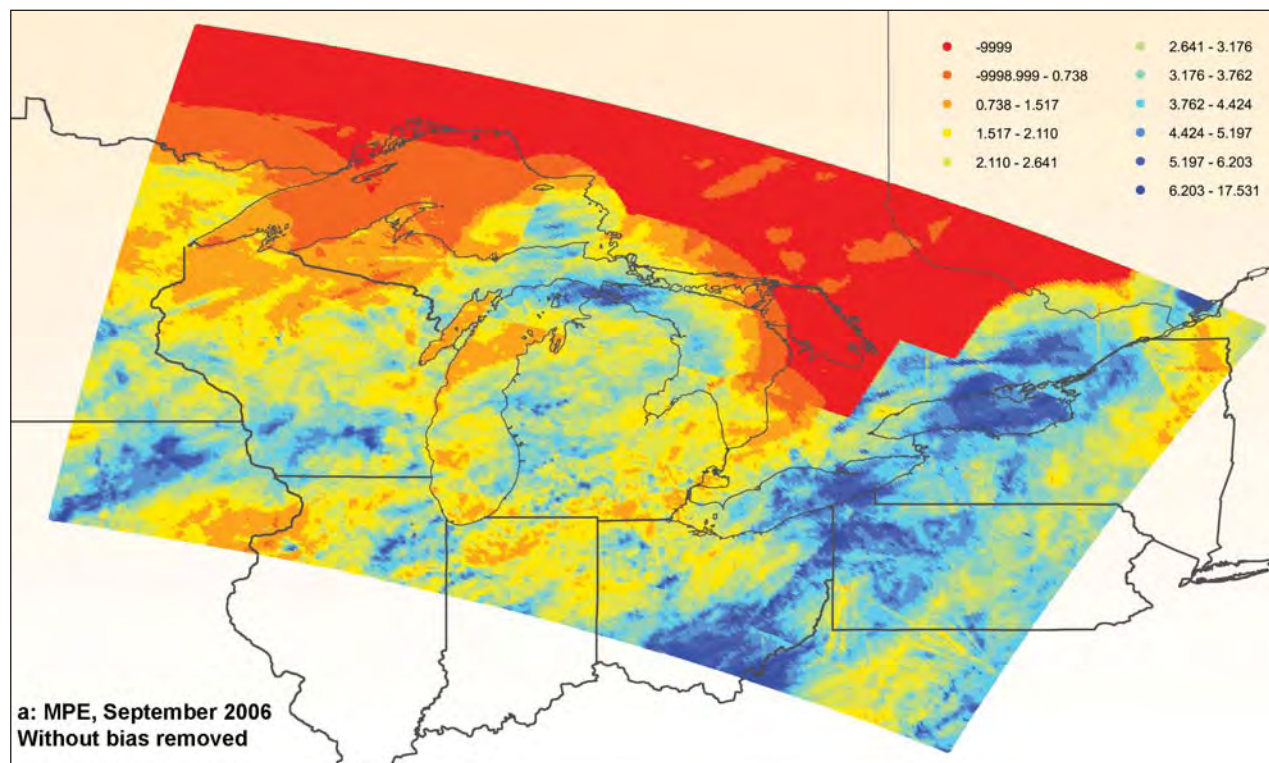
Table 7-14 reports the preliminary comparison between interpolated IMPE*, GLERL's Thiessen Polygon overland (TP-Land) and overlake (TP-Lake), and CaPA (Fortin and Charpentier, 2008) for Lake Ontario, Lake Erie, and Lake St. Clair, Lake Michigan, Lake Huron, and Lake Superior. Only IMPE* and GLERL's estimates were considered for Lake Michigan and Lake Huron, while only CaPA and GLERL's were considered for Lake Superior and the aggregated Michigan-Georgian Bay-Huron. This is because MPE is not reliable for Lake Superior and Georgian Bay, while Fortin and Charpentier (2008) reported results for the aggregated MGH and not for individual lakes.

Table 7-14 Comparison between IMPE*, CaPA and GLERL Overlake Precipitation Estimates

| | Superior | Michigan-Huron | Michigan | Huron | Erie |
|--|----------------|----------------|----------------|----------------|----------------|
| Average Precipitation (mm) January 2002 to December 2007 | | | | | |
| IMPE | - | - | 73.3 | 63.0 | 85.1 |
| GLERL | - | - | 67.9 | 71.8 | 83.0 |
| Average Precipitation (mm) – June 2005 to December 2006 | | | | | |
| CaPA | 63.5 | 71.4 | - | - | 81.9 |
| GLERL | 61.5 | 72.4 | - | - | 84.7 |
| Correlations and RMSE Percent | | | | | |
| IMPE | - | - | 0.98 (13.5) | 0.82 (33.3) | 0.96 (12.2) |
| CaPA | 0.96 (10.7) | 0.87 (22.5) | - | - | 0.92 (17.7) |
| Lower (2.5 percentile) and Upper confidence (97.5 percentile) Limits (as a fraction of mean) | | | | | |
| IMPE | | | -22 to 26% | -22 to 240 % | -20 to 18 % |
| CaPA | -43 to 45% | -18 to 26% | | | -20- 39 % |

Note: Due to the different Doppler Radar coverage , IMPE* estimates were done separately for Lakes Michigan and Huron.

Figure 7-21 Multi-sensor Precipitation Estimates



Note: The colours denote the average monthly rainfall as per the key shown in each figure.

Furthermore, CaPA was available only for July 2004 to December 2006. The confidence limits are derived using a 50,000 element Monte Carlo ensemble, assuming in each case that either the IMPE* or CaPA estimates were correct.

Estimating Uncertainty in NBS

As a first estimate of the uncertainty associated with NBS, the errors in the three components of NBS were assumed to be independent of each other. It is recognized that there is likely autocorrelation at least between the overlake precipitation and runoff, if not lake evaporation. This will be explored in the second phase of the Study for Lake Superior regulation. This approach allowed generating an ensemble of 50,000 equi-probable alternative NBS estimates simply by combining each element of the precipitation, evaporation, and runoff ensembles. Uncertainty estimates for runoff and precipitation were based on the above discussions. Quantifying the uncertainty in evaporation estimates is difficult, because there are no historical measures of evaporation with which to compare the estimates. As noted, a field study is being carried out under the second part of the Study to directly measure evaporation over Lake Superior and Lake Huron (Spence *et al.*, 2009). When that project produces a time series of sufficient duration, its estimates will be compared to GLERL estimates. For this report, the generation of the evaporation ensemble was based on earlier estimates that characterize evaporation uncertainty as between 10 and 35 percent (Neff and Nicholas, 2004).

Table 7-15 summarizes the findings to date. Monte Carlo analysis indicates that, assuming evaporation uncertainty is at 35 percent, the comprehensive NBS uncertainty varies between 30 and 60 percent. Such uncertainty is actually higher than the uncertainty on each single component and is magnified by the fact that evaporation is subtracted from precipitation and runoff, decreasing the value of the combination and increasing the impact of uncertainty. Indeed, despite being the most well monitored watershed, Lake Erie has one of the highest uncertainties, probably due to the fact it is the only lake for which evaporation is higher than both overlake precipitation and runoff. However, while monthly error values can be substantial, over a longer period (annual) they should nearly average out, given that the bias is small (but negative).

7.4.2 New Modelling Techniques

In an effort to improve component NBS estimates, the Study used three independent models to assess limitations and further refine the component water balance. The first model is based on the Environment Canada Numerical Weather Prediction system. Environment Canada has been developing a community environmental modelling system, Modélisation environnementale communautaire (MEC), which is designed to facilitate coupling between models focusing on different components of the earth system. The ultimate objective of MEC is to use the coupled models to produce operational forecasts. MESH (MEC – Surface and Hydrology), a configuration of MEC, is being evaluated for the Great Lakes for the second phase of the Study. It relies on and takes advantage of data assimilation systems, including testing and evaluating the CaPA system noted above (Fortin and Charpentier, 2008). Similarly, lake evaporation, based on current lake temperature assimilations systems will be compared to the estimates provided from the eddy co-variance system. The results will be used to establish historical estimates of lake evaporation starting in 2004. Lastly, the MESH-MEC system will be used to assess lake runoff using a gridded routing model on the land surface, along with a series of surface vertical water and atmospheric transfer schemes. These individual components will be compared with the GLERL model outputs in the second part of the Study.

The second model is the CRCM. Like the MESH system, the CRCM complements the existing quasi-operational modelling system developed by the GLERL. This model is prognostic in nature and can be nested within a General Circulation Model (GCM) for climate change estimates. Indeed, further work will allow for regional climate modelling and assessment of climate change impacts in the region. The CRCM was run in a hindcast mode to assess and compare the NBS components with those derived from the GLERL model. As such, the Study completed an assessment of monthly mean simulated NBS and its components using the CRCM. Results indicated that the model reproduces the GLERL data relatively well for most months, and for each component. The largest differences

Table 7-15 Estimating the Uncertainty of NBS

| Lake | Overlake Precipitation | GLERL NBS (mm/month) | Monte Carlo Analysis NBS (mm/month) | Bias (Percent) | Correlation | Confidence interval of 95 percent |
|-----------------|------------------------|----------------------|-------------------------------------|----------------|-------------|-----------------------------------|
| Superior | CaPA | 59.0 | 64 | -7.8 | 0.986 | -47 to 59% |
| Michigan-Huron | CaPA | 74.6 | 76.6 | -2.7 | 0.997 | -38 to 42% |
| Michigan (only) | IMEP* | 63.0 | 72.9 | -13.6 | 0.997 | -34 to 38% |
| Erie | IMEP* | 66.48 | 70.87 | -6.2% | 0.999 | -52 to 60% |

were for monthly runoff estimates (Figure 7-22). This finding is not surprising, given that the routing component of the model has not yet been implemented. The same routing component that is being developed for the MESH modelling system will be used for CRCM. Both are derived directly from the CGLRRM described in section 7.3.3.

The Study examined evaporation estimates from the CRCM, GLERL and measured evaporation. The GLERL model compares better with actual measurements in June and July than the CRCM, successfully modelling both the direction and general magnitude of evaporation and condensation. In other months (August to November), both models simulate evaporation measurements well. This work will be re-assessed as part of the ongoing work for the second part of the Study on Lake Superior regulation. While annual estimates of both models agreed well, the significant monthly differences require further investigation. Observed data collected at Stannard Rock Lighthouse in Lake Superior suggest that the atmosphere above the lake in June and July is highly stable, with most energy directed to heating the water (Table 7-16).

Finally, the Study used CHARM, a regional climate model that simulates both the atmosphere and the land and lake surfaces in the Great Lakes basin. This model includes full interaction between the surface and the atmosphere and calculates runoff on its native 40-km² (15.4 mi²) grid. CHARM has output of a full range of atmospheric and hydrological variables, notably including surface-atmosphere energy fluxes (sensible heat, latent heat, and long-wave and shortwave radiation) that can aid in interpreting the reasons behind changes in these hydrological phenomena. CHARM will be run for the time period appropriate for comparison with GLERL's AHPS and CRCM model. This model is also being run in a prognostic (prediction) mode for climate change scenarios. Due to changes of the super-computer at the NOAA Earth System Research Laboratory, and due to the work required to enable CHARM to input datasets compatible with the CRCM, CHARM results have not yet been available.

In summary, initial investigations indicated that the current suite of models of the component NBS show no large differences annually. However, there can be large monthly differences between the methods. The techniques being developed are providing insights into the error structure and confidence limits that can be expected from the component estimates of NBS.

Figure 7-22 Comparison of GLERL and CRCM Models
Computed monthly NBS and overlake precipitation (P), basin runoff (R) and lake evaporation (E) for 1998-2005

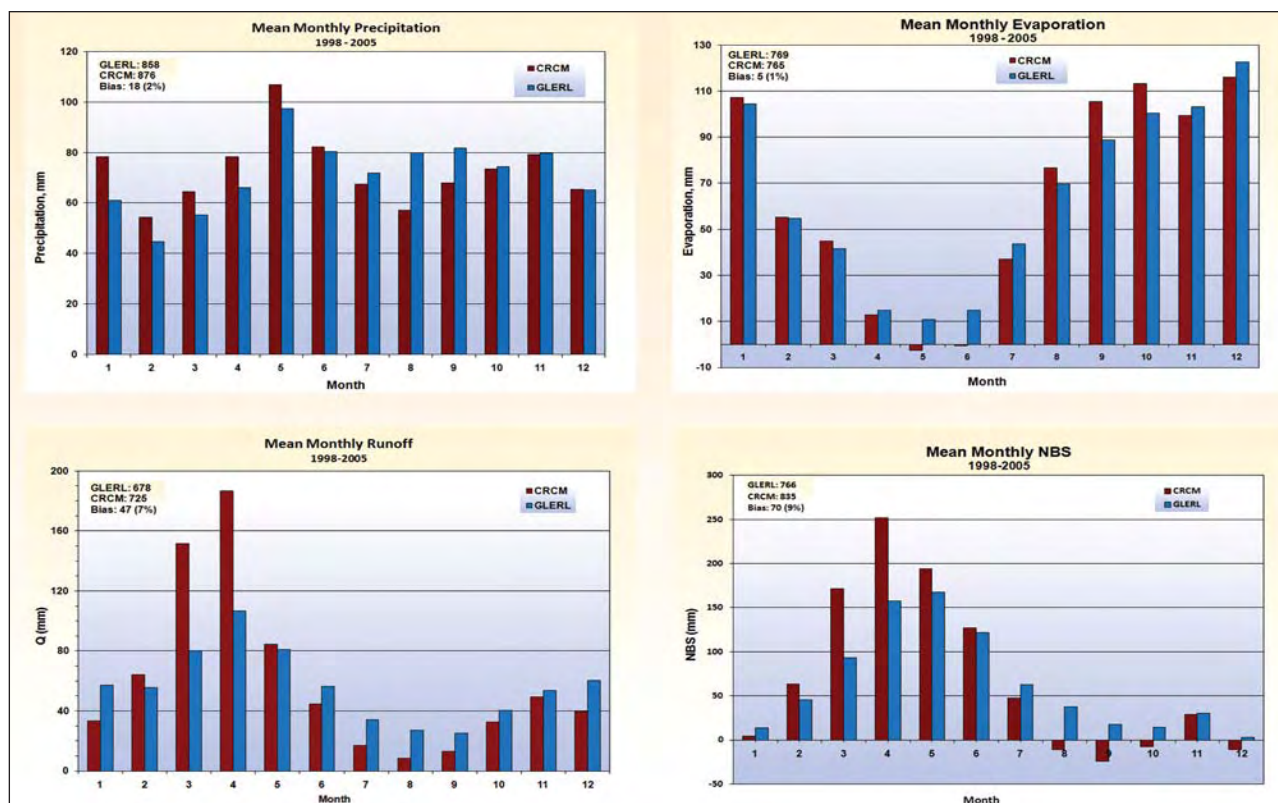


Table 7-16 Lake Superior Monthly Evaporation Rates, 2008
(mm/month)

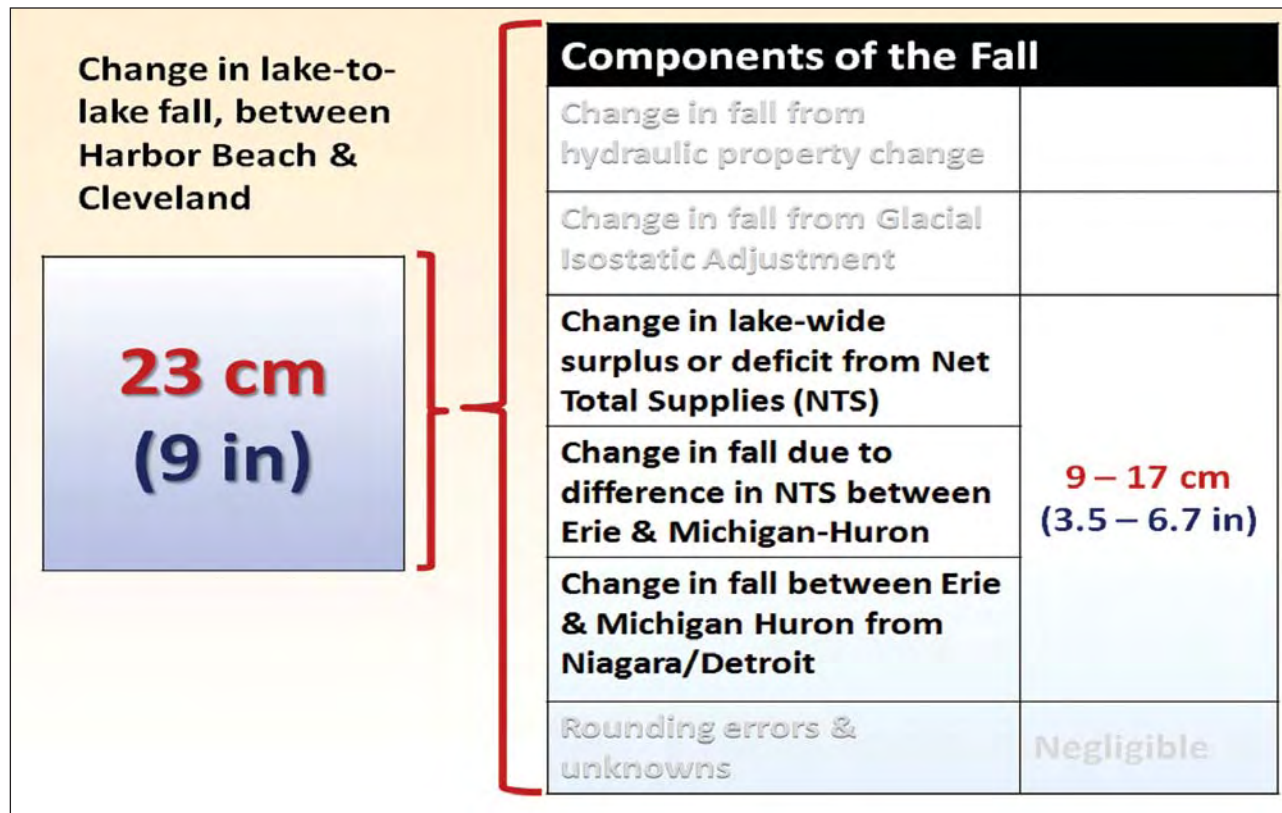
| Month | Observed | Extrapolated | GLERL | CRCM (Stannard) | CRCM (Superior) |
|-----------|----------|--------------|-------|-----------------|-----------------|
| June | -3.0 | -2.4 | -1.2 | -24.7 | -19.9 |
| July | 1.8 | 1.2 | 5.9 | -15.8 | -10.9 |
| August | 14.9 | 20.3 | 28.3 | 16.3 | 22.2 |
| September | 55.6 | 62.8 | 51.9 | 54.0 | 61.0 |
| October | 76.9 | | 83.1 | | |
| November | 18.2 | | 32.9 | | |

Note: Negative evaporation indicates condensation on the lake surface.

7.5 KEY POINTS

- Climate is the main driver of the lake level relationships between lakes and over time. Although the water levels of the Great Lakes in the latter half of the twentieth century have been higher compared to the first half, there has been a persistent decline in NTS to Lake Superior and Lake Michigan-Huron over the past two decades. This has led to declining levels in the lakes since the record high levels of 1986.
- Hydroclimatic factors (such as declining NBS and reduced St. Marys River inflows) have been major factors in the 23 cm (9 in) decline of the head difference between Lake Michigan-Huron and Lake Erie between 1962 and 2006. From deterministic modelling, the Study estimated that the hydroclimatic factors account for 40 to 74 percent of the decline or 9 to 17 cm (3.7 to 6.8 in) (Figure 7-23).

Figure 7-23 Study Findings: What factors are responsible for the change in lake-to-lake fall?



- ▶ Based on three different mid-lakes routing analyses, the impact of the St. Clair River conveyance change accounted for 7 to 13 cm (2.3 to 5.1 in) of the decline in lake-to-lake fall (Table 7-12). Changes in the conveyance of the St. Clair River are responsible for up to 30 to 57 percent of the 23 cm (9 in) change in fall between Lake Michigan-Huron and Lakes Erie from 1962 to 2005.
- ▶ Climate was by far the major contributing factor in the change in lake-to-lake fall for the 1996-2005 period, accounting for 58 to 76 percent of the decline. A substantial decline in Lake Michigan-Huron NTS was the primary cause of the change in lake level relationship to Lake Erie, contributing from 46 to 73 percent of the decline.
- ▶ Comparison of recorded historical mean lake levels, unadjusted for the present hydraulic conditions of the system to present day water levels results in a misperception of the historical significance of recent conveyance changes and low water levels. These adjusted levels place the 1996-2006 change in fall in a more realistic historical context and indicate that similar steep changes in fall have been experienced in the past (1860-1963).
- ▶ Great Lakes water supplies and connecting channel flows. The uncertainty in the NBS accounted for up to 34 percent of the change in fall for the 1962-2005 period, obscuring precise attribution of causes to the change in fall. Careful monitoring will become particularly important as part of an ongoing adaptive management effort to deal with the emerging but, as yet, unknown effects of climate change. New methods based on weather radars, direct sensing of lake evaporation and better estimates of basin runoff have been investigated by the Study. Similarly, new hydroclimatic models are required to predict climate effects on lake levels more accurately. The Study has advanced the use of regional climate models to improve prediction of NBS.
- ▶ The Study's approach to addressing hydroclimatic patterns and trends in the upper Great Lakes basin was independently peer-reviewed. Peer reviewers confirmed the validity of the Study's overall strategy. In reviewing the hydroclimatic scientific reports and draft chapter, the peer reviewers identified the need for additional analysis in the areas of data consistency and the attribution of climate change factors to observed lake levels. They also provided suggestions for improving the overall integration and presentation of the results of the various analyses and modelling in the final report. The Study addressed each comment from the peer reviewers, undertook the recommended analysis and substantially revised the text for the final report.

CHAPTER 8

INTEGRATION OF STUDY RESULTS AND CONCLUSIONS

Chapter 8 integrates the findings of the Study's work in the focus areas of sediment, hydraulics, glacial isostatic adjustment (GIA) and hydroclimatology. It reviews the Study's mandate, science framework and consideration of scientific uncertainty. It outlines the Study Board's decision framework based on degrees of confidence, and reviews the approach to addressing the key policy question regarding the consideration of remedial options. Finally, the chapter summarizes the Study's major scientific conclusions.

8.1 STUDY MANDATE AND REVIEW PROCESSES

8.1.1 Mandate of the Study Board

The St. Clair River part of the Study was established to address widespread concerns among governments at all levels, property owners and other interests about the long term economic and environmental effects of low water levels in the upper Great Lakes. The Study Board was created by the International Joint Commission in early 2007 as an independent bi-national advisory entity to organize and manage a large scientific and planning effort to address these concerns as the first part of a five-year study on upper Great Lakes levels.

Following is the principal part of the International Joint Commission's Directive to the Study referring to the specific mandate of the Study Board with respect to the St. Clair River:

1. *This directive establishes the International Upper Great Lakes Study Board (Study Board). The mandate of the Study Board is to undertake the studies required to provide the Commission 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 Treaty, and the Board shall be guided by this mandate in pursuing its studies. These studies include:*
 - a. *examine physical processes and possible ongoing St. Clair River changes and its impacts on levels of Lake Michigan and Huron. Additionally, depending on the nature and extent of St. Clair River changes and impacts, recommend and evaluate potential remedial options;*

The Study Board is only authorized to offer non-binding recommendations to the International Joint Commission that are consistent with its mandate established in the Directive. The Study Board is not empowered to implement any solutions. The International Joint Commission is responsible for making recommendations to the Canadian and U.S. governments, in accordance with its authority under the *Boundary Waters Treaty of 1909*.

The Directive to the Study Board is clear about what issues should be studied and what considerations needed to be reported back to the International Joint Commission. The Directive articulates that the resolution of the science issues are the prerequisite to addressing the basic policy issue, namely whether remediation is warranted: “*depending on the nature and extent of St. Clair River changes and impacts*”. Any substantive deviation from the Directive would require approval from the International Joint Commission. During public consultations on the draft report (held from May 1st to August 1st, 2009), two issues were raised that required the Study Board to obtain clarification from the International Joint Commission prior to finalizing this report. These two issues were:

Issue 1: *Can the Study Board incorporate the impacts of the 1962 dredging event, rather than just restricting the analysis to post-1962 dredging?*

Response: The International Joint Commission determined that the Study Board's mandate was limited to addressing the impacts of ‘ongoing’ changes to the channel after the 1962 dredging event and that the Study Board was not mandated to assess the impacts of the 1962 dredging. It was noted that the two governments did agree to compensate for the 1962 dredging, though no remedial works were ever undertaken.

Issue 2: *Can the Study Board consider remedial options regardless of whether changes in the St. Clair River were caused by human or natural causes?*

Response: The International Joint Commission determined that consideration of remedial options not be restricted to particular cause (i.e., human or natural), but whether the changes are significant enough to warrant remediation. The Study Board subsequently focused on the magnitude of the change in the deliberations on its recommendations.

8.1.2 Study Review Processes

The Directive stipulates a high degree of oversight, reporting and built-in peer review, public consultation and iterative feedback during the Study's various stages of planning, analysis and reporting. Throughout the Study process, there was an unprecedented intensive, multi-level review process consisting of the following elements:

- members of a peer review group, working independently of the Study, provided their views directly to the International Joint Commission on the draft St. Clair River Report, drafts of the key scientific chapters, and eight of the major scientific/technical reports. They reviewed the methodologies of the different components of the Study and the scientific validity of the analyses and findings;
- intensive, systematic internal peer reviews, together with a continuous series of exchanges of data and reviews, were undertaken throughout the Study by the various principal investigators engaged in the technical work groups as well as by Study Board members; and
- a broad series of public consultations on Study strategies and reports were conducted, with the assistance of the Public Interest Advisory Group.

These multiple and continuous levels of review resulted in a dynamic and responsive Study process. Many different hypotheses were explored and discussed, results were compared, and analyses were undertaken to accommodate the various public and peer review concerns. In some cases, original hypotheses were adjusted or rejected, while in others, new ones were introduced to explain apparent phenomena that were identified in the projects. Technical work groups met frequently to share information, identify key issues and reconcile any differences. New methods and approaches were frequently proposed and implemented to deal with the uncertainties of the data. These continuous internal and external peer reviews resulted in improved Study outcomes, a higher degree of confidence in the results and a substantially modified and improved final report from the draft report released for comment May 1st, 2009.

8.2 THE SCIENCE FRAMEWORK

8.2.1 Identification of the Issues

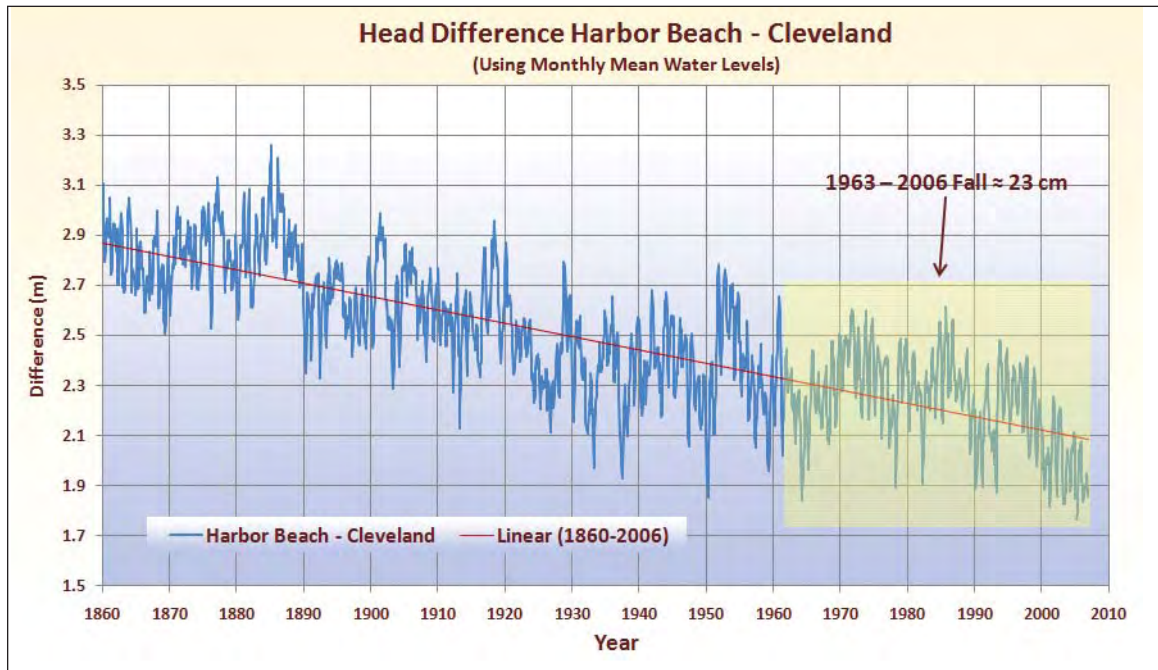
A progressive decline in the lake-to-lake fall or head difference between Lake Michigan-Huron and Lake Erie since measurements of lake levels began in 1860 is well-documented. The Study's mandate was to review the possible natural forces and human-induced changes that could account for these changes in the lake-to-lake fall, and how much of the decline could be attributed to changes in the St. Clair River conveyance since 1963.

Figure 8.1 illustrates how this difference has changed considerably from 1860 to the present day and how it fluctuates from year to year. Records of annual mean water levels recorded at Harbor Beach, Michigan on Lake Huron (about 100 km [62 mi] north of the lake's outlet) and Cleveland, Ohio on Lake Erie show that the head difference between the two lakes was about 2.9 m (9.5 ft) between 1860 and 1880. The difference then decreased sharply through the turn of the century and generally continued to decline for more than 100 years. In 2008, the head difference was about 1.9 m (6.2 ft). Between 1963 and 2006, the time period on which the Study focused, the head difference declined by about 23 cm (9 in).

Note that there is a distinction between the actual head difference in individual years, which can vary from one year to the next, and the trend line shown in Figure 8.1, which represents the best linear fit to the changes in the measured data over the longer time period.

There are several possible causes that can explain the decline. These factors have been documented since the early 1900s. Increases in conveyance in the St. Clair River were brought about by a sequence of dredging operations to deepen the navigation channel (the last of which was completed in 1962) and by sand and gravel mining (which ended in the mid-1920s). Each of these activities was associated with a computed head decline. Yet dredging and mining do not account for the total decline over that period, as highly variable hydroclimatic factors masked many of the effects for long periods of time. For example, the Great Lakes have experienced relatively high lake level regimes in the 1970s, 1980s and 1990s, enough so that the long-term average (1918-2008) lake levels have not changed much, despite the substantial head difference decline. GIA has been determined to account for about 10 cm (3.9 in) of the decline over the last century. There may have been other undetected naturally-occurring episodic phenomena in the earlier records, such as ice jam scouring of the St. Clair River. Based on the observed data, the largest absolute decline in the head difference occurred sometime in the mid-1880s, well before any

Figure 8-1 The Head Difference (Lake-to-Lake Fall) between Lake Michigan-Huron and Lake Erie



major alterations of the hydraulic regime of the Great Lakes. This timeframe coincides with construction activities that occurred in the St. Marys River, the completion of the International Railway Bridge and the completion of the Edison Sault Light and Power Company hydropower diversion channel in 1888. Simultaneously, a significant drought occurred in the upper Great Lakes basin during that period.

A core number of scientific questions needed to be addressed to provide the Study Board with an adequate basis on which to understand what is contributing to this fall and to answer the basic policy question of whether any remediation is warranted. These core questions were:

- ▶ *Has the “morphology” (the shape and composition of the river bed) of the St. Clair River been altered since the 1962 dredging?*
 - *Is the St. Clair River bed stable or eroding?*
 - *If the bed of the St. Clair River is eroding, what initiated the erosion, and when?*
- ▶ *What is causing the declining head difference between Lake Michigan-Huron and Lake Erie?*
 - *Has the conveyance of the St. Clair River changed since 1962?*
 - *If the conveyance has changed, what were the causes?*

- ▶ *How has GIA affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?*
- ▶ *How has climate affected the change in lake level relationship between Lake Michigan-Huron and Lake Erie?*

8.2.2 Scientific Analysis Results in Terms of Uncertainty

While the science questions that guided the Study were relatively straightforward, collecting the appropriate data and conducting the proper analyses to address the questions presented significant challenges. For example, as outlined in the previous chapters, members of the technical work groups and the Study Board had concerns about much of the historical data, as well as about some of the new data that were collected for the Study, and about the limitations of various models used in the analyses.

It is a truism of research that the analysis of natural phenomena has inherent scientific uncertainties. These uncertainties stem from different data collection methods, different models and assumptions, and a basic lack of understanding or failure to capture other secondary phenomena that may be influencing system behavior. Furthermore, despite best efforts to employ the most advanced instrumentation and models for contemporary data collection and analysis, it is very difficult to examine natural processes *retrospectively*, over many past decades, primarily because the technologies used in the past have lesser degrees of accuracy and precision. While reconstructing databases and linking

them together to a common platform can be a reasonable approach, this process often introduces an additional suite of unknown errors and uncertainties. Thus, even answering the basic question of whether conveyance has changed since 1962 creates challenges. A key concern with the 1971 bathymetric dataset, for example, focused on the depth-measuring technology that used an imprecise ship-positioning system that cannot adequately take into account the pitching and rolling of the ship as it measured the bottom profile. This, in turn, contributed to substantial measurement errors in the 1971 dataset associated with determining the bed configuration. The Study Board and technical work groups concluded that despite these concerns, this 1971 set was the only dataset available prior to 2000 on which to base estimates of conveyance changes and therefore had to be used, though with this caveat.

The first challenge for the Study was to determine whether a change in conveyance had occurred, and, if so, when? If there was a change in conveyance, then was it episodic or progressive? What could have caused the change? As noted, given the limited number of bathymetric surveys between 1963 and 2000, it was extremely difficult to address these fundamental questions without developing and testing a number of plausible alternative hypotheses. Not only did the scientists have to deal with the normal suite of data and modelling errors and uncertainties, but also a set of unknowns that could only be tested as a set of reasonable assumptions and through a strategy of modelling redundancy and extensive uncertainty analyses.

To address the issue of scientific uncertainty with respect to the findings, the Study developed a comprehensive strategy for dealing with the data and information issues. The strategy, which was independently peer-reviewed, consists of the following components:

- **Modelling redundancy** – using several different models focused on the same problem, and selected models using the same data to increase confidence in the results that converged;
- **Sensitivity analysis** – conducting parametric uncertainty analysis within each selected model to identify those parameters that were most sensitive to uncertainties in data, resulting in the largest differences in model outcomes;
- **Classical uncertainty analysis** – examining the propagation of errors and uncertainties from selected sources and models, and the contribution of respective uncertainties to the ultimate value; and
- **Multiple analytical approaches** – examining an issue from various related perspectives, such as sediment transport and bed morphological analysis, hydraulic modelling and hydroclimatology to address the issue of conveyance change.

Uncertainty analysis was most effectively conducted essentially in reverse, using specific statistical sampling techniques known as bootstrapping, to determine the relative contribution of various naturally occurring phenomena (such as conveyance changes and net basin supplies [NBS]). These techniques allowed investigators to determine more accurately the relative contributions of the various factors to the overall issue of the head difference decline. In addition, this approach helped better define the relative periods during which these changes occurred, because the closest data bathymetric points the Study had available for the period of interest were widely separated by nearly 30 years, 1971 and 2000.

The core challenge was attempting to attribute the head difference decline to a combination of various factors while simultaneously dealing with highly variable hydroclimatic factors that resulted in substantially changing lake level regimes and conveyance changes. To analyze one factor, the other has to remain fixed. Yet this is a dynamic system, and both factors are relatively important and constantly in flux, varying in importance during different periods of time. Thus, the reverse uncertainty analysis was used to determine the relative effects of hydroclimatology and conveyance changes since 1963. As the results were provided from the various projects commissioned by the Study Board, investigators were able to isolate the principal causative factors and translate these into a framework that accounts for all these factors and effectively summarizes the inherent uncertainties in the information.

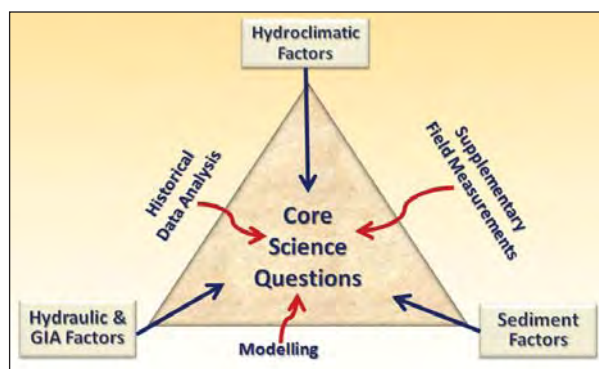
8.3 SCIENTIFIC ANALYSIS

8.3.1 Analytical Framework

The analytical framework (Figure 8-2) for addressing the science questions was structured to reflect four distinct but inter-related perspectives that are central to determining whether conveyance changed, when it changed, and how much it changed. The four perspectives were:

- **Sediment (morphology)** – examining the sediment processes in the St. Clair River to determine whether the river bed is eroding or stable;
- **Hydraulic** – focusing on understanding the relationships between lake levels and flows in the St. Clair River, and how changes in the river bed have affected the river's conveyance and ultimately water levels in the Great Lakes;

Figure 8-2 The Study Methodology



- **GIA** – addressing the implications on water balance calculations of the rise and fall of the earth’s crust across the upper Great Lakes Basin; and
- **Hydroclimatic** – examining the components of the water balance: precipitation, evaporation and runoff, along with other factors, to determine what portion of the observed changes in water levels is due to changes in basin supplies.

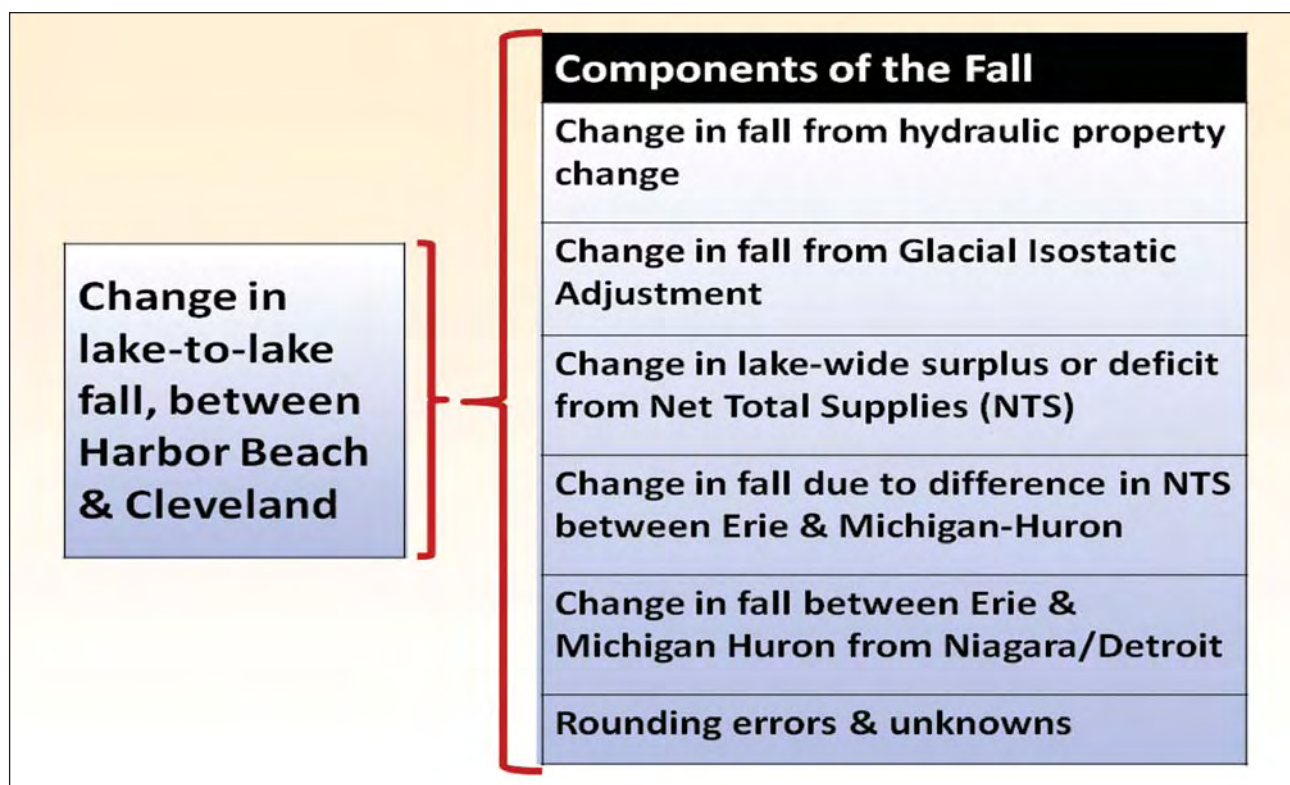
The Study recognized that new field data, in the form of supplementary measurements, had to be collected to address all four perspectives. Historical data needed to be analyzed and reformatted to match the needs of current models and data analysis methods, so that different time periods could be compared with a better understanding of their accuracy and uncertainties. Existing models had to be reconfigured to deal with different aspects and periods of St. Clair River conveyance changes.

8.3.2 Scientific Findings

The Study identified the pertinent factors that contributed to the change in lake-to-lake fall and accounted for them in the following framework (Figure 8-3). There are basically three contributing factors: conveyance of the St. Clair River; GIA; and hydroclimatology.

The Study recognized that, from a scientific perspective, rounding errors and unknowns are an additional contributing factor. However, given the scale of uncertainties associated with the analyses of the three key factors, the influence of rounding errors and unknowns is likely negligible.

Figure 8-3 Contributing Factors in the Change in Lake-to-Lake Fall



Conveyance Change Contribution

The contribution of conveyance changes in the St. Clair River to the average head difference decline since 1963 was estimated to be from 7 to 14 cm (2.8 to 5.5 in). This range was based on 15 different analyses from three different approaches: six hydraulic modelling; five water level and flow analyses; and four hydroclimatic modelling (Table 8-1).

Prior to the dredging of 1962, conveyance was predicted to increase in the St. Clair River, as a direct result of the 1962 dredging. According to studies undertaken at that time, the conveyance change was expected to account for about 13 cm (5.1 in) in the decline of the head difference (as documented in Table 7-7, in Chapter 7).

Hydraulic Performance Graphs – An Integration Tool for Visualizing Conveyance Change

In response to recommendations from the independent peer reviewers, the Study incorporated the use of HPGs as an integrator and visualization tool to illustrate the change in conveyance of the St. Clair River. The true value of the HPG tool is seen when the results of different hydraulic models from two or more different periods are placed on the same graph. If the curves from two periods are the same, it implies that there has been no change in the channel conveyance. If there is a separation between the two curves, a conveyance change has occurred over the period. The analysis using HPGs can be extended to model results from a wide range of flow rates in the river.

Table 8-1 Summary of Conveyance Change Estimates

| Type of Analysis | Water Level Change* cm (in) | Flow Change m ³ /s (ft ³ /s) |
|--|--------------------------------|---|
| Modelling – Chapter 5 | | |
| 1-D Basic HEC-RAS Modelling | 10 (3.9) | 290 (10,233) |
| 1-D Inverse HEC-RAS Modelling | - | 320 (11,292) |
| 1-D Conveyance analysis** | 2.5 to 3.2% | 140 - 290 (4940 to 10,233) |
| RMA2 2-D Modelling | 12 (4.7) | 290 (10,233) |
| TELEMAC 2-D Modelling | 13 (5.1) | - |
| HydroSed 2-D Sediment Modelling | 9 (3.5) | - |
| Data and Flow Analysis – Chapter 5 | | |
| Lake-to-lake water level analysis | 8 to 10 (3.1 to 3.9) | - |
| Gauge-to-gauge water level analysis | Up to 14 (5.5) | - |
| Flow generation with HPG*** | - | 170 (6000) |
| HPG analysis | 12 (4.7) | 290 (10,233) |
| Stage-Fall-Discharge equation analysis | 8 (3.1) | - |
| Hydroclimatic Modelling – Chapter 7 | | |
| Mid-lakes Routing | 13 (5.1) | - |
| Coordinated Routing – Component | 8 (3.1) | - |
| Coordinated Routing – Residual | 7 (2.8) | - |
| Deterministic Mid-lakes Routing | 7 (2.8) | - |

* All positive values indicate a decline in Lake Michigan-Huron water level

** Change expressed as percent change in conveyance since 1971

*** Value reported from dynamic simulation of flows; average change reported.

Figure 8-4 illustrates the results of a comparison of HPGs derived from five models over two different time periods under a specific rate of flow. The models were:

- two from hydraulic modelling: the one-dimensional (1-D) HEC-RAS (graph legend *RAS*) and the two-dimensional (2-D) SMS-RMA2 (*RMA2*); and
- three from sediment modelling: the HydroSed 2-D (*SED2D*) model, the Coordinated Great Lakes Routing Model (CGLRM) (*LWA*), and stage-fall discharge relationships (*SFD*).

The dashed lines depict the HPG for an early period (1963 to mid-1980s), while the solid lines denote a later period (mid-1990s to 2007). Note that in all cases, the HPG for the later period is below the earlier period, indicating that the conveyance of the river has increased. The separation of the curves shows the different approaches to modelling, hydraulic versus hydrological. The RMA2 and SED2D HPGs occupy the same space and therefore provide similar estimates of conveyance change as manifested at the upstream boundary.

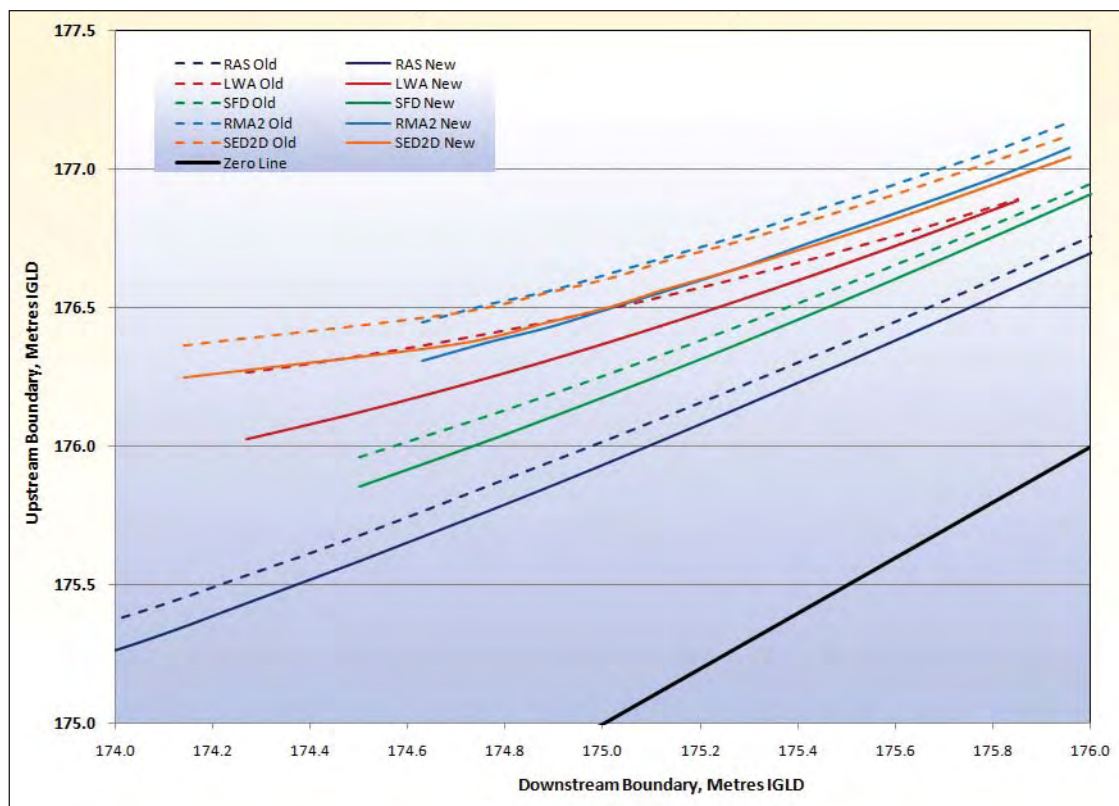
Glacial Isostatic Adjustment Contribution

This factor takes into account the effect that differential glacial uplift, tilting and subsidence has had on the basin, and specifically, the effect on the lake level measurement gauges. The net effect of GIA to head difference decline between 1963 and 2006 was estimated to be about 4 to 5 cm (1.6 to 2.0 in), based on a comprehensive analysis.

Hydroclimatology Contribution

The contribution of climate, in the form of a quantitative estimate of Net Total Supply (NTS)¹ to the decline in head difference was more problematic, because the variability was much greater from year-to-year. As a result, the estimate of the contribution of hydroclimatic factors to conveyance change has much greater variability over the time period from 1963 to 2006 than the other factors. In addition, the calculation of NTS was dependent on accurate computations of changes to the conveyance in the St. Clair River, as those channel outflows had to be included in the computations of NTS. It also was shown that over the period of 1963 to 2006, the climatic regime was significantly different over Lake Michigan-Huron than over Lake Erie. This difference affected the computation of the change in NTS for Lake Michigan-Huron and Lake Erie.

Figure 8-4 Integrated Hydraulic Performance Graphs for Conveyance Change Analysis



¹ NTS equals the sum of precipitation, runoff and channel inflows into a lake, minus channel outflows and evaporation.

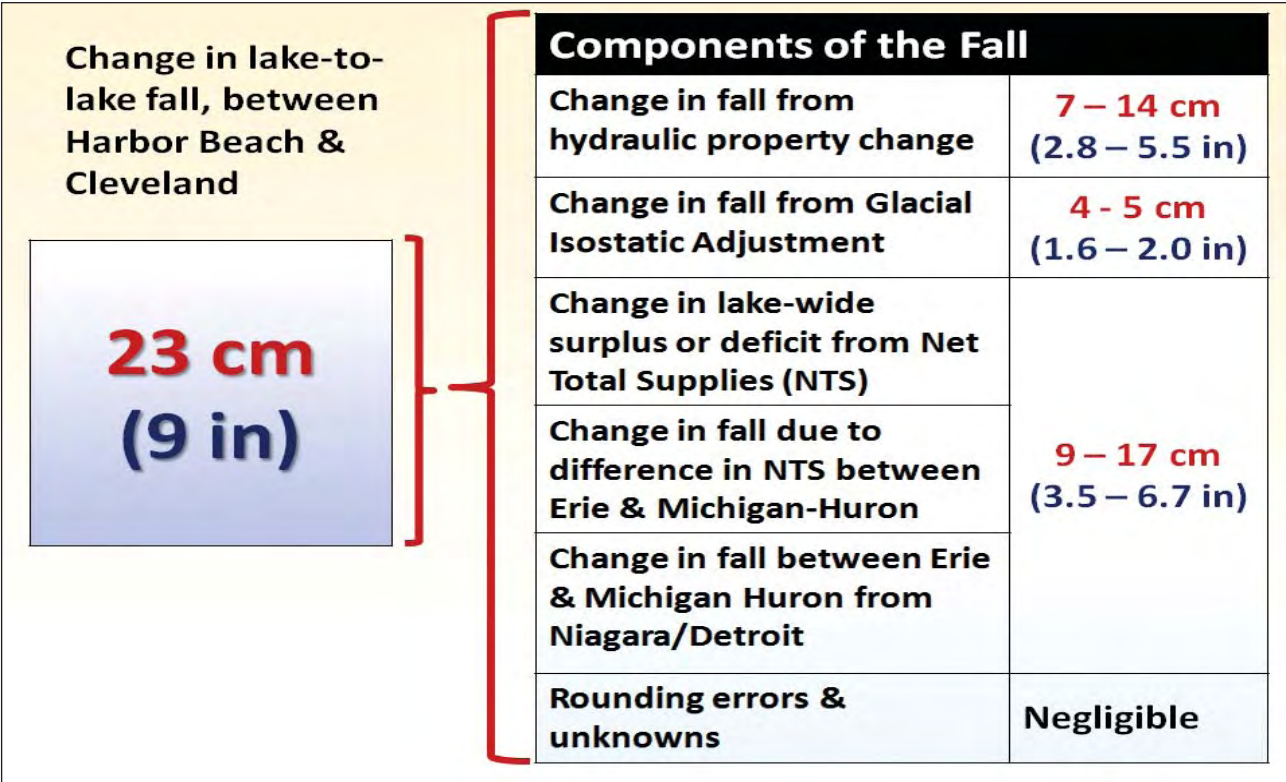
These estimates were derived over different periods and any comparison of changes in each of the contributing factors has its limitations. Comparing a linear average head difference decline computed over 150 years of record, with more variable climate-related changes during the more recent period of 1963-2006 is a case in point. The Study's analyses show that climatic factors have played a much greater role in the head difference decline in more recent periods, particularly during the last decade. The range of contribution to head difference decline of hydroclimatic factors reflects this variability. The Study estimated that the contribution of hydroclimatic factors ranged from 9 to 17 cm (3.5 to 6.7 in), depending on the particular time period under consideration.

Figure 8-5 summarizes the Study's findings regarding the contributions of each of the three key factors to the conveyance change in the St. Clair River from 1963 to 2006. Determining the total head difference decline is not as simple as adding up the estimates of the three contributing factors. These estimates are highly dependent on the choice of the specific time period being analyzed within the 1963 to 2006 timeframe and reflect the level of uncertainty around each factor and thus the confidence in the estimates.

8.4 STUDY BOARD'S DECISION FRAMEWORK BASED ON DEGREES OF CONFIDENCE

The Study Board's principal policy decision, whether to recommend remedial measures for the St. Clair River, was made considerably more challenging by the numerous independent threads of information from the various lines of inquiry, each with their own inherent uncertainties. Despite the best efforts of many scientists and engineers, the Study Board had to confront gaps in the information, unexplained discontinuities from a variety of statistical methods and limitations in the models used. These challenges, of course, are typical in any analysis of complex physical systems. Probabilistic or statistically-based uncertainty analysis provides some insights into the degrees of confidence one may have in a particular dataset or model. Outcomes are rarely scientifically clear, precise or predictable, thus leading to some ambiguity in the findings. An interpretation of all the different pieces of information is still required. This synthesis involves a type of scientific forensic analysis of past events and phenomena, coupled with an imperfect understanding of how the present physical system works. The Study Board addressed all these issues related to the inherent scientific uncertainties as part of its work in developing a series of conclusions and recommendations.

Figure 8-5 Summary Results of Contributing Factors



The Study Board recognized the need to translate the scientific uncertainties embodied in the sources of information, the various physical factors, model outputs and statistical ambiguities, into a coherent set of decisions that displayed degrees of confidence in the various contributing pieces of information. This was important not only for the Study's own internal decision processes and transparency, but also for reporting its findings and recommendations to the International Joint Commission and the public.

Therefore, the Study Board adopted the approach that was effectively used in the recent report of the UN Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007). In that report, IPCC scientists and policymakers expressed their relative degrees of confidence to deal with the scientific uncertainties inherent in the various sources of information upon which their conclusions were based. The Study Board used a modified version of this confidence scale that factored in the uncertainty of the information.

The Study Board's key evaluations are summarized here according to the levels of confidence associated with each. Overall, the Study Board was highly confident in the scientific underpinnings of the quantification of conveyance change, but had a lesser degree of confidence in attributing the causes of those changes. The Board examined several different plausible causes – maintenance dredging, navigation traffic, ice jams – but could not substantiate any specific cause.

“Highly Confident”

The Study Board had a high degree of confidence in the following findings:

- *Determining there has been a change in conveyance in the St. Clair River.* This confidence was based on 15 different analyses from three different perspectives that all found a common direction and magnitude of conveyance change, with a range in the order of 7 to 14 cm (2.8 to 5.5 in). This convergence emerged despite the fact that much of the foundational conveyance analysis was based on comparisons that relied on a relatively questionable set of bathymetric data from 1971.
- *The analysis on GIA.* There is a high level of confidence in the analysis of both the total, long term adjustment from 1860 to the present, and in the adjustment since 1962 as a result of GIA. The latter accounted for about 4 to 5 cm (1.6 to 2.0 in) of the 23 cm (9 in) decline in head difference between 1963 and 2006.

- *Analysis of velocity measurements throughout the critical upper reach from Fort Gratiot to the mouth of Black River that revealed a predominant streamwise direction.* The vertical and transverse velocity components were less than 10 percent of the longitudinal velocities. This finding substantiated the Study strategy to employ 1-D and 2-D hydraulic models to investigate conveyance issues, a decision that was supported by independent peer review.

“Confident”

The Study Board was confident in the following findings:

- *Where in the St. Clair River conveyance change has occurred.* It was clear from the analysis that most of the conveyance change occurred in the lower part of the St. Clair River, from Dry Dock to Port Lambton gauging stations.
- *Findings that a combination of events contributed to the change in conveyance.* Based on several different lines of evidence and statistical analyses, it appears that the conveyance of the St. Clair River changed sometime in the mid-1980s. There were a number of important and unusual events affecting water levels in that period of a few years, including the record ice jam of 1984, followed by the record high water levels in 1986 and culminating in a severe basin-wide drought in the upper Great Lakes in 1988.
- *Analyses that addressed the question of whether there has been ongoing erosion since 2000 in the St. Clair River bed.* Given that the data are based on a series of more reliable bathymetric measurements since 2000, there is evidence that there has not been any net erosion or associated conveyance changes since that time. However, the Study Board could not determine the exact period of time when the erosion did occur.
- *Sediment analysis, coupled with velocity measurements throughout the entire St. Clair River, demonstrated that stream velocities were insufficient to erode and transport the bed material in any section of the river.* An earlier hypothesis, that ongoing erosion was occurring, particularly in the upper reach of the St. Clair River, was not validated. There was no evidence from the Study's analyses of velocity measurements and bed mobility that such erosion was possible given the sediment sizes currently on the river bed.

- *Results of the hydroclimatic analysis accounting for 9 to 17 cm (3.5 to 6.7 in) of the decline in the head difference.* This level of confidence was justified despite the fact that this factor had the greatest degree of uncertainty, based as the information is on a number of different data sources and methods of computation. There was a relatively good convergence of different approaches undertaken for the Study, as well as a comprehensive uncertainty-based modelling effort to compare the different methods. The Study Board determined that this information was sound, and could be used effectively to conclude that hydroclimatic factors played a dominant role in the decadal decline in the head difference since 1996.

“Less Confident”

The Study Board was less confident in the following findings:

- *Attributing which factors may have contributed to channel conveyance changes during the period 1963–2006.* The Study Board instituted additional analyses of three factors discussed as potential causes.
- *The contribution of the 1984 ice jam to the conveyance changes in the St. Clair River.* Early in the Study, several lines of evidence pointed to the 1984 ice jam as possibly the key trigger in the changes, but further detailed modelling could not substantiate this claim. It may have played some contributing role, but could not be substantiated as the key factor in the conveyance change.
- *The degree to which navigation traffic has caused some degree of bed mobility in the navigation channel.* There was some evidence that ship propeller turbulence can disturb the bottom sediments, putting them into suspension and leading to transport and erosion. However, upon further analysis, it was unclear whether navigation could be a significant contributor to net erosion, and hence increase in conveyance, in any particular reach of the river. While navigation traffic associated with deep draft vessels can be responsible for the larger bedform features that reflect localized bed mobility, it likely does not contribute to net erosion in the river.

- *The contribution of ongoing maintenance dredging to any net erosion and associated conveyance changes.* The Study Board initiated an analysis of the historical dredging record, and maintenance dredging needed to keep the 8.2 m (27 ft) channel in the St. Clair River at its design depth. The analysis showed that since 1962, the volume of maintenance dredging was low and sporadic and therefore likely was not a contributing factor to any conveyance change.

8.5 THE POLICY FRAMEWORK

8.5.1 Remediation Considerations

With the scientific knowledge gained from the full range of the Study’s data analyses and modelling, and acting within the context of the Directive from the International Joint Commission, the Study Board turned to the question of whether remediation in the St. Clair River was warranted. The Directive does provide some flexibility to the Study Board to determine whether remediation is warranted:

“...depending on the nature and extent of St. Clair River changes and impacts, recommend and evaluate potential remedial options...”

The key questions the Study Board had to consider were:

- What degree and extent of conveyance change would warrant remedial actions?
- Is the erosion “on-going”?
- What could have initiated the conveyance change?

As the projects progressed, the focus of the Study Board began shifting as new evidence, data and modelling results began to suggest that there was no significant ongoing erosion of the St. Clair River bed, at least since 2000, and that much of the conveyance change may have been caused by one or more episodic events sometime between 1971 and 2000. Furthermore, other factors appeared to have contributed to the decline in the head difference, notably GIA and large changes in NBS. Not only was it important for the Study Board to quantify the relative contributions to the head difference since 1962, but also to determine the causative factors.

The Study Board's deliberations with respect to remediation were centered on a core group of important considerations:

- the conveyance change due to erosion was relatively small, 7 to 14 cm (2.8 to 5.5 in), and within the uncertainty of the underlying data;
- there was no ongoing erosion, and since 2000, when more reliable bathymetric data were collected, there have not been any significant changes to the St. Clair River bed; and
- changing hydroclimatic conditions have been an increasingly important contributing factor in the changes in head difference since 1963.

8.5.2 Review of Remedial Options

The challenges to determining the need for remediation included the high degree of uncertainty as to the factors contributing to conveyance changes, as well as the relative importance of those factors. An additional consideration was a concern over the impacts on lake levels if permanent remedial measures, such as submerged sills (weirs) were implemented as originally recommended as part of the 1962 dredging. The recommendation of the earlier studies was to restore Lake Michigan-Huron levels by up to 50 cm (19.7 in), to account for the head losses since 1860.

The Study Board recognized that if these submerged sills had been implemented by the governments, as recommended, then the damages due to erosion and flooding during subsequent high lake level stands in the 1970s, 1980s and 1990s would have been measurably greater (Levels Reference Study Board, 1993). This concern was identified repeatedly at many public meetings held at communities in the populated southern areas of the Lake Michigan-Huron region, which have been subsiding (relative to northeastern areas) as a result of GIA. These communities had experienced considerable storm and erosion damage during those high lake level periods.

As part of its consideration of the question of remediation, the Study Board authorized the preparation of a report on the likely range and types of remedial options, *Preliminary Study of Structural Compensation Options for the St. Clair River* (Baird, 2008). The report was in the form of a preliminary feasibility study of specific technologies that could be employed, including structural and non-structural measures. This 2008 report provided the Study Board with information on a range of conventional measures that could be considered, such as underwater weirs, fixed sills, wing dikes, and training walls. In addition, the investigators were asked to review newer technologies that could be feasible in the St. Clair River setting, such as temporary inflatable dams, submerged hydropower turbines (in stream power generation), and ice booms.

8.5.3 Review of Implementation of Remedial Options

During the course of early public meetings on the subject of remediation, many members of the public concerned about low lake levels in the upper Great Lakes basin expressed a desire to see remedial measures implemented as soon as the Study's findings were released. The Study commissioned a review of the typical steps and procedures required to implement a remedial project on the St. Clair River under the contemporary complex network of laws, permits and consultative procedures. The report, *Preliminary Appraisal of the Institutional Feasibility of Potential Compensating Works in the St. Clair River* reviewed the various types of potential remedial measures and set out a sequence of statutory and administrative requirements and steps needed for approval and construction of such a project (Pentland, 2009).

The 2009 report concluded that, given past experience with comparable projects, it may require up to 20 years for a remedial project to go from the time of a decision by the International Joint Commission to advise the U.S. and Canadian governments to initiate such a process, all the way through to completion of construction. This lengthy period is required because any structure, whether permanent or temporary, would require a sequential series of extensive feasibility and design studies, coupled with a parallel series of environmental assessments that would constitute the basis for a series of regulatory permit decisions at the federal, state and provincial levels.

8.6 SUMMARY OF CONCLUSIONS

The Study's conclusions are linked to the basic science questions and the findings of the analyses undertaken in the four key areas of study: sediment/morphology; hydraulics; GIA; and hydroclimatology. On the basis of these findings, the Study Board made the following conclusions:

- ▶ The total decline in the head difference between Lake Michigan-Huron and Lake Erie between 1963, following the last major dredging, and 2006, based on a long-term linear trend of data since 1860, is calculated to be about 23 cm (9 in).
- ▶ There is no evidence of ongoing erosion in the St. Clair River, according to the comprehensive bathymetric surveys undertaken since 2000. It is difficult to state when the period of a stable morphologic regime began, but it may have coincided with the relatively low lake levels of the past decade.
- ▶ Based on numerous analytical results, the decline in head difference specifically due to conveyance changes since 1971 accounts for 7 to 14 cm (2.8 to 5.5 in) of the 1963 to 2006 decline.
- ▶ Given that there are no bathymetric surveys between the two measurements from 1971 to 2000, it is difficult to determine when the conveyance in the St. Clair River may have changed and whether this change was progressive or episodic in nature. There are three indirect lines of analysis to suggest that the conveyance change was episodic and occurred in the mid-1980s, followed by a gradual transition to the current regime.
- ▶ Overall, the change in conveyance in the St. Clair River likely has been the result of a combination of several factors. The Study determined that while the record ice jam of 1984 was not the key contributing factor, seasonal ice jams do appear to play a role. Fluctuations between extreme highs and lows of upper Great Lakes water levels, such as those experienced in the mid-1980s, also could have contributed to the increase in the river's conveyance. Other possible minor contributing factors to the change in conveyance could include maintenance dredging in the river, shipwrecks and the construction of shore-line protection works.
- ▶ GIA also contributed to the head difference decline. Between 1963 and 2006, it accounted for about 4 to 5 cm (1.6 to 2.0 inches) based on a comprehensive analysis.
- ▶ Changing hydroclimatic conditions (particularly a substantial decline in Lake Michigan-Huron NTS) have been major factors in the 23 cm (9 in) decline in the head difference. Hydroclimatic factors accounted for 40 to 74 percent, or about 9 to 17 cm (3.5 to 6.7 in), of the decline over this full 43-year period. The influence of hydroclimatic factors appears to be increasing in more recent years, however, accounting for 58 to 76 percent of the decline in the 1996-2005 period.
- ▶ Given the nature of the hydraulic relationship between head and discharge, the relative levels between the lakes adjust to the new hydraulic regime. In an assumed steady state, a new lower water level equilibrium is established, typically within two to three years of any change in conveyance. The St. Clair River is dynamic in nature, however, and the steady state assumption is rarely realized.

CHAPTER 9

STUDY RECOMMENDATIONS

The International Joint Commission's 2007 Directive, establishing the Study, directed the Study Board to:

“...examine physical processes and possible ongoing St. Clair River changes and its impacts on levels of Lake Michigan and Lake Huron. ... Additionally, depending on the nature and extent of St. Clair River changes and impacts, recommend and evaluate potential remedial options.”

9.1 INTRODUCTION

The International Joint Commission is mandated to prevent and resolve disputes regarding many of the lakes and rivers along the border between Canada and the United States. The Commission is responsible for making recommendations to the Canadian and U.S. governments, in accordance with its authority under the *Boundary Waters Treaty of 1909*. These recommendations can relate to *remedial measures* to address past damages or adverse effects and *mitigative measures* to address future changes that might result in adverse effects.

In the 1960s, Canada and the United States agreed to construct compensating works in the St. Clair River following the 1962 dredging of the navigation channel. Those works were never built, as the Great Lakes region moved from record low water levels in the mid-1960s to highs in the mid-1970s and then record highs again in the mid-1980s. The scope of recommendations in this Study does not include the remedial measures associated with that 1960s agreement between the two governments.

As part of its mandate, the Study was directed to evaluate and recommend potential remedial options, depending on the nature and extent of changes and impacts in the St. Clair River. The Study reviewed past proposed remedial works and more recent innovative approaches to modifying flows in the St. Clair River. With this information, the Study identified a range of options that might be employed if remediation were deemed necessary. In addition, work was undertaken to determine the institutional, legal and environmental requirements that would need to be considered in implementing any of these options.

In addressing the key science questions, the Study identified a set of findings based on the analysis and integration of extensive data collection and modelling work in the four focus areas of sediment transport, hydraulics, glacial isostatic adjustment and hydroclimatology. The results have contributed to a significantly improved level of understanding of the St. Clair River – its geology, its sediment transport, its flow, and ultimately its effect on water levels in the upper Great Lakes, and how various natural forces and human activities have changed it since 1963.

On the basis of these findings, and in accordance with the Directive, the Study Board has developed two sets of recommendations to the Commission:

- two principal recommendations; and
- a series of secondary recommendations related to strengthening the capacity of Canada and the United States to understand and manage this unique resource that they share, the Great Lakes.

Compensation Measures

Remedial measures are those designed to address *past* damages or adverse effects.

Mitigative measures are those designed to address possible *future* changes that might result in adverse effects.

9.2 PRINCIPAL RECOMMENDATIONS

9.2.1 Compensation Measures

The Study Board recommends that:

Remedial measures not be undertaken in the St. Clair River at this time.

The Study's findings indicated that the increase in conveyance in the St. Clair River is not ongoing, and that, based on bathymetry from 2000 on, conveyance has slightly decreased. Furthermore, the conveyance change is likely the result of a combination of factors, rather than any single factor. In addition, the change is small relative to the degree of scientific uncertainty associated with the various analyses and data measurements.

Given these findings, and in accordance with its mandate, the Study Board concludes that remedial measures for the St. Clair River to address adverse changes in the river since the navigational dredging in 1962 are not warranted at this time.

9.2.2 Addressing Effects of Long-Term Climate Change

The Study Board recommends that:

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.

Climate change has emerged as a critical but uncertain factor in the future of the upper Great Lakes. There is general world-wide consensus among scientists that climate change, driven by increasing concentrations of greenhouse gases in the atmosphere, is occurring and will continue, though its effects will differ from one region to another. Understanding the effects of climate change is essential to the management of the Great Lakes, including government and community efforts to reduce and adapt to those effects.

The second part of the Study, now underway, is examining current and emerging issues related to the regulation of Lake Superior, including the effects of climate change on water supplies in the upper Great Lakes basin. It is appropriate, therefore, to consider any possible future mitigative measures in the St. Clair River in the context of this broader assessment of future water supplies in the entire upper Great Lakes.

9.3 “LEGACY” RECOMMENDATIONS: STRENGTHENING DATA COLLECTION, SCIENTIFIC KNOWLEDGE, INSTITUTIONAL CAPACITY AND ACCOUNTABILITY

Over the past two years, Study investigators have made substantial contributions to the understanding of the St. Clair River and the upper Great Lakes. They collected new data using advanced techniques. They improved existing models and developed new ones. At an early stage, the Study developed an information management system to make the data and reports available to all the Study's investigators. The information will be stored in this system and will be available in the future for other researchers and decision-makers.

These achievements are important, and will stand as part of the legacy of the Study, a foundation to support future scientific and engineering studies of the Great Lakes basin.

At the same time, however, Study investigators faced serious barriers to their work. They confronted a lack of historical data fundamental to an understanding of sediment transport, hydraulics and hydroclimatology. Even when available, historical data often either were unreliable or difficult to compare with new data. Equally important, there was limited standardization of data collection and reporting among the many federal, state, provincial and local agencies and organizations responsible for managing various components of the Great Lakes' waters and related water resources sectors.

Together, these barriers reduce the ability to understand the complex systems affecting the Great Lakes and to identify and evaluate trends. Their implications are certain to become more evident in the years ahead. As the Study's findings indicate, the complexity, scale and interrelationships of the challenges facing the Great Lakes will likely only increase in the future. More and more, governments will be called upon to respond to the concerns of a wide spectrum of interests in the Great Lakes on such challenges as long-term climate change, ecosystem and species preservation, competing water uses and water quality. These data also form the cornerstone for implementing and monitoring any *adaptive management* approaches that are developed for the upper Great Lakes.

Adaptive Management

Adaptive management is a process that supports flexible decision making that can be adjusted in the face of uncertainties as outcomes from previous management actions and other events become better understood. Careful monitoring of these outcomes advances scientific understanding and helps adjust policies or operations as part of an iterative learning process (Williams *et al.*, 2007).

In response to these concerns, the Study Board has developed the following recommendations to the International Joint Commission that:

- key data be collected, using bi-nationally agreed upon standard methodologies;
- scientific knowledge of the Great Lakes system be improved and scientific capacity strengthened; and
- a formal mechanism be established to address overall coordination and accountability.

These additional recommendations are addressed in more detail below. Implementation of these measures will, as much as the new data and models, be an important part of the legacy of the Study. By addressing these issues, governments will have the essential information they need to regulate the upper Great Lakes effectively under future conditions, particularly under a changing climate regime.

9.3.1 Key Data Collection Programs

Long-term data collection is fundamental to improving scientific understanding of how the Great Lakes function and how they are being affected by both natural forces and human activities. The Study Board recommends that the International Joint Commission endorse the following data collection programs as a priority and strongly recommend government support for their continuation after the Study is completed:

- ▶ **Conduct bathymetric surveys every five years to monitor any changes in the bed of the St. Clair River.** Governments should continue the important bathymetric survey work of the Study by conducting periodic standardized bathymetric surveys at least every five years. This work will improve understanding of



Researchers used the Department of Fisheries and Ocean's *Shark* to carry out bathymetric surveys on the St. Clair River. Such surveys need to be conducted on a regular basis to help improve understanding of how the river bed reacts to changing conditions.

how the St. Clair River bed reacts to changing conditions. In addition, the survey methodologies need to be standardized to reduce the survey error and permit meaningful comparison over time.

- ***Support the operation of the Study's new stream flow gauging stations after the Study is completed in 2012.*** To date, four such stations have been installed in the upper Great Lakes basin, one each on the connecting channels of the St. Marys, St. Clair, Detroit and Niagara Rivers. These stations are essential for deriving accurate data on flows in these interconnecting channels. Governments should support this important ongoing data collection program by designating these new stations as official "International Gauging Stations" and operating them to the approved international standards established by Canada and the United States.

- ***Maintain the operation of the two eddy co-variance (evaporation) gauges after the Study is completed in 2012 and enhance the coverage to the other lakes.*** Evaporation plays an important role in determining the water balance for each lake, yet generally remains poorly understood. The two lake evaporation gauges installed as part of the Study directly measure evaporation rates, eliminating the need for investigators to use evaporation estimates. One gauge has been installed on Lake Superior, and the other on Lake Huron. Additional gauges are needed on Lake Huron, Lake Michigan and Lake Erie.

9.3.2 Scientific Knowledge through Implementing Improved Models and Methodologies

New data modelling approaches and methodologies are needed to reduce current scientific uncertainties and to address important gaps in understanding how the Great Lakes system functions. This increased capability will enable responsible government agencies on both sides of the Great Lakes to derive more accurate information to support their decisions.



A new hydrometric (water quantity) gauging station on the St. Marys River, one of four new stations on the connecting channels of the upper Great Lakes installed under the Study. Government support for the continued operation of these stations after the Study is completed will provide key data to help Canada and the United States manage the Great Lakes under a changing climate regime.





Installed on a lighthouse in Lake Superior as part of the Study, this is one of two gauging stations collecting important new data on evaporation over the Great Lakes. The Study Board found strong support among many Great Lakes interests for continuing the operation of these stations after the Study is completed in 2012.

The Study Board recommends that the International Joint Commission endorse the following modelling and methodological recommendations, so as to develop a strengthened and more scientifically credible information system. The Commission should encourage the governments to improve scientific capacity in the various scientific agencies so that this important work may be incorporated and continued:

- ▶ ***Integrate new hydraulic and hydrological models developed as part of the Study into the operational framework to provide improved estimates of the water balance in the upper Great Lakes.*** There is a need to strengthen the scientific capability and expertise in the various institutions by implementing and integrating these new models and computational techniques.

- ▶ ***Strengthen the standardization of data collection, analysis and reporting.*** The Study expended considerable effort and resources to develop revised flow data and new rating curves for the St. Clair River. An improved data production system needs to be put in place that takes into account the approaches, methods and scientific scrutiny that have been introduced through this Study.
- ▶ ***Develop improved regional climate models, interactive with the Great Lakes, for use in assessing the effects of climate change.***

9.3.3 Accountability Structure

There is an urgent need to introduce greater accountability and coordination in the collection, management and reporting of essential physical data and information on the Great Lakes that are within the mandates of numerous agencies in both Canada and the United States. As part of this effort, there needs to be greater collaboration and sharing of information among these agencies.

The Study Board recommends that the International Joint Commission endorse the following recommendation that will help move forward the issue of overall accountability and coordination:

- ***Formalize the existing ad-hoc Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.*** Governments should clarify and strengthen the mandate of the bi-national Committee, have it formally report to the International Joint Commission, and see that all key agencies from both countries are represented and engaged.

ANNEX

ACKNOWLEDGEMENTS

The *St. Clair River Report* represents a bi-national team effort. Successfully completing the report, particularly under an accelerated schedule, has been possible only through the leadership, cooperation, expertise and enthusiasm of many individuals in both Canada and the United States. Nearly 100 scientists and engineers, 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. This report greatly strengthens our understanding of the St Clair River system and how it affects water levels in the upper Great Lakes.

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 nearly 100 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. Study Board members also were responsible for writing the introductory chapters, 1-3, the conclusions chapter, 8, and the recommendations chapter, 9.

The Study greatly benefitted from the leadership of the Study Board and its two Directors and co-chairs, Dr. Eugene Z. Stakhiv and Ted R. Yuzyk.

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The International Joint Commission also 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.

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ST. CLAIR RIVER TASK TEAM

The St. Clair River Task Team provided the strategic direction and management oversight for the numerous projects undertaken to address various aspects of Great Lakes water supplies and the conveyance of the St. Clair River. The Task Team also reviewed the analysis and findings of the projects in detail, and supervised the preparation of the final report. The efforts and leadership of Task Team co-chairs Dr. Syed Moin and James Nicholas were particularly important 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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Technical work groups were 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, and were responsible for writing the core scientific chapters of the report (Chapters 4-7).

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Public Interest Advisory Group

The bi-national Public Interest Advisory Group was established by the International Joint Commission 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. The Advisory Group, with members drawn from a wide range of organizations with an interest in the Great Lakes, assisted the Study Board in organizing and conducting public meetings and workshops, and in preparing newsletters and related public information documents. The work and insights of the co-chairs, Dr. James Bruce and Kay Felt, were of great value to the Study, particularly in coordinating the extensive public information and engagement activities undertaken in both Canada and the United States.

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LIST OF ACRONYMS

| | |
|-------------------|---|
| ADCP | Acoustic Doppler Current Profiler |
| AHPS | Advanced Hydrologic Prediction System |
| AVM | Acoustic Velocity Meter |
| AWRA | American Water Resources Association |
| CCGLHHD | Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data |
| CGLRRM | Coordinated Great Lakes Regulation and Routing Model |
| CHARM | Coupled Hydrologic Atmospheric Research Model |
| CLASS | Canadian Land Surface Scheme Model |
| CRCM | Canadian Regional Climate Model |
| ECNWDAS | Environment Canada's Numerical Weather and Data Assimilation System |
| EDF | Environnement d'Electricité de France |
| FDC | Flow Duration Curves |
| GCM | General Circulation Model |
| GIA | Glacial Isostatic Adjustment |
| GIS | Geographic Information System |
| GLERL | Great Lakes Environmental Research Laboratory |
| GPS | Global Positioning System |
| HEC-RAS | Hydrologic Engineering Center – River Analysis System |
| HPG | Hydraulic Performance Graphs |
| HyDAS | Hydraulic Data Assimilation System |
| HydroSED2D | Hydraulic Sediment 2-D Model |
| IGLD | International Great Lakes Datum |
| ILSBC | International Lake Superior Board of Control |
| INRS-ETE | L'Institut National de la Recherche Scientifique – Eau, Terre, Environnement |
| IPCC | Intergovernmental Panel on Climate Change |
| LBRM | Large Basin Runoff Model |
| LLTM | Large Lake Thermal Model |
| LOSLRS | Lake Ontario – St. Lawrence River Study |
| MOBED | Mobile Bed (1-D hydraulic and mobile bed model by Environment Canada) |
| MPE | Multi-sensor Precipitation Estimates |
| NBS | Net Basin Supply |
| NCEP CDAS | National Center for Environmental Prediction Climate Data Analysis System |
| NCEP MPE | National Center for Environmental Prediction Multi-Sensor Precipitation Estimates |
| NOAA | National Oceanic and Atmospheric Administration |
| NTS | Net Total Supply |
| NWS | U.S. National Weather Service |
| OMNR | Ontario Ministry of Natural Resources |
| PCMDI | Program for Climate Model Data and Intercomparison |
| POS | Plan of Study |
| RCM | Regional Climate Model |
| RMA2 | Resources Management Associate 2-D Hydraulic Model |
| SFD | Stage-fall discharge equation |
| SI | Système International d'Unités (International System of Units) |
| USACE | United States Army Corps of Engineers |
| USGS | United States Geological Survey |

GLOSSARY

ACOUSTIC DOPPLER CURRENT PROFILER (ADCP) – Sonar device that operates using a principle of sound waves called the Doppler effect, and consisting of transducers placed on river bed or in a moving vessel to transmit and receive sound waves to measure water current velocities for a range of depths.

ACOUSTIC VELOCITY METER (AVM) – Instrument for measuring water velocity and discharge in a stream and operating on the principles that the point-to-point upstream travel-time of an acoustic pulse is longer than the downstream travel-time and that this difference can be measured by electronic devices.

AGGRADATION, AGGRADE – Increase in river bed or land elevation due to the deposition of sediment. To raise a river bed by depositing sediment. The contrast is degradation, which refers to a lowering of a river bed level. See also **EROSION** and **SEDIMENTATION**.

ALLUVIAL – Of or pertaining to soil or sediments deposited by a river.

ANALYTICAL FRAMEWORK – An integrated and systemic approach using science and analytical techniques to understand the physical processes and the relationships between natural and man-made factors, and Great Lakes water levels and flows.

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.

ARCHIPELAGOS – Expansive water with many scattered islands or a group of islands.

ARMOUR, ARMOR – Works built to protect shore, river banks, and buildings threatened by water levels, erosion and storms; examples include revetments, seawalls, groins, breakwaters. In this report, the terms armouring and hardening are considered interchangeable.

ASSESSMENT – Evaluation, comparison or judgement using measureable terms or knowledge.

BACKSCATTER – The reflection of waves, particles or signals back to the direction from which they came.

BACKWATER EFFECT – Effect that a change in a river's water level has on water levels upstream from the river. The change can be caused by obstructions in the river such as a bridge pier, sunken vessel, ice jam, or the result of dam operation in the river.

BAR – A typically long and narrow landform resulting from deposition of granular material in a lake or river.

BASIN, DRAINAGE – Surface area contributing runoff to a stream, river or lake. In this report, the term basin and watershed are considered interchangeable.

BATHYMETRY – Measurement and charting of water depths, channel configurations and cross-sections to describe the channel's width, depth, geometry and alignment.

BEAM – An echo sounding beam (also called acoustic line) sent through water by a transducer attached to a moving vessel, which also receives the reflected signal from the river bed to generate a line of water depth across or along the channel. A multi-beam bathymetry system uses more than one transducer to collect a continuous stream of water-depth information.

BEDFORM – A feature on a river bed formed by the flow of water, such as a ripple or hollow.

BINNING – A data management technique involving the grouping of information or data to reduce the effects of minor observation errors.

BOOTSTRAP STATISTICAL TECHNIQUES – A modern, computer-intensive, general purpose approach to statistical inference.

BORINGS – See **CORE DATA**.

BOULDER – Rock usually at least 256 mm (10 in) in diameter.

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.

BREAKWATERS – Barriers built offshore or with one end linked to the shore, designed to protect a harbour or beach from the forces of waves. The common types of breakwater are rubble mound structures and steel sheet pile groins.

CHANNEL CONFIGURATION – The type of morphology of a river as determined by the interaction of a number of channel related factors, including width, depth, shape, slope and pattern. In this report, channel configuration, geometry and dimensions are considered interchangeable.

CHANNELIZATION – Alteration of a stream or river by widening, deepening or straightening.

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.

CLAY – Mineral particle with a diameter less than 0.004 mm (0.00016 in)

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 – Long-term significant change in the expected patterns of average weather of a specific region over an appropriately significant period of time as a result of changes in atmospheric conditions and/or oceanic conditions.

CLIMATE VARIABILITY – Naturally occurring climate phenomenon reflecting the interaction between the ocean and the atmosphere for a specified period of time.

CLINOFORM – A subaqueous land form.

COBBLES – Rocks that are larger than gravel.

COEFFICIENT (ROUGHNESS) – A term used in a hydraulic formula calculating channel velocity and flow to represent resistance to flow due to channel roughness.

COHESIVE SOIL – Fine-grained soil that does not crumble and exhibits significant cohesion when submerged. Cohesive soils include clayey silt, sandy clay, silty clay, clay and organic clay. Contrast: non-cohesive soils.

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). See also **REMEDIATION**.

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.

CONDENSATION – Process of water vapour in the air turning into a liquid.

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. For example, the St. Clair River, Lake St. Clair and the Detroit River comprise the connecting channel between Lake Michigan-Huron and Lake Erie.

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 (dams, spillways, canals and channel improvements) built to control outflows and levels of a lake or lake system.

CONVEYANCE – A measure of the discharge carrying capacity of a channel (after Chow, V.T., 1959). In uniform flow assumptions, it is sufficient to define the conveyance at a channel cross-section. On the other hand, when this definition is extended to gradually varied flows under sub-critical regimes, conveyance is defined by the reach (a linear segment of the channel) properties rather than the section properties. The reach conveyance is commonly defined as the geometric mean of a number of section conveyances. For this Study, the term “conveyance” is defined to encompass the reach properties.

CORE DATA – Characteristics of the materials collected from a river bed and those below the river bed by drilling. Also known as borehole data or borings.

CRITERIA – Principle or standard by which a judgement or decision is made when assessing a measure or a policy or comparing different measures or policies.

CURRENT – Flow of water described by its velocity or speed and direction.

DATUM – Elevation reference for measuring water levels. For example, Great Lakes levels are measured in metres above mean water level at Rimouski, Quebec on the St. Lawrence River. See also **IGLD (1985)**.

DEGRADATION – Reduction in river bed or lowering of bed elevation due to erosion process. The contrast is aggradation.

DEPOSITION – Settlement of sediments on a lake or river bed transported by water, ice or wind. See also **SEDIMENTATION**.

DETERMINISTIC MODEL – A mathematical model or representation in which outcomes are precisely determined through known relationships pertaining to hydraulics, hydrology and water balance.

DEVONIAN – The geologic period and system of the Paleozoic era spanning from about 416 to 359.2 million years ago.

DIRECTIVE – An International Joint Commission 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 m³/s and ft³/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.

DREDGING – Removal of lake bed or river bed material to increase water depth for navigation or other purposes.

ECOSYSTEM – Biological community in interaction with its physical environment, and including the transfer and circulation of matter and energy.

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.

EPHEMERAL – A process that is transitory in nature.

ERODIBILITY – Sensitivity of a river bed to the effects of water flow that can cause erosion.

EROSION – The wearing away of river beds, shorelines, and land surfaces through the action of water, waves and wind.

EVALUATION – The application of data, analytical procedures and assessment criteria to judge the relative merit of a measure or action, or to quantify or to determine the relative importance of the various factors in a process.

EVAPORATION – Process of liquid water becoming water vapour, including vaporization from water surfaces, land surfaces, and snow fields, but not from plant surfaces. See **TRANSPIRATION**.

EVAPOTRANSPIRATION – Sum of the evaporation from water bodies and soil and the transpiration from plant surfaces.

FLOW – See **DISCHARGE**.

FROUDE NUMBER – A dimensionless number comparing inertial and gravitational forces.

GEOGRAPHIC INFORMATION SYSTEM (GIS) – Information system used to store and analyze geographical data.

GEOLOGY – Study of the composition, structure, physical properties, dynamics and history of Earth materials, and the processes by which they are formed, moved, and changed.

GEOMORPHIC – Of or resembling the earth or its shape or surface configuration. See also **GEOMORPHOLOGY**.

GEOMORPHOLOGY – Study of the origin and distribution of landforms, with special emphasis on the nature of erosion processes.

GEOSPATIAL – Combination of spatial software and analytical methods with terrestrial or geographic datasets.

GLACIAL ISOSTATIC ADJUSTMENT (GIA) – Gradual rising 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).

GLACIATION – Period of time during an ice age when glaciers advance because of colder temperatures.

GLACIOFLUVIAL – The process associated with rivers and streams and the deposits and landforms created by them during glaciation.

GLACIOLACUSTRINE – Pertaining to lakes fed by melting glaciers, or to the sediments deposited into lakes that have come from these glaciers.

GRAVEL – Loose rock between 2 and 64 mm (0.08 and 2.52 in) in diameter.

GROINS – Structures that perpendicular or nearly perpendicular to the shore, typically built with steel, rock, timber or concrete, designed to prevent erosion, by holding beach material in place or by trapping sediment carried along-shore causing it to deposit on the upstream side of the structure.

GROUNDWATER – Underground water occurring in soils and in pervious rocks.

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 (for example, the analysis of geomorphologic features of the Great Lakes shores to generate hydrographs of pre-historic water levels).

HOLOCENE – A geological epoch which began about 11,700 years ago.

HYDRAULIC PERFORMANCE GRAPHS – Method for determining the flow carrying capacity of a channel capable of accounting for the interacting backwater effect among channel reaches. The graphs are in the form of water surface elevations or depths at the end of the channel reach for different constant discharges.

HYDRAULIC REGIME – A period of time during which the water level and flows in a river can be characterized by, or are consistent with, a definite water level and flow relationship for each of the reaches of the river. A change in hydraulic regime occurs when one or more of these relationships are changed.

HYDRAULICS – Study of the mechanical properties of liquids, including energy transmission and effects of the flow of water.

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. In this report, the terms hydro-climatic and hydrometeorological are considered interchangeable.

HYDRO-ELECTRIC, HYDROPOWER – Electrical energy produced by the action of moving water.

HYDROGRAPH – Graph relating water levels or flows over time.

HYDROLOGIC 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.

HYDROLOGY – Study of the properties of water, its distribution and circulation on and below the earth's surface and in the atmosphere.

HYDROMETEOROLOGICAL – see **HYDROCLIMATIC**.

HYDROMETRIC – Pertaining to water discharges or flows, water levels and sedimentation.

HYPOTHESES – A suggested explanation for an observable phenomenon or a reasoned proposal predicting a possible causal correlation among multiple phenomena.

INSONIFICATION – Involving the exposure of an area of a sea bed, lake bed or river bed to sound energy, as with imaging sonar.

ICE JAM – Accumulation of ice that obstructs the flow of water in a river or at the outlet of a lake.

INTERESTS, INTEREST GROUPS – Identifiable groups that perceive that the welfare of their constituents/ members is or can be influenced by lake level fluctuation or policies to address lake level fluctuation, and that work to protect this welfare through participation in the planning and review phases of the Study.

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.

LACUSTRINE – Of a lake or relating to a lake.

LEVEL – Elevation of the surface of the water at a particular site on a lake or river. Lake-wide average (or mean) level is the average of the readings taken from a network of gauges on the lake. See also **IGLD (1985)**.

LEVEL FLUCTUATION – Changes in water levels in response to natural and human influences.

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.

LOAD – BED LOAD – Material or sediment that moves along the river bed without being permanently suspended in the flowing water. **SUSPENDED LOAD:** Material that is carried generally continuously suspended in flowing water. **STREAM LOAD OR TOTAL LOAD:** All material carried by a stream or river, consisting of bed load and suspended load.

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.

METHOD, METHODOLOGY – Techniques or procedures involving computations and assumptions to generate results to answer certain questions.

MICRON – A unit of length equal to one millionth of a metre.

MITIGATION – In the context of this Study, structural or non-structural measures designed to address future actions that might result in adverse effects.

MODEL CALIBRATION – Process of modifying the input parameters to a model until the output from the model matches an observed set of data.

MODEL, COMPUTER – Use of computers to develop mathematical models of complex systems or processes from which predictions or inferences can be made.

MODEL, GENERAL CIRCULATION (GCM) – Computer model using mathematical equations from the basic laws of physics, fluid motion and chemistry for weather forecasting, understanding climate and projecting climate change. (Also known as global climate models).

MODEL, HYDRAULIC – Model using mathematics and or physical techniques to simulate water systems and make projections relating to water levels, flows and velocities.

MODEL, HYDROCLIMATIC – 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. For this report, the term hydroclimatic and hydrometeorological are considered interchangeable.

MODEL, HYDRODYNAMIC – Hydraulic models used to describe the motion of water under the influence of forces acting on it.

MODEL, SEDIMENT – Hydraulic or hydrodynamic models having a component to simulate sediment processes.

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. For this report, the terms validation and verification are interchangeable.

MONTE CARLO SIMULATION – Class of computational algorithms that rely on repeated random sampling to compute their results. For example, Monte Carlo methods were used in this Study to analyze scientific uncertainties.

MORPHOLOGY, RIVER – Study of changes of river planform and cross-section shape due to sedimentation, erosion processes, and other physical changes.

MULTIPLE ANALYTICAL APPROACH – An examination of an issue from various related perspectives, such as: sediment analysis, bed morphological analysis, coupled with hydraulic modelling of erosion processes and conveyance changes.

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 include inflow from an upstream lake. **NET TOTAL SUPPLY (NTS)** is the net basin supply for a lake plus the inflow from the lake located immediately upstream of it.

ORDERS OF APPROVAL – Approval issued by the IJC for projects that affect boundary or transboundary waters.

OUTFLOW – The quantity of water flowing out of a lake through surface rivers or streams, measured in time units at a given point.

Pa – A measure of the magnitude of fluid shear stress, measured in Newtons per m² or in pounds per ft² (psf).
1 Pa = 0.02 psf.

PARAMETERS, MODEL – Mathematical terms, variables and constants, used in computer models.

PEER REVIEW – Process of subjecting a study method and associated analytical techniques and assumptions to the scrutiny of independent experts.

PHYSIOGRAPHY – Descriptive study of the earth and its natural phenomena, such as climate, surface.

PRECIPITATION – Condensation of atmospheric water vapour that falls to the earth's surface in the form of rain, snow, hail and sleet.

PROFILE, WATER LEVELS/SURFACE – Continuous plot of the water surface elevations or depths along a channel.

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.

PUBLIC INTEREST ADVISORY GROUP (PIAG) – Independent advisory group set up by the IJC to promote effective communication between the public and the Study Board over the course of the Study.

QUATERNARY PERIOD – The geologic time period spanning about 1.8 million years ago to the present.

RATING CURVE – Mathematical formula or a drawn curve showing the relation between the rate of water flow and water surface elevation in the river or at a lake's outlet. In this report, the terms rating curve and STAGE-DISCHARGE RELATIONSHIP are interchangeable.

REACH – A segment of a river, typically referring to a segment with fairly uniform physiographic and/or hydraulic features.

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.

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.

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.

REVERTMENTS – Sloping structures placed on banks or cliffs typically covered with two or three layers of rock or concrete, and designed to protect them from waves and/or currents.

ROUGHNESS COEFFICIENT – Resistance of the bed of a channel to the flow of water. In open channel hydraulics, it is the numerical term in a formula that shows the relationships among the flow rate and the channel configuration including size and channel geometry, and gradients (slopes of water surface profile and channel bed).

RUNOFF – Portion of precipitation that falls on a water body's land basin that ultimately reaches the water body.

SAND – Natural granular mineral particles ranging in size from 0.06 to 2.0 mm (0.0024 to 0.079 in) in diameter

SAND LENSES – A geologic sand body deposit where groundwater flow occurs and is bounded by converging surfaces, typically wider in the middle and thinning out toward the edges resembling a convex lens.

SCENARIO, CLIMATE – Description of an event or series of events.

SCIENTIFIC UNCERTAINTY – A state of having limited knowledge where it is impossible to exactly describe the existing hydroclimatic or hydraulic conditions. The inability to have perfect confidence level of the modelling of future outcome.

SCOURING – The removal or loss of sediment caused by fast moving water that is the result of, for example, bridge piers and the propeller wash of large vessels.

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. The common materials used are reinforced concrete, boulders, steel and gabions which are wire mesh boxes filled with rock.

SEDIMENT – Transported and deposited particles derived from rocks, soil or biological material. Sediment is also referred to as the layer of soil, sand and minerals at the bottom of surface water, such as streams, lakes and rivers.

SEDIMENT BUDGET – Accounting system for the moveable material (sand, silt, clay and gravel) within a defined study boundary (spatial extents). Related terms: sediment processes; sediment transport.

SEDIMENTATION – Motion of marine material (pebbles, gravel, sand, silt and clay) in streams and rivers in response to external forces such as gravity and currents. Also refers to the deposition by settling of a suspended material.

SEDIMENTOLOGY – Study of sediments (sand, silt and clay) and the processes that deposit them.

SEISMIC PROFILE – A technique of seismic measurements used for correlation with surface seismic data, for example, to provide high-resolution image of the immediate vicinity of the borehole.

SENSITIVITY ANALYSIS – A conduct of parametric uncertainty analysis within each selected model to identify which parameters are most sensitive to uncertainties in data, resulting in the largest differences in model outcomes.

SHALE – Laminated, indurated rock composed of more than two-thirds clay-sized minerals.

SHAREPOINT – A dedicated server with a software program designed to provide for the sharing of information and data generated and collected during the Study.

SHEAR STRESS – Stress (force per unit surface area) acting parallel to the river bed resulting from the flow of water. Bed load movement and sediment transport is a function of shear stress. The magnitude of shear stress required to move a given particle is known as the critical shear stress.

SHOAL – A landform within or extending into a body of water, typically composed of sand, silt or small pebbles. Also called a sandbar.

SHORELINE – Intersection of a specified plane of water with the shore.

SIDE-SCAN SONAR – A sonar system, towed by a moving vessel, for mapping the river bed and identifying underwater objects and bathymetric features.

SILT – Naturally occurring non-cohesive soil particles of a grain size between sand and clay – from 0.004 mm to 0.06 mm (0.00016 to 0.0024 in) in diameter.

SILTATION – Settling of silt and other fine material in slow-moving water such as upstream of a dam or in a channel.

STAGE-DISCHARGE RELATIONSHIP – See **RATING CURVE**.

STEADY STATE – No change over time. Opposite term: **UNSTEADY STATE**.

STOCHASTIC SUPPLIES – Simulated sequences of water supply conditions that reflect variable climatic conditions.

STRATIGRAPHY – A branch of geology studying rock layers and layering, primarily applied in the study of sedimentation.

SUBCRITICAL FLOW – Flow in a channel where gravitational forces are the dominant factor determining the flow conditions. Where the inertial forces become the dominant force, the flow is said to be supercritical, with the flow velocity larger than the wave velocity.

SUBSTRATE COMPOSITION – Categorical assignments of the lake/river bottom, from silt to bedrock-size classes.

SURFICIAL GEOLOGY – Geology of material at or near the Earth's surface.

SUSPENDED SEDIMENT – Very fine soil particles that remain in suspension in water for a considerable period of time without contact with the bottom.

TELECONNECTIONS – Study of climate anomalies related to each other over large distances (typically thousands of km).

THALWEG – Line of deepest water in a stream or river as seen from above.

TILL (GLACIAL) – Material, including clay, sand, gravel and boulders, that was deposited directly by glaciers.

TOPOGRAPHY – Representation on maps or charts of the surface features of a region in such a manner as to illustrate their relative positions and elevations.

TRANSDUCER – A device that converts one type of energy or physical attribute to another for measurement or information transfer.

TRANSECT – Path, typically a straight line, along which a measuring device continuously collects water depth data.

TRANSPIRATION – Process by which water that is absorbed by plants, usually through the roots, is evaporated into the atmosphere from the plant surface, such as leaf pores. See **EVAPOTRANSPIRATION**.

UNCERTAINTY ANALYSIS – An examination of the propagation of errors and uncertainties from selected sources and models, and the contribution of respective uncertainties to the ultimate value.

UNSTEADY STATE – A state of flow in an open channel where the flow parameters – depths, velocities and rate of flow – change with time. Opposite term: **STEADY STATE**.

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.

WATERSHED – All land and water within the confines of a drainage basin. Similar term: **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 man-made overflow dam with the latter designed to raise the water level upstream or to compensate the lowering impacts due to other causes. The height of the weir above the riverbed depends on the hydraulics of the river and the intended magnitude of the compensation.

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

1 knot (Int.) = 1 mi (naut., Int.)/hr or 1.15 mi (statute)/hr or 1.85 km/hr

Area

1 square kilometre (km²) = 0.3861 square mile (mile²)

1 mile² = 2.59 km²

Weight

1 kilogram (kg) = 2.22 pounds (lb)

1 lb = 0.45 kg

1 metric tonne (mt) = 1.1 short tons (2,000 lb)

1 short ton = 0.907 mt

Volume

1 litre = 0.22 gallon (British) or 0.26 gallon (US liq) or 0.001 cubic metre (m³)

1 m³ = 1.308 yard (yd)³

1 yd³ = 0.7645 m³

Flow Rate

1 m³ a second (m³/s) = 35.315 cubic feet a second (ft³/s)

1 ft³/s = 0.02832 m³/s

1 million gallons (British) / day = 0.0526 m³ or 1.858 ft³ a second flow for one day

1 million gallons (US) / day = 0.0438 m³ or 1.547 ft³ a second flow for one day

Temperature

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

