Chapter 5
St. Clair River Hydraulic Regime

5.1 Introduction

This chapter summarizes and integrates the findings of the various hydraulic analyses conducted for 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.

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.

5.1.1 Science Questions

The primary and secondary science questions addressed with respect to the St. Clair River Hydraulic regime are:

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

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

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 a number of analytical approaches. This strategy (Moin, 2008) was reviewed and endorsed by the independent peer review group. Elements of the strategy 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 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 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 m$^3$ (181,900 ft$^3$) a second. The St. Clair River contains three distinct reaches. The uppermost 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 portion of the 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 (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 bifurcates 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 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 numbers$^1$ for the St. Clair River reach a maximum of 0.17, well below a value of one, which is the criterion for the establishment of a critical flow control section. This means that 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 capacity of the river. There is backwater in the St. Clair River from both Lake St. Clair and Lake Erie.

### 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

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$^1$ The Froude number establishes the hydraulic conditions of a river and determines whether the flow is laminar, critical or supercritical. The flow in the St. Clair River is laminar.
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 what factors contribute to the conveyance is easily illustrated using this equation. The Manning’s equation for uniform flow is as follows:

\[ Q = \frac{1}{n} \cdot A \cdot R^{2/3} \cdot S^{1/2} = K \cdot S^{1/2} \tag{1} \]

where \( Q \) is the discharge of the channel (m\(^3\)/s), \( n \) is the channel roughness, \( A \) is the cross-sectional area at the location of interest (m\(^2\)), \( R \) is the hydraulic radius (m), \( S \) is the energy slope (m/m), and \( K \) is the conveyance. 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 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 latter 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 to the upstream and downstream lakes and resulting effects on their water levels. The resistance of the channel can also change due to the seasonal growth and decay of weeds and the presence of ice cover on the river in most winter months.

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 channel 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 is conducted in several different ways: from a boat that measures the velocity of the water moving under the boat using either a mechanical flow meter (Price current meter); or acoustic techniques (Acoustic Doppler Current Profiler [ADCP]). Because the velocity in a natural, unsteady channel like the St. Clair River is constantly changing, so is the discharge. Therefore, the measured discharge is only valid for a particular instant in time and represents an estimate of true discharge, which remains unknown. Since 1996, the discharge in the St. Clair River has been measured primarily using ADCP technology (Simpson, 2001).

The technique that uses the mechanical flow meter is referred to as the conventional method. Most discharge measurements made on the St. Clair River prior to 1996 used this method. This method begins with the establishment of a measurement cross-section, the division of the cross-section into a number of sub-sections, called 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.

This method 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 that reflects off tiny particles in the water creating backscatter. The return energy 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 velocity measured in each bin and its area is 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 point 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 5-1 compares the different lengths of time required to make conventional and ADCP measurements.

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 5-2). 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. The stage-fall-discharge relationships are generally developed for ice-free, weed-free conditions. Variable ice and weed conditions cause variable backwater that can cause retardation of the flow that needs to be considered.

**Figure 5-1**

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

In an attempt to measure the velocity continuously in the St. Clair River, an Acoustic Velocity Meter (AVM) has been installed in the river as part of the overall Study. An AVM can be mounted on the side of the channel to profile the velocity in a channel 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. An AVM 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 simultaneously operating the AVM and a water level monitoring gauge. The velocities and discharge measured by the ADCP are related to the velocities observed by the AVM 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. This effort could take several years to complete for the St. Clair River. AVM technology is still relatively new, and a meter recently installed in the St. Clair River in 2008. Robust index velocity relationships cannot be developed until sufficient flow measurements, over a range of flows, have been collected. Once fully operational and rated, the AVM measurements will be compared against 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. Researchers conducted analyses with these basic data to identify possible changes that have occurred over time to detect changes in conveyance.

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, 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 could be quantified, and the effect of this uncertainty on the results of the analyses could be readily assessed. In the analyses involving water levels and measured flows, 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 capacity 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.

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). 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. The water levels used in these analyses are monthly mean levels in metres on International Great Lakes Datum (IGLD) (1985). The data for the U.S. gauges were obtained from the National Oceanic and Atmospheric Administration (NOAA). Data for Canadian gauges were obtained from the Department of Fisheries and Oceans (DFO).

Holtshlag (2009) performed statistical analyses to detect trends in the water level fall along the river defined by the gauges listed above. In any given ice-free season (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 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 with time in
reaches 1 and 2.2 relative to downstream reaches, and increasing in reaches 2.1 and 4 relative to downstream reaches. Reach 6 appeared to be stable.

Table 5-1
St. Clair River Water Level Gauges

<table>
<thead>
<tr>
<th>Water Level Gauge/Operating Agency</th>
<th>Abbreviation</th>
<th>Modelling Reach</th>
<th>Reach #</th>
<th>Reach Length km (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fort Gratiot, NOAA</td>
<td>FG-DP</td>
<td>FG</td>
<td>1</td>
<td>0.45 (0.28)</td>
</tr>
<tr>
<td>Dunn Paper, NOAA</td>
<td>DP-PE</td>
<td>DP-MBR</td>
<td>2.1</td>
<td>1.47 (0.91)</td>
</tr>
<tr>
<td>Point Edward, DFO</td>
<td>PE-MBR</td>
<td>PE</td>
<td>2.2</td>
<td>2.44 (1.52)</td>
</tr>
<tr>
<td>Mouth of Black River, NOAA</td>
<td>MBR-DD</td>
<td>MBR-SCP</td>
<td>4</td>
<td>15.6 (9.70)</td>
</tr>
<tr>
<td>Dry Dock, NOAA</td>
<td>DD-SCP</td>
<td>SCP-PL</td>
<td>5</td>
<td>18.5 (11.50)</td>
</tr>
<tr>
<td>St. Clair State Police, NOAA</td>
<td>ALG</td>
<td>PL-ALG</td>
<td>6</td>
<td>5.09 (3.16)</td>
</tr>
</tbody>
</table>

Note: Distances between gauges taken from Holtschlag (2009)

These results may be affected to some degree by water level gauge instability caused by any number of factors, as outlined above, but these issues were assumed negligible. These 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 Holtschlag’s investigations, Quinn attempted to identify the times 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. 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 Harbor Beach and St. Clair Shores gauges and the fall between St. Clair Shores and Gibraltar (later changed to Cleveland) gauges. The differences between the annual falls are plotted against time in Figure 5-3. 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 glacial isostatic adjustment. Between 1985 and 1989, the difference 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.

![Figure 5-3](image)

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 5-4.
Changes in the difference between the levels indicate that some change has occurred in the reach defined by the gauge relationship. Visual patterns may also, however, 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, 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. These approximate decreases in fall between reaches, 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. 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 accurately assess the quantitative effect of the change, because these relationships do not include river flow in assessing changes. 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.

5.3.2 Measured Flow Data Comparisons

Bruxer (2009) performed an analysis on discharge measurements and corresponding water level data available from 1962-2006. This analysis identified pairs of 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 m$^3$ (3531 ft$^3$) a second 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 also 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 caused by differences in measurement techniques, water levels, weed growth and meteorological effects, among other things, the vast majority of measurement pairs indicated increases in conveyance over time. Up to 69.0 percent of all pairs indicated an increase in conveyance in “Dataset 1”, while only 12.6 percent showed a decrease in conveyance. Similarly, up to 54.3 percent of all pairs indicated an increase in conveyance in “Dataset 2”, with only 17.9 percent showing a decrease. The magnitude of potential conveyance changes could not be quantified accurately due to uncertainties in the analysis. However, these results illustrate that the system is dynamic, and the results support the hypothesis that conveyance has changed, and likely 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 in the late 1970s or early 1980s, though this cannot be determined with certainty due to data limitations, in particular the lack of measured data available from 1985 to 1996. Additional analysis regarding the timing and location of changes determined from measured discharge data comparisons has not been pursued further at this time.
5.3.3 Bathymetric Data Analysis

The bathymetry of the St. Clair River has been measured as far back as 1859 and was generally done for the purpose of aiding navigation. Many early depth surveys were more concerned about mapping shallow hazards than obtaining the true depth of the river. As a result, many early surveys are considered to be “shallow biased”. The last bathymetric survey made of the St. Clair River before the major dredging for the 27-foot (8.2 m) project was done in 1954. Portions of the river were not surveyed in 1954 because it was felt the 1929 survey was sufficient. 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 done in 1971. This is the earliest bathymetric survey used in these analyses because of its full river coverage and it was collected during the period of interest for the Study (1962-present).

To address questions concerning ongoing geomorphic processes in the St. Clair River, analysis of select bathymetric datasets spanning 36 years was performed by 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 kilometres (2.5 miles) of the river, from the head to just below the mouth of the Black River. The 2002-2007 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 and therefore had to be considered in this analysis.

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 volumetric analysis results, however, did not exceed the error threshold associated with the dataset comparisons, and so these can be used only anecdotally and not as any firm measures of change.

Bennion shows that some statistically significant changes in bathymetry have occurred over time. The changes are not constant, but rather vary both temporally and spatially. The bathymetry data indicate that, in general, the elevation of the river bed was deeper in 2007 than in 1971. Specific areas of change are difficult to quantify, however, due to the quality of the 1971 bathymetry compared to the 2007 bathymetry. The data indicate additional changes between 2000 and 2007, but these for the most part show a rising of the bed elevations and thus deposition. A generally consistent pattern of limited erosional and depositional areas can be seen in the 2005-2007 high density data for the upper river. While the areas of change seem rather constant, certain areas switch back and forth from deposition to erosion within the analysis time frames. These changes indicate a highly variable process is at work in the upper St. Clair River.
Figure 5-5 highlights areas of the upper river where change was consistently indicated by the high density data, and it 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, which they attributed to the introduction of
the zebra mussel and subsequent increases in weed growth due to increased water clarity, though any possible changes were found to be difficult to quantify. Noorbakhsh (2009) used the same procedure Quinn (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 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 5-6). The differences between the computed levels and the observed levels are shown in Figure 5-7. Differences in relationships seem to occur in all three reaches in 1998. This very likely is due to a persistent change in the backwater from Lake Erie (Figure 5-3). 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 5-6**

*Detroit River Water Level Gauge Locations*
Unfortunately, there is insufficient evidence to make any certain conclusions regarding changes in conveyance in the Detroit River, and currently not enough data 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 hydrometric data analyses performed 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 uncertainty caused by the discrepancies between datasets was quantified and documented.

The general conclusion from these analyses is that the conveyance in the St. Clair River has likely 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 likely has increased. Bathymetric data comparisons show that the channel changed between 1971 and 2007, and has generally become somewhat deeper, but that the channel is also dynamic, with both erosion and
deposition occurring throughout the river. Water level relationship analyses indicate changes in conveyance may have occurred episodically and in different reaches of the river, with likely periods of change being: 1973-1977; 1985-1989; and 1998-2000. Discharge measurement comparisons indicate changes may have occurred prior to the mid-1980s, though this cannot be said with certainty due to a 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 8-10 cm (3.1-3.9 in).

Evidence regarding changes in conveyance in the Detroit River was not strong enough to make any strong conclusions, but other 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.

5.4 Hydraulic Modelling Analyses

As described in section 5.3, the hydrometric data analyses used basic data to try to detect conveyance changes in the river. The findings suggest that there likely have been changes in the conveyance of the St. Clair River since the 1962 dredging. However, the magnitude of the change and the precise timing could not be determined through hydrometric analysis. To address this deficiency, hydraulic models were developed to try to quantify the change in conveyance. Hydraulic models use bathymetry and shoreline information to characterize the geometry of a river, and water level and discharge data to supply boundary conditions, for calibration and validation.

This Section explains how the selection of the hydraulic models was made and the types of scenarios that were evaluated. There were several different categories of scenarios tested using multiple hydraulic models. The first utilized historic bathymetry datasets for the St. Clair River to estimate conveyance change since 1962. Next, scenarios were executed to evaluate the effect of small scale, sub-surface features like deep sections or raised sediment features on the conveyance of the river. Similarly, scenarios were developed to quantify the potential effects of glacial isostatic adjustment 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 attempted to quantify the propagation of uncertainty in the bathymetry datasets to the estimate of conveyance change.

Inverse modelling is where the bathymetry of the channel was assumed to remain constant over the time period of simulation and the models’ 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 utilized to look at the 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 a number of 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. The flow 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 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 in part based on the information provided by these data. Figure 5-8 contains a map indicating the locations of the ADCP cross-sections. Figures 5-9 through 5-13 illustrate the velocities measured at a number of cross-sections in the upper-most portion of the river. In these figures, 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. This is necessary because the vertical velocities are so small.

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 but predominantly in the streamwise direction. There is a constriction and accompanying acceleration of velocities near the International Blue Water Bridge (Figures 5-8 through 5-10). 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 5-11 and 5-12). 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.

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 but 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 5-14).

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.
Figure 5-8
Locations of ADCP Cross-Sections

Figure 5-9
ADCP Cross-Section 6
Figure 5-10
ADCP Cross-Section 7

Figure 5-11
ADCP Cross-Section 8

Figure 5-12
ADCP Cross-Section 9
While a 2-D model is a reasonable choice of model for the St. Clair River, out of all the existing, peer-reviewed operational models that exist, a 1-D model is more than adequate for the task. It can also be justified because the flow in the river is predominantly in the streamwise direction and vertical velocities are negligible in most of the river. As described, for the longest portion of the river (the section below the mouth of the Black River), there are negligible cross-currents and horizontal variation in velocity across the cross-section is minor. 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 are data requirements, computational requirements, previous applications 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. As was demonstrated in Figures 5-9 to 5-14, 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 better support 1-D and 2-D models than 3-D models. Computational requirements were also considered. 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 commissioned for the Study agreed and supported the Study strategy that the 1- and 2-D models are sufficient and adequate to answer the science questions.

The main 1-D model used in this study 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 was used as the standard 1-D model for a number of analyses, including evaluating the effects of channel geometry changes, inverse modelling to detect changes in conveyance over time, and the evaluation 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.

5.4.2 Bathymetric Change Type 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 historic bathymetry into the hydraulic models and the evaluation of changes in computed water levels and flows under historic 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 historic bathymetry datasets available for the St. Clair River outside the period of interest, which for this study was 1962 – 2008, 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. A full explanation of these differences is documented by Bennion (2008) and is summarized in section 5.3.3. These differences 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 5-2.

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 5-15. 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.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Type</th>
<th>Transect Spacing</th>
<th>Data Point Spacing</th>
<th>Transect Orientation</th>
<th>Grid Spacing</th>
<th>Data Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>Single-beam</td>
<td>~100 m (328 ft) or more</td>
<td>~20 m (65.6 ft) plus</td>
<td>Perpendicular to flow</td>
<td>--</td>
<td>Fort Gratiot to Algonac</td>
</tr>
<tr>
<td>2000</td>
<td>Single-beam</td>
<td>~100 m (328 ft) or more</td>
<td>~7.5 m (24.6 ft) plus</td>
<td>East-west, except in delta</td>
<td>--</td>
<td>Fort Gratiot to Lake St. Clair, including delta</td>
</tr>
<tr>
<td>2002</td>
<td>Multi-beam</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.5 m (4.9 ft)</td>
<td>Upper River (Fort Gratiot to just below Black River)</td>
</tr>
<tr>
<td>2005</td>
<td>Multi-beam</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.5 m (4.9 ft)</td>
<td>Upper River (Fort Gratiot to just below Black River)</td>
</tr>
<tr>
<td>2006</td>
<td>Multi-beam</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.5 m (4.9 ft)</td>
<td>Upper River (Fort Gratiot to just below Black River)</td>
</tr>
<tr>
<td>2007</td>
<td>Multi-beam</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1.5 m (4.9 ft)</td>
<td>Fort Gratiot to Algonac</td>
</tr>
<tr>
<td>2008</td>
<td>Multi-beam</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.5 m (1.6 ft)</td>
<td>Upper River (Fort Gratiot to just below Black River)</td>
</tr>
</tbody>
</table>
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 of which are presented in Table 5-3. Using bathymetry data of equal density, since 1971 the water level of Lake Michigan-Huron was found to have decreased from 10 to 13 cm (3.9 to 5.1 in) due to an increase in conveyance. In terms of discharge, the models indicated for the same Lake Michigan-Huron and Lake St. Clair water levels, the St. Clair River can now convey between 250 and 275 m$^3$ (8,829 and 9,712 m$^3$) a second more water than it could in 1971.

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 5-3. 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 a meaningful 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.

### Table 5-3

<table>
<thead>
<tr>
<th>Scenario</th>
<th>HEC-RAS</th>
<th>RMA2</th>
<th>TELEMAC-2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 SSB1971 vs 1971</td>
<td>-10 (-3.9)</td>
<td>-12 (-4.7)</td>
<td>-13 (-5.1)</td>
</tr>
<tr>
<td>2007 MB vs 1971 SB</td>
<td>-23 (-9.1)</td>
<td>-25 (-9.8)</td>
<td></td>
</tr>
<tr>
<td>2007 MB vs 2000 SB</td>
<td>-7 (-2.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007 SSB2000 vs 2000 whole river</td>
<td>3 (1.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007 SSB2000 vs 2000 above Black River</td>
<td></td>
<td>0.6 (0.24)</td>
<td></td>
</tr>
<tr>
<td>2007 SSB1971 vs 1971 above Black River</td>
<td></td>
<td>-3 (-1.2)</td>
<td></td>
</tr>
</tbody>
</table>


From 1971 to 2007, all of the models show the conveyance has increased in the river, but the amount varies from model to model and simulation to simulation. Efforts were made to standardize the data that the simulations were based on (bathymetry), and the simulations that were executed (i.e., using the same water levels and flows for boundary conditions). However, there are differences in 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 plausible conveyance change estimates can be provided.

Comparisons of the velocities in the St. Clair River that would have been present in 1971 versus 2007 were made to address one of the secondary questions posed. Using the Telemac-2D model, comparisons were made of the models using bathymetry from 1971 and 2007. Comparisons indicate the velocity patterns did not change significantly from 1971 to 2007.

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. 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. Initial 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, but 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 chosen for calibration.

Three calibrations were performed on each of the 1971 and two 2007 models (2007 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 5-4 shows a comparison of the difference in simulated Fort Gratiot water level for 1971 and the two 2007 models, and the average difference in observed Fort Gratiot water level 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 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 even more questionable, given that the data, as well as the calibrations themselves, are not free of error.

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Comparison</th>
<th>Calibration 1</th>
<th>Calibration 2</th>
<th>Calibration 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference in Fort Gratiot water level simulated by calibrated models</td>
<td>1971-2007</td>
<td>0.08 (0.26)</td>
<td>0.03 (0.10)</td>
<td>0.07 (0.23)</td>
</tr>
<tr>
<td></td>
<td>1971-2007SSB71</td>
<td>0.09 (0.30)</td>
<td>0.04 (0.13)</td>
<td>0.08 (0.26)</td>
</tr>
<tr>
<td>Average difference in Fort Gratiot water level from observed data</td>
<td>1971-2007</td>
<td>0.09 (0.30)</td>
<td>0.04 (0.13)</td>
<td>0.08 (0.26)</td>
</tr>
</tbody>
</table>

### 5.4.3 Effects of Small Scale Features and Hydraulic Control in 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 bed material deposits that may be migrating through the river. A number of cut and fill scenarios were conducted 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 tests showed that these small scale features have little effect on conveyance in the river (Bruxer and Thompson, 2008; Faure, 2009a; Giovannettone, 2008). 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 only range from 0.05 to 0.17 and are not nearly high enough to cause critical flow control sections, which require a Froude number of 1 or greater. Liu and Parker (2009) demonstrated that dredging 4 m (13 ft) of material over a 10 km (6.2 miles) 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 Police) or the lower half (St. Clair Police to Algonac) resulted in the same effect on conveyance. These results are expected as 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 effect of glacial isostatic adjustment on the hydraulics of the St. Clair River was also investigated. Gradient changes of the river bed due to glacial isostatic adjustment 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 glacial isostatic adjustment, 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 Section 5-6 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/century (4 in/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 glacial isostatic adjustment on St. Clair River discharge that might be reasonably expected.

With this in mind, the Telemac-2D model 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) in 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, and it was found to have a negligible effect on discharge over this time. Another way of performing the experiment would have been to hold the river bottom at Fort Gratiot static, lower the lake bottom of Lake St. Clair and lower intermediate points linearly within the river. This was not undertaken as the results would also be expected to be negligible.

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 size and locations of ineffective flow areas. For 2-D models, assumptions include grid size, interpolation methods and boundary elevation data. Simulations were conducted to evaluate the influence of these decisions to 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 reports (Giovannettone, 2009; 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 a high level of accuracy; yet there is still a degree 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 due primarily to improvements in measurement techniques (see Table 5-5). Additional error is created 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.

Table 5-5

<table>
<thead>
<tr>
<th>Bathymetry Year</th>
<th>Survey Error</th>
<th>Interpolation Error</th>
<th>Total Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>0.3000</td>
<td>0.89 (2.92)</td>
<td>0.93 (3.05)</td>
</tr>
<tr>
<td>2000</td>
<td>0.3000</td>
<td>0.77 (2.53)</td>
<td>0.81 (2.66)</td>
</tr>
<tr>
<td>2007</td>
<td>0.1524</td>
<td>0.23 (0.75)</td>
<td>0.28 (0.92)</td>
</tr>
</tbody>
</table>

(Note: Errors expressed are standard errors in metres (feet))

Bruxer and Thompson (2009) quantified how the errors in bathymetry affect the estimates of change in conveyance of the St. Clair River through uncertainty analysis. 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 5-6 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 (9712 +/- 2401 ft³) a second from 1971 to 2007, and decreased by 74 +/- 61 m³ (2,613 +/- 2154 ft³) a second 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. More details on this analysis are described in Bruxer (2009).

Table 5-6

<table>
<thead>
<tr>
<th>Conveyance Change Estimate (water level)</th>
<th>Mean WL Difference (m and ft)</th>
<th>Standard Error (m and ft)</th>
<th>95 % Confidence Interval (m and ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 SSB1971 vs 1971</td>
<td>-0.115 (-0.38)</td>
<td>0.027 (0.089)</td>
<td>0.053 (0.184)</td>
</tr>
<tr>
<td>2007 SSB2000 vs 2000</td>
<td>0.028 (0.092)</td>
<td>0.024 (0.079)</td>
<td>0.047 (0.155)</td>
</tr>
</tbody>
</table>

5.4.6 Hydraulic Modelling Analysis Using Inverse Modelling Approach

The HEC-RAS model of the St. Clair River developed using the 2007 multi-beam bathymetry was used to investigate conveyance changes over time using 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, the net change in conveyance capacity between 1962 and 2007 is an increase of 5.8 percent or approximately 320 m³ (11,301 ft³) a second if the annual discharge is taken as 5,500 m³ (194,233 ft³) a second. The uncertainty in these estimates resulting from uncertainties in measured flows and water levels was not documented.

5.4.7 Effects of Ice on St. Clair River Conveyance

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 5-16, for the winter of 1983-1984, the largest conveyance reduction occurred during 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.

**Figure 5-16**

*Influence of 1984 Ice Jam on St. Clair River Conveyance and Stages*
The conveyance of the sub-reach from Algonac to St. Clair State Police gauges 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 suggest that this ice jam may have had a significant and long-term effect on the conveyance of the St Clair River.

The other sub-reaches also show overall trends with time and annual variations. However, these trends are not as clear as for the downstream reach. In general, the conveyances of the other reaches are the largest for the most recent period, 1996-2006.

This work demonstrates the possible effect of river ice on the conveyance of the St Clair River. It suggests that the “record St Clair ice jam” of 1984 may have had a significant and long-term effect on the conveyance of the St Clair River. While erosion of sediment during ice jams has been documented in other river reaches (Ziegler et al., 2005), attempts to validate this effect in the St. Clair River by numerical modelling of the ice jam to determine the possibility of erosion of channel sediment during the jam would be difficult due to the lack of flow and velocity measurement data during the 1984 event.

5.4.8 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 10 to 13 cm (3.9 to 5.1 in). In terms of discharge, the St. Clair River can now convey 250 to 275 m³ (8,830 to 9,710 ft³) a second 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. 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 (9,710 +/- 2,400 ft³) a second for the same water level differences in 1971 and in 2007.

The hydraulic models indicate 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 (2,610 +/- 2,150 ft³) a second.
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 conveyance in the St. Clair River is not controlled by any one section, rather, by the entire channel.

Glacial isostatic adjustment 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 time.

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 capacity change between 1962 and 2007 is estimated as 5.8 percent or about 320 m³ (11,301 ft³) a second. Ice modelling on the St. Clair River quantified the possible effect of river ice on the conveyance of St. Clair River. It suggested that the “record St. Clair ice jam” of 1984 may have had a significant and long-term effect on the conveyance of the St. Clair River. A lack of flow and velocity measurement data during the 1984 ice jam event and in the years following, however, makes it difficult to confirm this finding with certainty.

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 hydraulic performance graphs (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 this 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 historic data record keeping, limits of the measuring equipment, malfunction of measuring equipment, and evolving hydraulic theories on which the data are based. The measurement of a water level may seem to be relatively straightforward, but local conditions, location of the gauge, datum changes, glacial isostatic adjustment, and gauge malfunctions can all affect the long-term record and contribute to the uncertainty of any analysis that uses the measured data. 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 comparisons based on these data.
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 5-17 is an example of an HPG for the St. Clair River.

Schmidt (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, due possibly to an increase in conveyance after the 1962 dredging, coupled with record low water levels due to drought in the basin. 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 5-18 shows how the HPG generated flows compared to the 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 m$^3$ (6,957 ft$^3$) a second. 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 m$^3$ (6,392 ft$^3$) a second. For the period 1996 to 2006, the standard error is 217 m$^3$ (7,663 ft$^3$) a second.

The HPG-based flows generally are higher than the presently coordinated by the ad-hoc Coordinating Committee on the Great Lakes Hydraulics and Hydrology (Figure 5-19), 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. Schmidt, however, noted that differences between the HPG-based flows and the coordinated historic flows are often within the error of the measurements on which the HPGs are based. It was also 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 historic 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 5-19
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:

\[ Q = a(H_d - base)^b(H_u-H_d)^c \]

where \( Q \) is the discharge, \( H_u \) and \( H_d \) are the levels at the upstream and downstream gauges, \( base \) is an estimated effective river bottom elevation and \( a, b \) and \( c \) are empirically fitted parameters.

Fay (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 5-20) 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 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.

**Figure 5-20**
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).)
Using the two sets of equations and monthly mean water levels for ice-free months, Fay computed two sets of flows for the period 1962-2007. These computed flows were compared to the level of Lake Michigan-Huron (Figure 5-21) (Noorbakhsh, 2009).

**Figure 5-21**
Comparing Computed Flows to the Level of Lake Michigan-Huron at Lakeport Gauge  
(The conventional based ratings were derived using discharge measurements from 1968-1985. The ADCP based ratings were derived using discharge measurements from 1996-2006.)

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. The average difference between the two sets of computed flows is about 180 m$^3$ (6,358 ft$^3$) a second, with the 1996-2006 based equations giving higher flows. This would represent an increase in flow of about 3 percent. The significance of the 180 m$^3$ (6,358 ft$^3$) a second 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. There is also a degree of uncertainty in this analysis due to uncertainty in the measured water levels and discharges, as well as the fact that stage-fall-discharge rating equations are not a true representation of the physical system.

5.5.3 Conclusions from HPG and Traditional Rating Curve Analyses

Stage-fall-discharge equations and hydraulic performance graphs, derived using measured discharges and water levels, both point to the possibility that there has been a change in conveyance in the St. Clair River. Both show a change in the relationships 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 180 m$^3$ (6358 ft$^3$) a second, or about three percent for the same water levels, after the early 1970s for the same water levels.
5.6 Glacial Isostatic Adjustment

Although most people tend to think of land masses and elevations as being stable over time, this is not the case in the Great Lakes region. The earth’s crust continues to move, but at varying rates throughout the basin, as it continues to recover from deformation during the last ice age. This process is formally referred to as glacial isostatic adjustment (GIA). Since 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.

Based on their review of the physical and apparent impacts of GIA, Quinn and Southam (2008) concluded that, due to the impact of GIA and the use of IGLD on recorded water level data, 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. These are the Lakeport, MI and Buffalo, NY gauges on Lake Michigan-Huron and Lake Erie, respectively. Because of the relative vertical movement between Harbor Beach and Lakeport on Lake Michigan-Huron and Cleveland and Buffalo on Lake Erie, the reduction in head difference shown in Figure 5-22, which is based on water levels recorded at Harbor Beach and Cleveland, does not properly reflect the changed head difference between Lake Michigan-Huron and Lake Erie over short- or long-term.

Figure 5-22

If the change in the Lake Michigan-Huron and Lake Erie head difference over time is estimated based on water level differences, as in Figure 5-22, then the apparent impact of GIA on the estimated change in fall must be determined as well as the physical impacts of GIA. The apparent effects of GIA result from using water levels recorded at gauges on a lake located away...
from the lake’s outlet (i.e., Harbor Beach-Cleveland) versus gauges located at or very close to
the outlets that is, Lakeport-Buffalo. The physical impacts describe physical changes resulting
from GIA on actual lake levels (resulting in backwater effects), on the slope of the Lake
Michigan-Huron-Erie corridor, and on the volume of the Great Lakes over time, all of which
would affect the Lake Michigan-Huron and Lake Erie head differences based on either the
Lakeport-Buffalo or Harbor Beach-Cleveland plots equally.

5.6.1 Determining the Apparent Effects of GIA

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 recorded water levels at Harbor Beach
and Cleveland also reflect the impact of relative movement between their locations and their
lake’s outlet. Between periodic updates, IGLD is a fixed vertical reference system in a moving
environment. Since the Harbor Beach area is rising relative to the Lake Michigan-Huron outlet,
water levels observed (and recorded) at Harbor Beach appear to be falling over time compared to
those recorded at Lakeport for the same lake level. On the other hand, since the Cleveland area
is subsiding relative to the Lake Erie outlet, water levels observed (and recorded) at Cleveland
appear to be increasing compared to those at Buffalo over time. The actual water levels at
Harbor Beach and Cleveland relative to the true mean sea level are not falling nor rising over
time relative to those at Lakeport and Buffalo as suggested by the recorded data because both
Lake Michigan-Huron and Erie are considered to have geopotentially equal (i.e., level) water
surfaces (CCGLBHHDD, 1995). Allowing for short-period fluctuations due to meteorological
disturbances and local effects, all points on and around a given lake are at the same levels
relative to true mean sea level. The apparent downward and upward trends in water levels
observed at Harbor Beach and Cleveland reflected in their recorded data compared to those
recorded at Lakeport and Buffalo, respectively, are due to the change in the water-to-land
relationship at these locations as the land there rises or falls relative to their lake’s outlet over
time due to GIA.

Therefore, water levels at Harbor Beach and Cleveland do not adequately represent the levels of
Lake Michigan-Huron and Lake Erie at their outlet over time. If water levels recorded at Harbor
Beach and Cleveland are used (without being adjusted for the apparent impact of relative GIA)
to determine the change in head difference over time, as in Figure 5-22 and in Baird (2005), 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 their
lake’s outlet will be misinterpreted as a reduction in head between Lake Michigan-Huron and
Lake Erie. Southam (2009) showed that the portion of the apparent reduction in the head
difference shown in Figure 5-22 over a given period of time due to the use of Harbor Beach-
Cleveland differences instead of Lakeport-Buffalo can be determined taking the arithmetic
difference between the changes in the head difference based on Harbor Beach-Cleveland and
Lakeport-Buffalo over the length of time (i.e., $\sum \Delta GIA_{apparent} = \Delta(HB - CL) - \Delta(LP - B)$).

Ideally, a comparison of the Lakeport-Buffalo and Harbor Beach-Cleveland differences based on
recorded water level data over the entire 1860-2006 time period shown in Figure 5-22 could be
carried out to determine the portion of the reduction in the head difference over both the short-
and long-term that can be attributed to apparent impact of GIA on Harbor Beach-Cleveland
water level differences over time. Unfortunately, monthly water level data are only available at Lakeport beginning in September 1955, and 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. Further, a review of historical water level data by Quinn and Southam (2008) also raised some concerns regarding the quality of the earlier data available at Harbor Beach, Cleveland and Buffalo. Therefore, two analyses were carried out.

The first used the September 1955 to December 2006 common period of recorded data at Lakeport, Buffalo, Harbor Beach and Cleveland. Since recorded data are available for all but a few months during this period, this approach provides the best comparisons between the Harbor Beach-Cleveland and Lakeport-Buffalo head difference plots over the post-1962 period, which is the timeframe focus of this Study.

For the second analysis, several Lakeport-Buffalo difference plots were generated based on both recorded and synthesized Lakeport and Buffalo water level data in order to estimate the impact of using water levels recorded at Harbor Beach and Cleveland instead of Lakeport and Buffalo to determine the change in the head difference between Lake Michigan-Huron and Lake Erie over the 1860-2006 time period.

In both cases the primary analysis is based on the differences between the 4-month (June-September) mean water levels recorded at each location to limit the impact of seasonality on water level differences. Comparable difference plots were generated to determine the sensitivity of results to the water level data averaging period (e.g., monthly, annual, or summertime average) used.

5.6.2 Results of the Short-term Analysis

Plots of the year-to-year differences between the 4-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 5-22. The difference between the Harbor-Cleveland and Lakeport-Buffalo fall diagrams represents the apparent impact on GIA on the head difference due to the use of water levels recorded at Harbor Beach and Cleveland instead of Lakeport and Buffalo. As indicated by the steeper slope of the linear trend line plotted over the Harbor Beach-Cleveland differences, the use of water levels recorded at Harbor Beach and Cleveland instead of those at Lakeport and Buffalo overestimate the reduction in the head difference over time. In addition, due to the impact of the water level adjustments made to the historical data at each of these sites during the update of IGLD in 1985, which brought the elevations of the Great Lakes water level gauges back into harmony, the Lakeport-Buffalo and the Harbor Beach-Cleveland differences are virtually the same immediately before and after 1985 and their linear trend lines cross about that time. As a result, the Harbor Beach-Cleveland plot overestimates the head difference prior to 1985 and underestimates the head difference for years following 1985.

The standard errors of linear trend lines plotted over the Lakeport-Buffalo and Harbor Beach-Cleveland difference plots in Figure 5-23 are quite large. As a result, the linear trend lines are very poor estimators of either the Lakeport-Buffalo or Harbor Beach-Cleveland differences in any given year. Their slopes are also sensitive to the period of record used to determine them. Therefore, one must exercise caution in interpreting the slopes of the Harbor Beach-Cleveland
and Lakeport-Buffalo trend lines in the figure, except to help identify the portion of the fall in the Harbor Beach-Cleveland plot that is due to the impact of GIA on their recorded water levels over time.

The apparent reduction in the Lake Michigan-Huron Lake Erie head difference over time due to the use of Harbor Beach-Cleveland pairing instead of Lakeport-Buffalo can be determined based on the difference between the slopes of the Harbor Beach-Cleveland and Lakeport-Buffalo trend lines over time; however, it is more easily perceived in the plot of the year-to-year differences between the Harbor Beach-Cleveland and Lakeport-Buffalo plots, also shown in Figure 5-22. The -0.00102 m (-0.0033 ft) a year slope of the linear trend line plotted over Harbor Beach-Cleveland minus Lakeport-Buffalo indicates that using Harbor Beach-Cleveland instead of Lakeport-Buffalo, overestimates the reduction in the fall between Lake Michigan-Huron and Lake Erie at a rate of about 10 cm (3.9 in) a century. Therefore, if the change in the Lake Michigan-Huron Lake Erie head difference is based on water levels recorded at Harbor Beach and Cleveland instead of Lakeport and Buffalo, it will overestimate the change in the head difference by about 4 cm (1.6 in) over the 1962-2006 time period.

**Figure 5-23**

*Estimation of the Effect of Apparent GIA on Recorded Water Levels*

**Comparison of LP-B (MH-E at their Outlets) and HB-CL (Using 4-month (June - September) Mean Water Levels)**
5.6.3 Results of the Long-term Analysis

Although much less certain, Southam (2009) following Quinn and Southam (2008) estimated the head difference between Lake Michigan-Huron and Lake Erie over the 1860-2003 time period based on a combination of recorded and estimated 4-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). The resulting reduction in the Lake Michigan-Huron to Lake Erie head difference was about 61 cm (24 in), 19 cm (7.5 in) less than the 80 cm (31.5 in) Harbor Beach-Cleveland reduction shown in Figure 5-22 and given in the 2005 Baird report.

The analysis suggests that about 14 cm (5.5 in) of the estimated 19 cm (7.5 in) difference is the result of using Lakeport-Buffalo instead of Harbor Beach-Cleveland to determine the head difference. In other words, about 14 cm (5.5 in) of the 80 cm (31.5 in) reduction is due to the apparent impact of GIA on water levels recorded at Harbor Beach and Cleveland. Southam (2009) compared similar Harbor Beach-Cleveland and Lakeport-Buffalo difference plots based on monthly, annual and 4-month (June-September) mean levels. The comparisons indicate that almost 2 cm (0.8 in) of the 19 cm (7.5 in) difference can be attributed to the use of the 4-month (June-September) mean levels to estimate the change in Lake Michigan-Huron Lake Erie head 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 any Lake Michigan-Huron Lake Erie head differences based on them. Finally, the remaining portion of the 19 cm (7.5 in) difference might be due to the level of precision used to calculate and report the 1860 and 2003 water levels and their differences in the two studies. 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 our confidence in the early Lakeport-Buffalo and Harbor Beach-Cleveland differences. Therefore, estimates of the long-term reductions in the head difference between Lake Michigan-Huron and Lake Erie based on recorded and interpolated data and on the project findings on the comparisons of the differences cannot be considered definitive.

5.6.4 Determining the Physical Effects of GIA

The Study also investigated the potential physical impacts of GIA on the head difference between Lake Michigan-Huron and Lake Erie over time. As noted earlier, the physical impacts describe physical changes resulting from GIA on actual lake levels (resulting in backwater effects), on the slope of the Lake Huron-Erie corridor, and on the volume of the Great Lakes over time, and as noted these would affect the head difference based on either the Lakeport-Buffalo or Harbor Beach-Cleveland plots equally.

Although absolute vertical movement due to GIA may be changing the relative vertical difference between 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 diagram 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. Since 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; however, the slope of their differences plot will remain the same.

However, the relative movement between key sites on the two lakes due to GIA may cause both backwater effects and changes to the gradient of the Lake Michigan-Huron to Lake Erie corridor. If the outlet of Lake Erie is rising with respect to the outlet of Lake Michigan-Huron over time due to GIA, then it would result in an actual increase in Lake Erie water levels relative to Lake Michigan-Huron. As a result, there would be a related backwater effect, which would cause the water level of Lake Michigan-Huron to increase proportionally. This in turn would offset a portion of the reduction in the head difference due to the increase in Lake Erie levels over time. Conversely, if the outlet of Lake Erie is falling with respect to the outlet of Lake Michigan-Huron over time due to GIA, this would represent an actual decline in Lake Michigan-Huron water levels. As a result, the effect is reversed, such that Lake Michigan-Huron water levels would be lowered, which would increase the reduction in head due to the decline in Lake Erie levels over time. Furthermore, if the gradient through the Lake Michigan-Huron to Lake Erie corridor is changing due to GIA it could have an effect on the discharge relationship of the St. Clair and Detroit Rivers. Specifically, an increase in gradient over time could cause the outflow of Lake Huron to also increase given the same water levels on the two lakes.

Figure 5-24 (Mainville and Craymer, 2005), provides a recent estimate of the vertical movement over the whole Great Lakes region. The contours in Figure 5-24 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 at Buffalo is rising at about 7 to 8 cm/century relative to the outlet of Lake Michigan-Huron, which is believed to be stable. Similarly, gradient changes due to GIA between Sarnia, Ontario-Port Huron, Michigan at the head of the St. Clair River and Bar Point, Ontario on Lake Erie seem to be negligible according to the contours in Figure 5-24. However, the contours provided in Figure 5-24 are estimates only, established by combining the results of a global postglacial rebound model and lake gauge-derived relative velocities, and as such are not definitive. Hence, one must exercise caution in using the velocities shown in Figure 5-24 at any one site or using them to determine the relative movement between sites on two different lakes (Mainville and Craymer, 2005). Therefore, it cannot be said for certain whether the outlet of Lake Michigan-Huron is moving in an absolute sense or how it is moving relative to Lake Erie, nor can it be determined with certainty how the two ends of Lake Erie are moving in an absolute sense or how they are moving relative to the outlet of Lake Michigan-Huron.

The use of satellite-based GPS positioning techniques is seen as the technology for determining the absolute velocities of the earth’s crust around the Great Lakes, and has the potential for allowing the accurate determination of absolute rates of vertical movement at points throughout the region and to estimate accurately the relative rates of movement between each of the Great Lakes as well as Lake St. Clair (Mainville and Craymer, 2005). However, based on the results of an experts’ workshop (Quinn and Southam, 2008a), at this point in time we are limited to estimating the relative movement between key locations on Lake Michigan-Huron and Lake Erie.
in order to estimate potential physical impacts of GIA on the change in their head difference over time.

**Figure 5-24**
Glacial Isostatic Adjustment in the Great Lakes Region

Based on a review of the range of published estimates presently available, a lower bound of -5 cm (-2 in) a century and an upper bound of +8 cm (3.1 in) a century were selected as an objective estimate for the range of relative movement of the outlet of Lake Erie with respect to Lake Michigan-Huron. Assuming a 40 percent backwater effect between Lake Erie and Lake Michigan-Huron, the estimated range would be about -2 to 3.2 cm (-0.8 in to 1.3 in) a century. This would mean that the impact of backwater from Lake Erie to Lake Michigan-Huron due to GIA could be offsetting as much as 1.4 cm (0.6 inches), or contributing up to 0.9 cm (0.4 inches) of the reduction in the head difference since 1962.

Considering the range in relative movement noted above and the relative movement between the two ends of Lake Erie as presented in Figure 5-23, it was suggested that investigators use one or more of their simulation models to test the sensitivity of St. Clair River discharge to a change in slope of at least this magnitude. The results of the simulations they carried out indicate that the impact of the possible small changes in slope that could have occurred since the dredging in 1962 would have a negligible effect on discharge over this time. As such, the potential impact of this physical impact of GIA on the Lake Michigan-Huron Lake Erie lake-to-lake fall as determined using Harbor Beach-Cleveland (or Lakeport-Buffalo) is considered negligible.
5.6.5 GIA Analysis for Several Stations

It is important to note that most of the stations measuring water levels around Lake Michigan-Huron and Lake Erie are subject to glacial isostatic adjustment. Some of the gauges are uplifting while others are subsiding. An analysis was carried out for several of the stations around the two lakes. Figure 5-25 illustrates the results. Based on four pairs of gauges, it appears that the Parry Sound, ON area is uplifting at a rate of 80.6 cm (31.7 in) a century with respect Cleveland, while difference between Milwaukee, WI and Buffalo is the shallowest at 16.3 cm (6.4 in) a century. When referring to the lake outlet at Lakeport, Parry Sound recorded water levels shows an uplift of approximately 11 cm (4.3 in) since 1962, while Milwaukee subsided by about 6 cm (2.4 in) in the same time. Therefore, any management decisions that are made in the Lake Superior Regulation component of the Study should consider these factors. For example, any climate change scenario that will show a drop in water levels will be exacerbated by the GIA impact in the Georgian Bay area.

![Figure 5-25](image_url)

Estimation of the Effect of Apparent GIA on Recorded Water Levels
PS – Parry Sound, B – Buffalo, CL – Cleveland, MilW - Milwaukee

5.6.6 Conclusions from GIA Analysis

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 with time due to the differential tilting of their lake basins. An analysis (Bruxer and Southam, 2008a) was undertaken to determine whether this effect of GIA on water balance and net basin supply calculations was significant and needed to
be addressed in terms of the Lake Michigan-Huron Lake Erie head difference. The results of this effort indicate that storage change because of GIA in the Great Lakes can be assumed negligible for water balance and net basin supply calculation purposes. Also, this physical impact of GIA would not affect the Lake Michigan-Huron Lake Erie head difference based on water level difference in elevations between Lake Michigan-Huron and Lake Erie unless the rates of movement at points around Lake Michigan-Huron relative to the lake’s outlet were to change enough to affect the redistribution of water over time, thus affecting the lake’s level at its outlet. If this were the case, the resulting impact on the head difference could be either an increase or a decrease depending on the changes that were experienced.

A review of relative movement trends between Lake Michigan-Huron water level gauges and the lake’s outlet (Bruxer and Southam, 2008b) indicates that the effect of the differential tilting of the Lake Michigan-Huron basin on the depth at its outlet is very small. Although 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, none of the changes is significant enough to have an impact on the head difference over time. Therefore, the potential impact of a change in storage on either Lake Michigan-Huron or Lake Erie due to GIA on the lake level difference determined using recorded water level data could be assumed negligible over both the short- and long-term.

### 5.7 Key Points

- The general conclusion of the St. Clair hydraulic regime investigations completed for the Study is that the conveyance in the St. Clair River has changed since the last navigational dredging project in 1962. This conclusion is supported by hydrometric data and hydraulic modelling analyses. Changes are seen in a number of reaches. Overall, the river channel seems to be deeper now than in 1971, and conveyance has generally increased.

- The increase in conveyance is estimated by hydraulic modelling to have caused Lake Michigan-Huron water levels to be lowered by 10 to 13 cm (3.9 to 5.1 in). In terms of discharge, the St. Clair River now can convey 250 to 275 m$^3$ (8,828 to 9,712 ft$^3$) a second more water than it could in 1971. This change in conveyance is attributed in this modelling solely to the different bathymetry data collected in 1971 in 2007. Using stage-fall-discharge equations, discharge in the St. Clair River is estimated to have increased by an average of about 180 m$^3$ (6,360 ft$^3$) a second, or about three percent (of annual flows) for the same water levels. Inverse modelling of the St. Clair River suggests that conveyance of the river has increased by about 5.8 percent between 1962 and 2007 or 319 m$^3$ (11,265 ft$^3$) a second if the mean annual discharge is taken as 5,500 m$^3$ (194,233 ft$^3$) a second. These individual estimates of conveyance change are all plausible; therefore the estimate of the size of the change in conveyance is 180 m$^3$ to 319 m$^3$ (6,357 ft$^3$ to 11,265 ft$^3$) a second.

- The timing of when the conveyance change occurred is difficult to state with certainty due to the deficiencies in measured discharge data. Stage-fall-discharge and hydraulic performance graphs show a change in the relationships between water levels and measured flows sometime in the early 1970s. Water level relationship analyses indicate changes may...
have occurred in the mid-1970s, mid- to late-1980s, and the late-1990s. Discharge measurement comparisons indicate changes may have occurred prior to the mid-1980s, though this cannot be said with certainty due to a lack of measured data available from 1985 to 1996. Hydraulic modelling analysis can only state that a change occurred some time between 1971 and 2007. The increased conveyance change seems to have stopped by around 2000. Hydraulic modelling shows that 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, and discharge decreasing of about 74 m$^3$ (2,613 m$^3$) a second. Inverse hydraulic modelling shows a decrease in conveyance of 4.2 percent or about 250 m$^3$ (8,829 ft$^3$) a second between 2002 and 2007.

- 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.

- Ice modelling on the St. Clair River quantified the possible effect of river ice on the conveyance of the river. The findings suggest that the “record St. Clair ice jam” of 1984 may have had a significant and long-term effect on the conveyance of the St. Clair River. However, a lack of flow and velocity measurement data during the 1984 ice jam event and in the years following makes it difficult to confirm this finding with certainty.

- Small scale, sub-surface features like deep sections of the river have little effect on conveyance in the river. Analyses of the water levels at gauge stations and inverse modelling on the St. Clair River indicate there have been conveyance changes in many, but not all, reaches of the river. Some of these changes indicate a positive change in conveyance over time, while others suggest a negative change. While helpful in identifying specific reaches of the St. Clair River where changes may have occurred, these analyses do not indicate how the overall conveyance has changed. The conveyance in the St. Clair River is not controlled by any one section of the river. It is a function of the conveyance capacity of the entire river, so channel changes anywhere along the river can change the conveyance of the river.

- Of the approximately 80 cm (31.5 in) drop in the lake-to-lake fall from about 2.9 m (9.5 ft) in 1860 to 1.9 m (6.2 ft) in 2006, the Study determined about 19 cm (7.5 in) is attributable to computation methods and apparent glacial isostatic adjustments in the recorded water levels at Harbor Beach on Lake Michigan-Huron and Cleveland on Lake Erie. The Study also endorsed the earlier work of using lake outlet gauges for computing relationships.

- For the 1962 to 2006 period, the glacial isostatic adjustment accounted for approximately 4 cm (1.6 in) or 17.4 percent of 23 cm (9 in) based on the regression line relationship. Depending upon the relative uplift or subsidence of the Buffalo gauge with respect to the Lakeport gauge on account of GIA could be offsetting as much as 1.4 cm (0.6 inches), or contributing up to 0.9 cm (0.4 inches) of the reduction in the head difference between Lake Michigan-Huron and Lake Erie head difference since 1962.