St. Clair River
Hydrodynamic Modelling Using RMA2
Phase 1 Report

Prepared for the
International Upper Great Lakes Study
St. Clair River Task Team
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1 Introduction

As part of the International Upper Great Lakes Study the Hydraulic Modelling Technical Working Group has been tasked with investigating changes in conveyance in the St. Clair River over time due to changes in channel geometry. This analysis is being conducted with the aid of a suite of hydrodynamic models, and this report outlines preliminary results obtained from one of these models, a two-dimensional RMA2 model.

2 Background

A two-dimensional hydrodynamic model of the St. Clair and Detroit River system was developed by the United States Geological Survey (USGS) and the United States Army Corps of Engineers (USACE) as part of a Source Water Assessment Program for the Michigan Department of Environmental Quality (MDEQ) (Holtschlag and Koschik, 2002). The model is an application of the Resource Management Associate’s two-dimensional, depth-averaged, finite element model, RMA2. The St. Clair – Detroit River application evaluates the water levels and two-dimensional velocities for the St. Clair River, Lake St. Clair and the Detroit River. The model utilizes bathymetry for the St. Clair and Detroit Rivers that was collected as part of the study in the year 2000. This model was extensively calibrated using measured water level, velocity and discharge data. The model is fully documented and can be accessed at the following url: http://mi.water.usgs.gov/pubs/WRIR/WRIR01-4236/.

A modified version of the model was adapted specifically for this study. Most model modifications were performed using the Surface-water Modelling System (SMS), which is a graphical user interface that can be used for pre- and post-processing of RMA2 models. The modifications made to the original model are outlined in the following section.

3 Model Modifications

3.1 Modifications Overview

The original RMA2 model of the St. Clair – Detroit River system was adapted for this project to determine the impact of channel changes on water levels and flows in the St. Clair River. The modifications made to the original model for this analysis are described, as well as their respective impacts on model performance. The modified model was compared to a range of observed water level and flow data as well as results for the same scenarios simulated by the original model. Water levels were simulated and compared to observed values at gauge stations located throughout the St. Clair River system (Fig. 3-1). The observed monthly average water level and flow values used as boundary conditions for this comparison are outlined in Table 3-1.
Figure 3-1: Location of water level gauges on St. Clair River.
Table 3-1: Observed average monthly values used for model verification.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Fort Gratiot WL (m)</th>
<th>St Clair Shores WL (m)</th>
<th>Lake Huron Outflow (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>8</td>
<td>177.34</td>
<td>175.89</td>
<td>6630</td>
</tr>
<tr>
<td>1995</td>
<td>10</td>
<td>176.38</td>
<td>175.08</td>
<td>5310</td>
</tr>
<tr>
<td>1997</td>
<td>9</td>
<td>177.09</td>
<td>175.68</td>
<td>6280</td>
</tr>
<tr>
<td>1998</td>
<td>5</td>
<td>176.86</td>
<td>175.63</td>
<td>5800</td>
</tr>
<tr>
<td>2001</td>
<td>4</td>
<td>175.79</td>
<td>174.74</td>
<td>4340</td>
</tr>
<tr>
<td>2004</td>
<td>7</td>
<td>176.34</td>
<td>175.15</td>
<td>5080</td>
</tr>
<tr>
<td>2006</td>
<td>6</td>
<td>176.11</td>
<td>175.00</td>
<td>4750</td>
</tr>
<tr>
<td>Min</td>
<td>4</td>
<td>175.79</td>
<td>174.74</td>
<td>4340</td>
</tr>
<tr>
<td>Max</td>
<td>10</td>
<td>177.34</td>
<td>175.89</td>
<td>6630</td>
</tr>
</tbody>
</table>

3.2 Unit Conversion

The model geometry was originally developed in the State Plane (Michigan South Zone 2113) projection using Imperial units. While the projection remained the same for this study, the units were converted to metric using the “Coordinate Conversion” function in the SMS software. In addition to converting the geometry file to metric units, a number of modifications had to be made to the boundary condition file during the conversion in order to maintain consistency. These modifications are listed below, and as expected, they did not impact model results:

- System International (SI) Card: Changed to metric units.
- Initial Conditions (IC) Card: Converted ELEV (average initial water surface elevation) and UNOM (nominal velocity for one-dimensional nodes at start-up) to metric.
- Peclet Method (PE) Card: Converted VPEC (initial guess for average elemental velocity (if Coldstart), or minimum velocity (if Hotstart)) to metric.
- Roughness with Depth (RD) Card: Converted depth at which vegetation affects roughness (RDD0) to metric. Also, changed maximum Manning’s roughness coefficient (RDR0) for each material type, depending on the value of the roughness with depth coefficient (RDCOEF). This was necessary due to the nature of the roughness with depth equation (Eq.3-1). When converted to metric, the average depth (AVEDEP) is multiplied by a conversion factor equal to 0.3048 m/foot. The first term of Equation 1 contains AVEDEP in the denominator, and so the term is divided by $0.3048^{RDCOEF}$. Since Manning’s $n$ is dimensionless, the first term in the metric form of the equation also had to be multiplied by $0.3048^{RDCOEF}$. A similar process is not necessary for the second term of the equation because the conversion factor cancels itself out in this term (ie. AVEDEP and RDD0 are both multiplied by the conversion factor).

$$NVALUE = \frac{RDR0}{AVEDEP^{RDCOEF}} + (RDRM \cdot e^{\frac{AVEDEP}{RDD0}})$$  \hspace{1cm} \text{(3-1)}
Where:

- **NVALUE** = Manning’s roughness coefficient
- **RDR0** = Maximum Manning’s roughness coefficient for non-vegetated water
- **AVEDEP** = Average water depth of element
- **RDCOEF** = Roughness with depth coefficient
- **RDRM** = Manning’s roughness coefficient for vegetated water
- **RDD0** = Depth at which roughness affects vegetation

- Boundary Conditions (BH and BQ) Cards: Converted all water level and flow boundary conditions to metric.

### 3.3 Downstream Boundary Modification

In addition to converting the original model units to metric, the downstream boundary of the model was moved from the outlet of the Detroit River to the approximate location of the St. Clair Shores gauge in Lake St. Clair. This modification was made to improve the computational efficiency of the model and to focus on the hydraulics of the St. Clair River. The modification was made in SMS by deleting all elements below the St. Clair Shores gauge (which included all of the Detroit River and a portion of Lake St. Clair) and then adding a number of elements manually back into the model to provide for a downstream boundary that runs uniformly across Lake St. Clair. A nodestring defining this downstream boundary was subsequently created at this location. The final extent of the model mesh is shown in Figure 3-2, in addition to the model boundary conditions.
Moving the downstream boundary to Lake St. Clair had minimal effect on the computed water levels. In most cases, the modified model more closely matched observed water levels at water level gauge locations on the St. Clair River than the original model due to the decreased distance from the water level boundary condition supplied at the downstream boundary of the model.

3.4 Increased Mesh Density

The original model mesh consisted mainly of quadrilateral elements with nodes spaced 150 metres apart in the stream-wise direction and 50 metres across the width of the channel (Fig 3-3). In order to better capture some of the detail in the channel bed surface, the density of the mesh was increased in the river portion of the model using the refine mesh tool in SMS. This had the effect of increasing the mesh density four-fold, as it divided each element in the original model into four, thus decreasing the node spacing to approximately 75 x 25 metres. The mesh density in Lake St. Clair was unchanged.

Figure 3-3: Example of model mesh density modifications. As can be seen here in the upper portion of the St. Clair River, the model mesh was increased from approximately 150 x 50 metres to 75 x 25 metres (streamwise x width) throughout the main channel.
Model simulations were run using both the original low density mesh and the modified increased density mesh and it was determined that increasing the mesh density had the most significant impact on model results of any of the modifications. Specifically, when mesh density was increased the model underestimated both the observed water levels and the water levels simulated by the original, lower density model. This difference was accounted for by modifying the model’s roughness parameters.

3.5 **Marsh Porosity**

The marsh porosity method was added and used in the modified model to aid in model convergence. The original RMA2 model used the elemental elimination method to deal with wetting and drying of model nodes. In this method, entire elements are temporarily removed from the model mesh when water levels at any given node on that element drop below a certain depth (usually specified as close to or equal to zero). Any inactive elements are again included in the mesh once the water level recovers to a point where the depth at all nodes forming the element are greater than the depth specified. During simulations of the modified model it was noted that when low water levels were specified as the downstream boundary condition, a large number of model elements in Lake St. Clair went dry, creating a “saw-toothed” shaped mesh in Lake St. Clair, which caused the model to become unstable.

The marsh porosity method option in RMA2 was utilized to allow the model to converge more easily. When the marsh porosity option is utilized, all nodes forming an element must be dry before that element is removed from the model calculations. The element remains active in the solution with decreased conveyance ability until such time as all nodes within the element become dry. This provides a more gradual transition between wetting and drying. Model simulations to evaluate the sensitivity of computed water levels to the use of the marsh porosity option showed that it had an insignificant effect on model results. With this option enabled, the model became more stable and was able to perform computations with the low water levels and flows required for this study.

3.6 **Chenal Ecarte**

The location of the bathymetry data collected in 2000 for Chenal Ecarte, a small distributary of the St. Clair River, did not coincide with the location of the boundaries of the model mesh at some locations when plotted together (Fig. 3-4). This is possibly due to the transient nature of the delta itself or georeferencing of hydrographic charts to create the original RMA2 model. For this application, the model mesh was modified to more closely reflect the path of the bathymetry data. A comparison of simulations showed that the effect on model results due to this modification was insignificant.
3.7 Adjustment of Modified Model Calibration Parameters

Simulations were executed to verify that the modified model results reproduced observed data and results simulated using the original, full-system model. The modified model, including all amendments outlined above, tended to underestimate the water levels simulated at gauges throughout the St. Clair River system. These discrepancies were primarily the result of increasing the mesh density.

The modified model’s parameters were adjusted to improve the match between computed and observed water levels in the system. The parameter in hydrodynamic modelling with the greatest influence on computed water levels and velocities is the roughness coefficient. Turbulence parameters, specified in this model using a Peclet number, have lesser influence and are adjusted to ensure model convergence rather than for calibration purposes. The Peclet number was held constant and only roughness values were adjusted in this re-calibration of the model. In the original St. Clair-Detroit RMA2 model, roughness values were assigned at 40 material zones specified throughout the model mesh. In addition, the roughness with depth option was used such that the
roughness coefficients vary depending on the water depth in the channel at each given element. The same method was utilized in this analysis.

The original model was extensively calibrated and validated against measured water levels, velocities, and discharges, including flow distributions around islands and through the St. Clair River delta. To preserve these attributes of the model, Manning’s roughness coefficients in all material zones in the modified model were increased by the same relative amounts and compared to results from the original model.

Roughness coefficients were increased by two, three, four, and five percent for all material zones. Simulations were executed using the modified model coefficients for each of the scenarios defined in Table 3-1. Results of these simulations were compared to observed water levels at monitoring stations in Canada and the U.S. on the St. Clair River. It was determined that by increasing the Manning’s roughness coefficients by three-percent the simulated results most closely matched the observed values as defined by the sum of the square errors at all gauges (Table 3-2). Furthermore, the modified model with increased mesh density performed as well as or better than the model before mesh density was increased.

Table 3-2: Summary of model calibration simulation results.

<table>
<thead>
<tr>
<th>Observed – Simulated WL (m)</th>
<th>Modified High Density Mesh</th>
<th>Low Density Mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Error</td>
<td>0.122</td>
<td>0.092</td>
</tr>
<tr>
<td>Min Error</td>
<td>-0.065</td>
<td>-0.071</td>
</tr>
<tr>
<td>Average Error</td>
<td>0.030</td>
<td>0.009</td>
</tr>
<tr>
<td>Sum Error</td>
<td>1.876</td>
<td>0.545</td>
</tr>
<tr>
<td>Sum Sq. Error</td>
<td>0.170</td>
<td>0.082</td>
</tr>
</tbody>
</table>

4 Conveyance Analysis Methodology

4.1 Model Geometry

The purpose of this study was to determine whether changes in conveyance in the St. Clair River have occurred over time due to changes in the channel geometry. This was accomplished by inputting bathymetric (sounding) data collected in the St. Clair River in 1971, 2000, 2002, 2005, 2006 and 2007 into the modified RMA2 model, executing the different models under various hydrologic conditions, and noting any changes in simulated water level. A decrease in water level simulated by the different models for the same discharge value infers an increase in conveyance in the channel between these model years.

The bathymetry datasets for each of the different years were interpolated to the modified model mesh using SMS. One assumption made in this analysis was that the calibration parameters remain unchanged over time and these were therefore held
constant for the conveyance analysis. The only change made to the modified model in this analysis was that for each year the bed elevations at each of the model mesh nodes were interpolated from the respective bathymetry dataset. The models for each year were not recalibrated, and there was no attempt to quantify how well any of these models accurately represent observed water level and flow data for that year. This was by design, because with all other variables remaining constant the impacts of volumetric changes in the bed surface alone could be determined.

Bathymetry datasets were available for the years of 1971, 2000, 2002, 2005, 2006 and 2007. However, significant differences exist between the datasets in terms of data extent, collection methodology, density and uncertainty. A full explanation of these differences is beyond the scope of this project but will be addressed to a large extent by Bennion (2008) in a separate project for the International Upper Great Lakes Study.

These differences do have a significant impact 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. The transects themselves are spaced along the St. Clair River approximately 100 metres apart or greater, and the soundings in these transects are spaced approximately 20 metres apart or greater across the channel. The 2007 data, on the other hand, is high-density, multi-beam data, with soundings reported on a 1.5 by 1.5 metre grid. A summary of the differences in the various datasets is given in Table 4-1.

Table 4-1: Summary of Bathymetric Datasets Used in Modelling Analysis

<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 or greater</td>
<td>~20 m 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 or greater</td>
<td>~7.5 m 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</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</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</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</td>
<td>Fort Gratiot to Algonac</td>
</tr>
</tbody>
</table>

The RMA2 model uses a discretized finite element mesh to define the channel geometry. The bathymetry datasets for each year were interpolated to the RMA2 model mesh nodes using linear interpolation in SMS. The differences in the bathymetric datasets must therefore be closely considered when interpreting model results, since any differences in the results could be a reflection of the differences in the type of bathymetry data, rather than a difference in the channel geometry itself.

To assess these effects quantitatively, two additional bathymetry datasets were created, interpolated and evaluated using the RMA2 model. Two “simulated single-
“beam” datasets were created using a continuous surface 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. To create these datasets, each actual data point collected in the 1971 and 2000 datasets, respectively, were given an elevation value interpolated directly from the 2007 continuous surface at the same point. The 2007 surface overlaid with the 1971 data points is shown in Figure 4-1. Any points from 1971 or 2000 located beyond the extent of the 2007 data were given the same elevation they had 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.

Figure 4-1: 2007 surface overlaid with 1971 data points.
In addition to differences in bathymetric data density, the extent of the different datasets also varies. For instance, the 2000 single-beam data was collected for the entire St. Clair River, from Fort Gratiot to Lake St. Clair, including the delta. The 1971 single-beam and 2007 multi-beam datasets were collected for the main river only, from Fort Gratiot to approximately Algonac, and neither includes the St. Clair delta. Multi-beam bathymetry for 2002, 2005 and 2006 was collected only in the upper St. Clair River, from approximately Fort Gratiot to just below the Black River.

It was necessary to supplement the bathymetry data for the St. Clair River for certain years with data from other sources to complete this hydrodynamic modelling analysis. For example, the 1971 and 2007 models use the 1971 or 2007 data, respectively, for the main river channel from Fort Gratiot to Algonac. Since these datasets do not include data for the St. Clair delta, data for the delta collected in 2000 was supplemented in each of these models. Similarly, the 2002, 2005 and 2006 models use data from these years, where available, supplemented with 2000 data in the areas outside of the respective 2002, 2005 and 2006 data extents, including the delta. Gridded bathymetry data for Lake St. Clair obtained from the National Oceanic and Atmospheric Administration (NOAA) (http://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html) was used in all models. A summary of the datasets used for each of the different models is shown in Table 4-2.

Table 4-2: Summary of Bathymetric Dataset combinations used for each model.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Main Channel</th>
<th>Upper River</th>
<th>St. Clair Delta</th>
<th>Lake St. Clair</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>1971</td>
<td>N/A</td>
<td>2000</td>
<td>NOAA Gridded Data</td>
</tr>
<tr>
<td>2000</td>
<td>2000</td>
<td>N/A</td>
<td>2000</td>
<td>NOAA Gridded Data</td>
</tr>
<tr>
<td>2007</td>
<td>2007</td>
<td>N/A</td>
<td>2000</td>
<td>NOAA Gridded Data</td>
</tr>
<tr>
<td>2007 SimSB 00**</td>
<td>2007 interpolated to 2000 single-beam data points within 2007 data extent; 1971 outside 2007 extent</td>
<td>N/A</td>
<td>2000</td>
<td>NOAA Gridded Data</td>
</tr>
</tbody>
</table>

* 2007 Simulated Single-Beam at points collected in 1971
** 2007 Simulated Single-Beam at points collected in 2000

An additional dataset was used for each model to define the near-shore areas of the channel. Bathymetry data in the near-shore areas is typically not collected in hydrographic surveys due to limitations resulting from the shallow water depths in these areas. Since bathymetric data is collected from a boat, portions of the channel that are too shallow to navigate with the survey vessel are missed. Hydrographic surveys are usually performed to create hydrographic charts for the purpose of navigation. For this
modelling analysis, a shoreline file with an elevation of Low Water Datum (International Great Lakes Datum 1985) minus one metre was created with points spaced 15 metres apart and used to create the model grids. Low Water Datum minus one metre was utilized in order to limit wetting and drying issues in the RMA2 model. This assumption was kept constant for all of the different models used in this analysis. This assumption will be quantitatively evaluated in subsequent work as part of the model sensitivity analysis.

4.2 Boundary Conditions

A full range of water levels and flows were utilized as boundary conditions to determine if changes in conveyance have occurred. The boundary conditions used were water level at the downstream boundary (Lake St. Clair) and discharge at the upstream boundary (Lake Huron at Fort Gratiot). The boundary conditions used are shown in Table 4-3. These values were determined from average monthly water level and flow values from 1962-1999 (which represents post-dredging to the last available coordinated flow value) for the months of May to November (which represents the ice-free season) as recommended by the Data Verification and Reconciliation Technical Working Group of the International Upper Great Lakes Study. The average water level and discharge values were determined from this dataset (identifier ‘F’ and ‘6’, respectively), and the maximum and minimum values were specified as the average plus and minus two times the standard deviation, respectively (i.e. the water level and flow at the 5- and 95-percent exceedance probability). This range was then divided into 11 evenly spaced values so that a full range of expected values could be tested. Each water level condition was run with each discharge value, and each hydrologic scenario was identified by the corresponding letter and number. The models were simulated in unsteady state mode, but using constant water level and flow values, and were run using an hourly time step for a period of time that was long enough to reach steady state conditions (six hours).

<table>
<thead>
<tr>
<th>Discharge Identifier</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6 (Avg.)</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge (m³/s)</td>
<td>4720</td>
<td>4912</td>
<td>5104</td>
<td>5296</td>
<td>5488</td>
<td>5680</td>
<td>5872</td>
<td>6064</td>
<td>6256</td>
<td>6448</td>
<td>6640</td>
</tr>
<tr>
<td>Water Level Identifier</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F (Avg.)</td>
<td>G</td>
<td>H</td>
<td>I</td>
<td>J</td>
<td>K</td>
</tr>
<tr>
<td>Water Level (m)</td>
<td>174.63</td>
<td>174.76</td>
<td>174.89</td>
<td>175.03</td>
<td>175.16</td>
<td>175.29</td>
<td>175.43</td>
<td>175.56</td>
<td>175.69</td>
<td>175.82</td>
<td>175.96</td>
</tr>
</tbody>
</table>

5 Results

5.1 Changes in Water Level

Each of the different models developed for each of the years when bathymetric data existed were simulated for all combinations of downstream water level and upstream
discharge boundary conditions. The water level at each gauge station computed by each model was then compared. Table 5-1 shows an example of the results simulated by each model for average water level and discharge conditions. Figure 5-1 shows a plot of these same results. The results show that the computed water level at gauging stations throughout the river decreases substantially from 1971 to 2000. For example, the observed drop is 0.16 metres at Fort Gratiot when the 1971 and 2000 models are compared. From 2000 until 2006, the simulated water level remains fairly steady, with a maximum drop of only 0.03 metres between any of the years 2000 through 2006. The 2007 model, however, again shows a relatively large drop of 0.05 metres when compared to the 2006 model, or 0.07 metres when compared to the 2000 model. This corresponds to a difference of 0.23 metres between the 1971 and 2007 models under average boundary conditions.

Table 5-1: Simulated water level at St. Clair River gauge stations for each model using average water level and discharge boundary conditions.

<table>
<thead>
<tr>
<th>Gauge Location</th>
<th>Simulated Water Level (m)</th>
<th>1971</th>
<th>2000</th>
<th>2002</th>
<th>2005</th>
<th>2006</th>
<th>2007 SimSB71</th>
<th>2007 SimSB00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node</td>
<td>Name</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>68937</td>
<td>Fort Gratiot</td>
<td>176.85</td>
<td>176.69</td>
<td>176.67</td>
<td>176.66</td>
<td>176.67</td>
<td>176.62</td>
<td>176.73</td>
</tr>
<tr>
<td>68565</td>
<td>Dunn Paper</td>
<td>176.68</td>
<td>176.50</td>
<td>176.49</td>
<td>176.49</td>
<td>176.45</td>
<td>176.45</td>
<td>176.56</td>
</tr>
<tr>
<td>67190</td>
<td>Point Edward</td>
<td>176.61</td>
<td>176.44</td>
<td>176.44</td>
<td>176.44</td>
<td>176.40</td>
<td>176.40</td>
<td>176.49</td>
</tr>
<tr>
<td>63965</td>
<td>M. Black River</td>
<td>176.49</td>
<td>176.35</td>
<td>176.35</td>
<td>176.35</td>
<td>176.32</td>
<td>176.32</td>
<td>176.39</td>
</tr>
<tr>
<td>60922</td>
<td>Dry Dock</td>
<td>176.31</td>
<td>176.19</td>
<td>176.19</td>
<td>176.19</td>
<td>176.19</td>
<td>176.16</td>
<td>176.22</td>
</tr>
<tr>
<td>46619</td>
<td>St. Clair SP</td>
<td>175.94</td>
<td>175.89</td>
<td>175.89</td>
<td>175.89</td>
<td>175.87</td>
<td>175.87</td>
<td>175.90</td>
</tr>
<tr>
<td>28744</td>
<td>Port Lambton</td>
<td>175.49</td>
<td>175.48</td>
<td>175.48</td>
<td>175.48</td>
<td>175.48</td>
<td>175.48</td>
<td>175.49</td>
</tr>
<tr>
<td>23238</td>
<td>Algonac</td>
<td>175.45</td>
<td>175.45</td>
<td>175.45</td>
<td>175.45</td>
<td>175.45</td>
<td>175.45</td>
<td>175.45</td>
</tr>
<tr>
<td>274</td>
<td>St.Clair Shores</td>
<td>175.29</td>
<td>175.29</td>
<td>175.29</td>
<td>175.29</td>
<td>175.29</td>
<td>175.29</td>
<td>175.29</td>
</tr>
</tbody>
</table>

Figure 5-1: Simulated water level at St. Clair River gauge stations for each model using average water level and discharge boundary conditions.

![Figure 5-1: Simulated water level at St. Clair River gauges for various years.](image-url)
The 2002, 2005 and 2006 bathymetry datasets only extend from Fort Gratiot to just below the Black River. These datasets were supplemented with 2000 bathymetry data to create the model geometry for these years. Results from these models showed only minor differences in simulated water level, regardless of the boundary conditions used. The maximum difference in water level observed for all scenarios between any of these years was 0.02 metres at Fort Gratiot. No trend can be seen in the results, and any differences between models are likely the result of differences in the extents of the datasets. Furthermore, the differences are likely within the range of uncertainty of the models themselves.

Results from the full models (i.e. 1971, 2000 and 2007) were similar regardless of the boundary condition scenarios used. That is, a drop in simulated water level from 1971 to 2000 and to 2007 was observed. The scenario showing the greatest difference occurred when the maximum discharge of 6640 m$^3$/s was combined with the lowest Lake St. Clair water level of 174.63 metres (this combination will create the highest gradient). Using these boundary conditions the difference in water level simulated at Fort Gratiot was 0.21 metres between 1971 and 2000, and 0.30 metres between 1971 and 2007. A selected summary of results for water levels simulated at Fort Gratiot using various boundary conditions is shown in Table 5-2. From this table it can be seen that the water level difference between 1971 and 2007 ranges from 0.15 metres to 0.30 metres, depending on the boundary conditions used.

Table 5-2: Summary of simulated water levels at Fort Gratiot under selected boundary conditions.

<table>
<thead>
<tr>
<th>Boundary Conditions</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge (m$^3$/s)</td>
<td>St. Clair Shores Water Level (m)</td>
<td></td>
</tr>
<tr>
<td>4720</td>
<td>174.63</td>
<td>176.08</td>
</tr>
<tr>
<td>4720</td>
<td>175.29</td>
<td>176.45</td>
</tr>
<tr>
<td>4720</td>
<td>175.96</td>
<td>176.90</td>
</tr>
<tr>
<td>5680</td>
<td>174.63</td>
<td>176.54</td>
</tr>
<tr>
<td>5680</td>
<td>175.29</td>
<td>176.85</td>
</tr>
<tr>
<td>5680</td>
<td>175.96</td>
<td>177.24</td>
</tr>
<tr>
<td>6640</td>
<td>174.63</td>
<td>177.01</td>
</tr>
<tr>
<td>6640</td>
<td>175.29</td>
<td>177.27</td>
</tr>
<tr>
<td>6640</td>
<td>175.96</td>
<td>177.61</td>
</tr>
</tbody>
</table>

5.2 Effect of Bathymetric Data Density

The effect of the density of the bathymetric datasets was evaluated next. As previously noted, the bathymetric datasets differ in terms of data type, collection method, density and extent. In order to make a true comparison of the effects of the bathymetry data on channel conveyance over time, the 1971 and 2000 single-beam datasets were compared to two simulated single-beam datasets created from the 2007 multi-beam bathymetry data. That is, one 2007 dataset was simulated at the same points as were
collected in 1971, the other 2007 dataset was simulated at the same points as were collected in 2000.

Simulated water levels for the 2007 simulated single-beam models showed significant differences when compared to the 2007 multi-beam model. Figures 5-2 and 5-3 show comparisons of plotted water surface profiles for the 1971 and 2000 models, respectively, versus the original 2007 model and the 2007 simulated single-beam models for each year. Figure 5-2 shows that the water levels simulated for the 1971 model are higher than the water levels simulated for both of the other 2007 models; however, the 2007 simulated single-beam model shows less difference than does the original high-density model. The difference between 1971 and 2007 of 0.23 metres is reduced to 0.12 metres when models of the same bathymetric data density are compared.

Figure 5-2: Water surface profile comparison (1971 vs. 2007 vs. 2007 simulated single-beam at 1971)

Similarly, Figure 5-3 shows that the water levels simulated for the 2000 model are higher than those simulated by the original 2007 model; however, when the 2007 simulated single-beam model for the year 2000 is used, an increase in water level of 0.03 metres is observed, as opposed to a decrease of 0.07 metres observed when the 2000 model is compared to the original 2007 multi-beam model.

Therefore, some of the changes in water level observed over time can be attributed to the density of the bathymetry data used, rather than just volumetric changes in the channel geometry itself. A selected summary of results for water levels simulated at Fort Gratiot using the 1971, 2000 and 2007 simulated single-beam models for various boundary conditions is shown in Table 5-3.
Figure 5-3: Water surface profile comparison (2000 vs. 2007 vs. 2007 simulated single-beam at 2000)

Table 5-3: Comparison of 1971 and 2000 models to 2007 simulated single-beam models.

<table>
<thead>
<tr>
<th>Boundary Conditions</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
<th>Difference (m)</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge (m³/s)</td>
<td>St. Clair Shores Water Level (m)</td>
<td>2007 (Sim SB 1971)</td>
<td>2007-2007 (SSB71)</td>
<td>2000</td>
</tr>
<tr>
<td>4720</td>
<td>174.63</td>
<td>176.08</td>
<td>175.96</td>
<td>0.12</td>
</tr>
<tr>
<td>4720</td>
<td>175.29</td>
<td>176.45</td>
<td>176.35</td>
<td>0.10</td>
</tr>
<tr>
<td>4720</td>
<td>175.96</td>
<td>176.90</td>
<td>176.82</td>
<td>0.08</td>
</tr>
<tr>
<td>5680</td>
<td>174.63</td>
<td>176.54</td>
<td>176.40</td>
<td>0.12</td>
</tr>
<tr>
<td>5680</td>
<td>175.29</td>
<td>176.85</td>
<td>176.73</td>
<td>0.12</td>
</tr>
<tr>
<td>5680</td>
<td>175.96</td>
<td>177.24</td>
<td>177.14</td>
<td>0.10</td>
</tr>
<tr>
<td>6640</td>
<td>174.63</td>
<td>177.01</td>
<td>176.85</td>
<td>0.16</td>
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<tr>
<td>6640</td>
<td>175.29</td>
<td>177.27</td>
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<td>0.14</td>
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<tr>
<td>6640</td>
<td>175.96</td>
<td>177.61</td>
<td>177.49</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 5-4 shows a summary of the differences between models created with the high-density multi-beam bathymetry data, and those created with the low-density single-beam data. When the 1971 model is compared to the 2007 simulated single-beam model for 1971, the maximum difference observed is 0.16 metres, which occurred when the maximum discharge and minimum downstream water level were specified as boundary conditions. This corresponds to a 0.14 metre decrease in the difference as compared to the earlier estimate of 0.30 metres when the 1971 model was compared to the original 2007 multi-beam model (a result of different bathymetric data densities). Furthermore, when comparing the 2000 model to the 2007 simulated single-beam model for 2000, the maximum difference observed is negative 0.04 metres (i.e. the 2007 water level is higher than the 2000 water level, and therefore there is an observed decrease in conveyance), which also occurred when the maximum discharge and minimum downstream water level were chosen as boundary conditions. This corresponds to a 0.13 metre decrease and a
reverse in sign of the difference as compared to the earlier estimate of 0.09 metres when the 2000 model was compared to the original 2007 multi-beam model.

Table 5-4: Summary of differences between models created with bathymetry data of varying density.

<table>
<thead>
<tr>
<th>Model</th>
<th>Maximum Difference in Fort Gratiot Water Level (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vs. 2007 multi-beam model</td>
<td>vs. 2007 simulated single-beam model</td>
</tr>
<tr>
<td>1971</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>2000</td>
<td>0.09</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

These results indicate that the bathymetry data type and density have a significant effect on model results. Additional evidence of this effect is shown by the fact that the two 2007 simulated single-beam models give similar results to each other, but not to the multi-beam model for 2007. The water levels simulated by the lower density models show consistently higher water levels than those simulated by the models prepared with higher density data. Therefore, water levels simulated by the 1971 and 2000 models are overestimated when compared to water levels simulated by the original 2007 multi-beam model. It follows that the apparent increase in conveyance between 1971 and 2000 and 2007 is also overestimated.

5.3 Water Surface Profiles

Water surface profiles generated for the 1971, 2000 and original 2007 models under average boundary conditions are shown in Figure 5-4. These profiles indicate that the water levels begin to diverge just upstream of the Lake St. Clair delta, and continue to diverge progressively moving up the main river channel. Figure 5-5 shows the difference between water surface profiles simulated by the different models. If a certain section of the river channel were to cause less divergence of the water surface profile than another section (i.e. if the geometry at a certain section of the river caused less change in conveyance than at another section), the slope of the difference plot at the similar section would be less steep than the sections where greater changes in conveyance have taken place. In general, the slopes of the difference plots tend to be constant, with only relatively minor flatter areas or steeper areas. The 2000-2007 differences show a steep jump upstream of Black River; however, this is again likely a result of the differences in bathymetry data density, since the same effect is not reflected in the comparison of the 2000 vs. 2007 simulated single-beam for this year. These plots indicate that the changes in conveyance observed are a result of changes in channel geometry throughout the channel, rather than changes in geometry in any particular area.

Also of note is the higher scatter in the upper portion of the St. Clair River, upstream of Black River. The higher scatter indicates that the channel geometry at this part of the channel itself may be more variable for the different years than in other sections of the channel. This should be investigated in future work. Regardless, a linear trend line drawn through various sections of the plot of differences between 1971 and the
2007 simulated single-beam for this year show that the slope remains fairly constant for all years (Fig. 5-6), again indicating that the observed changes in conveyance are a result of changes throughout the channel, rather than the result of changes in any particular section.

**Figure 5-4:** Water surface profiles generated for the 1971, 2000 and original 2007 models under average boundary conditions.

**Figure 5-5:** Difference between water surface profiles generated for various years.
5.4 Cut and Fill Analysis

A subset of cut and fill scenarios were also tested in order to determine how changes in the bed surface in the upper portion of the channel (upstream of Black River) would affect water levels throughout the St. Clair River. A number of possible scour holes were “filled” and deposition areas were “cut” in these scenarios to the approximate bed surface elevation of the surrounding areas. In this way, the effect of these different features could be tested. The scenarios are described in Table 5-5 and illustrated in Figure 5-7. Table 5-6 shows results from these scenarios. Results showed only minor differences (maximum difference of less than 0.01 metres) between any of the scenarios tested, indicating that these minor features have little effect on conveyance in the St. Clair River.

Table 5-5: Description of cut and fill scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fill</td>
<td>All nodes in polygon 1 raised to elevation 160 m</td>
</tr>
<tr>
<td>B</td>
<td>Cut</td>
<td>All nodes in polygon 2 lowered to elevation 162.5 m</td>
</tr>
<tr>
<td>C</td>
<td>Both</td>
<td>Scenario A + Scenario B</td>
</tr>
<tr>
<td>D</td>
<td>Both</td>
<td>Scenario C + all nodes in polygon 3 lowered to elevation 163.5 m, all nodes in polygon 4 raised to 162.5 m</td>
</tr>
</tbody>
</table>
Table 5-6: Results of cut and fill scenarios

<table>
<thead>
<tr>
<th>Gauge Location</th>
<th>Simulated Water Level (m)</th>
<th>Max Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenaria A</td>
<td>Scenaria B</td>
</tr>
<tr>
<td>Node 68937 Fort Gratiot</td>
<td>176.625</td>
<td>176.622</td>
</tr>
<tr>
<td>Node 68565 Dunn Paper</td>
<td>176.451</td>
<td>176.447</td>
</tr>
<tr>
<td>Node 67190 Point Edward</td>
<td>176.398</td>
<td>176.400</td>
</tr>
<tr>
<td>Node 63965 M. of Black River</td>
<td>176.315</td>
<td>176.315</td>
</tr>
<tr>
<td>Node 60922 Dry Dock</td>
<td>176.157</td>
<td>176.157</td>
</tr>
<tr>
<td>Node 46619 St. Clair SP</td>
<td>175.869</td>
<td>175.869</td>
</tr>
<tr>
<td>Node 28744 Port Lambton</td>
<td>175.480</td>
<td>175.480</td>
</tr>
<tr>
<td>Node 23238 Algonac</td>
<td>175.448</td>
<td>175.448</td>
</tr>
<tr>
<td>Node 274 St. Clair Shores</td>
<td>175.290</td>
<td>175.290</td>
</tr>
</tbody>
</table>

6 Conclusions

Model results showed an increase in conveyance from 1971 to 2007 as inferred from a decrease in water level between these years for the same discharge value. Depending on the boundary conditions chosen, the water level of Lake Huron simulated by the 1971 model was 0.10 to 0.21 metres higher than the water level simulated by the
2000 model, and 0.15 to 0.30 metres higher than the water level simulated by the 2007 multi-beam model. However, when compared to the 2007 simulated single-beam models, the difference between 1971 and 2007 decreases significantly. The simulated single-beam models created for 2007 show a decrease in Lake Huron water level of between 0.08 metres and 0.16 metres compared to 1971, and show an increase in Lake Huron water level of 0.02 to 0.04 metres when compared to 2000. This indicates that the bathymetry data density has a significant effect on model results, which should be considered in any future work.

There are only minor differences in model results simulated by the models from the years 2000 to 2007. Differences in computed water surface profiles between the 2002, 2005 and 2006 models were negligible. Furthermore, there does not appear to be any trend in even the minor differences from these years. Comparison of the 2000 model to the 2007 multi-beam and the 2007 simulated single-beam model showed mixed results. Therefore, it is evident that if changes in conveyance have occurred between 1971 and 2000, these do not appear to have continued since 2000.

Lastly, water surface profiles indicate that the change in conveyance is a result of changes in channel geometry occurring throughout the river, and not in any specific location.

7 Recommendations

It is recommended that further investigations be carried out with regard to a number of issues.

First, in this study changes in conveyance in the St. Clair River over time were inferred from changes in water level. Further analysis should more directly address the conveyance question by determining specifically how discharge in the St. Clair River has changed over time. This could be done with the use of Hydraulic Performance Graphs relating discharge to water level of both Lake St. Clair and Lake Huron for the scenarios tested, and interpolating discharge values from these.

In addition, detailed uncertainty analysis should be conducted on the model results. There are numerous sources of uncertainty in hydrodynamic modelling. Many of the decisions and assumptions made in building and calibrating the RMA2 model have an effect on model results, and could therefore influence predictions of changes in conveyance inferred from changes in water level in the St. Clair River over time. Examples include the choice of roughness coefficients, the choice of shoreline elevation, etc. Additionally, uncertainty in the model inputs such as the bathymetry data and boundary conditions themselves can translate into uncertainty in the model results as well. By documenting the sources of uncertainty and testing their effect on model results, a qualified or probabilistic answer can be given regarding the degree of accuracy of the predicted changes in water level and conveyance in the St. Clair River system over time.
Lastly, further effort should be devoted to the effect of varying data densities on model results. Additional investigation should also be conducted to more specifically identify those areas of the St. Clair River that have the greatest effect on conveyance changes.

8 References


St. Clair River
Hydrodynamic Modelling Using RMA2
Phase 2 Report

Prepared for the
International Upper Great Lakes Study
St. Clair River Task Team
By
Jacob Bruxer
Aaron Thompson, P.Eng.

Environment Canada
November 2008
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1. Introduction

Changes in conveyance in the St. Clair River over time as a result of changes in channel bathymetry were investigated using a two-dimensional RMA2 model in Phase 1 of this project (Bruxer and Thompson, 2008). The RMA2 model was used to simulate the water level of Lake Huron for a number of years where bathymetric data was available. This included the years 1971, 2000 and 2007, for which bathymetric data was collected along the full length of the river. These bathymetry datasets were used to generate separate model geometries of the St. Clair River. All other model parameters were kept constant during model simulations. The water level at Lake St. Clair was used as the downstream boundary condition and Lake Huron outflow was used as the upstream boundary condition. Changes in conveyance resulting from changes in bathymetry alone were then inferred from changes in simulated Lake Huron water level.

The results of Phase 1 indicated that, given average boundary conditions, the simulated water level at Fort Gratiot on Lake Huron had decreased from 1971 until 2007 by approximately 12 centimetres when bathymetric data of the same density was used. From this it can be inferred that, assuming all other parameters have remained constant, the conveyance of the St. Clair River has increased during this time due to changes in channel geometry. Conversely, the results also showed that the water level had increased by three centimetres from 2000 until 2007 when bathymetric data of the same density was used, indicating that conveyance has decreased since 2000.

Phase 2 of this project is composed of two parts. First, the results of the St. Clair River two-dimensional RMA2 modelling are expanded upon to include changes in conveyance as a function of changes in discharge over time. In Phase 1, the changes in conveyance were inferred from changes in upstream water level, which was simulated using the RMA2 models for the different years with the same downstream water level and the same upstream discharge values used as boundary conditions. In this report, changes in conveyance are instead inferred from changes in discharge over the same time periods. This was done using Hydraulic Performance Graphs (HPGs) and average water levels of Lake St. Clair and Lake Huron.

The second part of Phase 2 involved performing an uncertainty analysis on the model geometries. Bathymetric uncertainty is a function of both survey error and interpolation error. A Monte Carlo analysis was performed on the bathymetric data and the model geometries to determine how uncertainty in the bathymetric data translates into uncertainty in the simulated Lake Huron water level and changes in conveyance over time. Whereas Phase 1 provided a deterministic estimate of conveyance changes in the St. Clair River, Phase 2 provides a more robust, probabilistic answer to the question of whether conveyance has changed and by how much, including the uncertainty of this estimate.
2. Conveyance Change as a Function of Discharge

The RMA2 model boundary conditions used in Phase 1 of the project included discharge as the upstream boundary and water level of Lake St. Clair as the downstream boundary. The model was then used to simulate the water level at Fort Gratiot on Lake Huron, and changes in this simulated level over time were used to infer changes in conveyance as a function of upstream water level.

The results from Phase 1 are shown in Table 2-1. One of the key findings was that the density of the bathymetric data was an important factor and differences in bathymetric data density could significantly affect model results. The 1971 and 2000 bathymetric datasets are low-density, single-beam data, whereas the 2007 dataset is high-density, multi-beam data. Due to these differences in data density the results from each model can not be compared directly.

To overcome this discrepancy, two additional 2007 models were created by interpolating elevation values from the 2007 multi-beam data onto the geographic locations of both the 1971 and the 2000 data separately. This in effect created two simulated single-beam (SSB) models. The “2007SSB71” model represents the 2007 data interpolated to 1971 locations, and similarly the “2007SSB00” model represents the 2007 data interpolated to 2000 locations.

To avoid issues with differing data densities, only two direct comparisons can be made: the 1971 and 2007SSB71 can be compared, as can the 2000 and 2007SSB00 models. Under average boundary conditions, results showed that the simulated water level had decreased by 12 centimetres from 1971 to 2007, but had increased by three centimetres from 2000 to 2007, indicating that the conveyance has increased from 1971 until present time, but since 2000 this increase has stopped or possibly even reversed.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Simulated Water Level (m) (Avg. Boundary Conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>176.85</td>
</tr>
<tr>
<td>2000</td>
<td>176.69</td>
</tr>
<tr>
<td>2007</td>
<td>176.62</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>176.73</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>176.72</td>
</tr>
<tr>
<td>Difference</td>
<td></td>
</tr>
<tr>
<td>1971-2007SSB71</td>
<td>0.12</td>
</tr>
<tr>
<td>2000-2007SSB00</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

Table 2-1: Simulated water level at Fort Gratiot under average boundary conditions.

The change in conveyance can also be estimated in terms of a change in discharge over time. In order to determine the change in conveyance as a function of the change in discharge, the upstream and downstream water level must be kept constant for all model runs for the various years. The RMA2 model can theoretically be run with water level as
both the upstream and downstream boundaries, but instability in the model solution often causes the model to fail before converging on a solution. In order to overcome this issue and provide an estimate of the changes in conveyance as a function of changes in discharge over time, Hydraulic Performance Graphs (HPGs) were used.

HPGs provide a tool for describing and visualizing the backwater profiles of a given river channel under a full range of hydraulic conditions (González-Castro and Ansar, 2003). Once developed, HPGs allow for the efficient estimation of discharge in a channel given an upstream and downstream water level. The RMA2 model becomes unstable when run at the most extreme water level conditions, which are required to create a full HPG as described by González-Castro and Ansar. In particular, the model becomes unstable as critical flow is approached. However, for the St. Clair River such a scenario is unrealistic, and estimates of discharge under these conditions were not required for the purposes of this study. Instead, partial HPGs were developed for each year by simulating each model over a full range of realistic water level and discharge conditions. This required more than 120 model simulations to produce HPGs for each model year.

An example of the HPGs produced is shown for 1971 in Figure 2-1. As described by González-Castro and Ansar, the zero flow line represents the state when the upstream water level is equal to the downstream water level. At such a state zero flow would occur, although in the case of the St. Clair River such a scenario would be unrealistic. The discharge for a given upstream and downstream water level can be interpolated directly from these graphs and compared in order to infer changes in conveyance over time as a function of discharge. Quadratic interpolation was used to estimate the discharge under average water level conditions for each year from each of the respective HPGs. The accuracy of the interpolated discharge values was also checked by running the model with the interpolated discharge and downstream water level as boundary conditions, and comparing the simulated upstream water level to the average.

Figure 2-2 shows a comparison of the HPGs produced for the 1971 and the 2007 simulated single-beam (SSB) models. The plot indicates that the water level required to convey a certain discharge in 1971 is consistently higher than the water level required to convey the same discharge in 2007. This again confirms that the conveyance has increased from 1971 to 2007 as a result of changes in channel geometry and assuming all other variables have remained constant during this time.
Figure 2-1: Hydraulic performance graph produced using RMA2 for 1971 model of St. Clair River.

Figure 2-2: Comparison of hydraulic performance graphs produced using RMA2 for the 1971 and the 2007 (Simulated single-beam at 1971) models.
The interpolated discharge values required to simulate average water level boundary conditions at both Lake St. Clair and Lake Huron are shown in Table 2-2. The results indicate that under average water level conditions at both the upstream and downstream model boundaries, the discharge increased by 275 m$^3$/s between 1971 and 2007, assuming bathymetric data of the same density is used. Conversely, the results also showed that the discharge decreased by 74 m$^3$/s between 2000 and 2007, assuming bathymetric data of the same density is used. These findings again illustrate that the conveyance increased some time between 1971 and 2007, but decreased between 2000 and 2007.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Lake St. Clair Water Level (m)</th>
<th>Lake Huron Water Level (m)</th>
<th>Discharge (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>175.29</td>
<td>176.61</td>
<td>5118</td>
</tr>
<tr>
<td>2000</td>
<td>175.29</td>
<td>176.61</td>
<td>5483</td>
</tr>
<tr>
<td>2007</td>
<td>175.29</td>
<td>176.61</td>
<td>5653</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>175.29</td>
<td>176.61</td>
<td>5393</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>175.29</td>
<td>176.61</td>
<td>5409</td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td></td>
<td>-275</td>
</tr>
</tbody>
</table>

Table 2-2: Discharge values interpolated from HPGs for average water level conditions.

3. Uncertainty Analysis

In Phase 1 and the first part of Phase 2 of the St. Clair River RMA2 modelling project, changes in conveyance resulting from changes in channel geometry over time were estimated. Bathymetry data for each of the available years was substituted into the model, and all other parameters were kept constant. The change in water level and discharge over time was then used to infer changes in conveyance.

For a number of reasons, the bathymetry data for each year is not known exactly. Rather, there is uncertainty in the data, which is a function of both survey error and interpolation error. Survey error is a function of the data collection method used and the accuracy of the measurement equipment. Interpolation error is a function of the density of the survey data, the method used to interpolate the survey data to the model mesh, and assumptions made regarding areas with missing data (e.g. shallow areas near shorelines, islands, etc.). In order to give an estimate of the conveyance change, it is necessary to
determine how the uncertainty in the bathymetric data used in the model propagates to uncertainty in the model results.

According to Bennion (2008), the uncertainty in the bathymetric data varies for each year, reflecting the different data collection methods used, the precision of the measurement instruments, the densities of the datasets, the spatial coverage, etc. Bennion provided estimates of the survey error, and according to the United States Army Corps of Engineers the survey errors reported are only estimates of the minimum error, and not actual measured values (S. Tule, personal communication, Nov. 4, 2008). The survey error has never been determined more precisely as there has not been a need for such precision. Since the estimated minimum errors reported by Bennion are the best estimates currently available, they were used and treated as standard errors for this study.

Bennion also estimated the uncertainty in the St. Clair River interpolated surfaces that he created for use in other modelling projects. This uncertainty estimate was obtained using an iterative method that basically involved removing 10-percent of the measured bathymetric data points, creating an interpolated surface with the remaining points, and comparing the removed, measured points to the same points from the interpolated surface and calculating the average and standard error values. A full description of this method is given by Maune et al (2001).

For the St. Clair River RMA2 model, a set of surfaces was created independently for each of the years of available data using the linear interpolation method included in the Surface-Water Modeling System (SMS) software. As a result, the interpolation error estimates provided by Bennion could not be used directly. The interpolation error was instead estimated independently for this study using one of two methods. The 10-percent method, outlined by Bennion and described above, was used to estimate the interpolation error for all datasets. An additional method, called the Simulated Single-Beam (SSB) interpolation method, was also used to estimate error for the low-density datasets only.

The 10-percent method compares 10-percent of the measured data points removed from a bathymetric dataset to points from an interpolated surface created using the remaining 90 percent of the measured bathymetry points. This method is useful in that it allows for comparisons of measured versus interpolated data points for a given year without requiring a second set of measured bathymetry data for comparison. For a high-density dataset, such as the multi-beam bathymetry data collected in 2007, it is believed that this method gives a good estimate of the interpolation error.

Conversely, when data density is low and irregularly distributed, such as in the single-beam bathymetry datasets collected in 1971 and 2000, this method is inappropriate. The single-beam data collected in 1971 and 2000 was collected primarily along transects spaced over 100 metres apart. By comparing the interpolated surface to the 10-percent of data points that were removed prior to interpolation, an estimate of the interpolation error is given, but only at points along the transects themselves. The interpolation error in the areas between transects can not be estimated using this method, yet this error can be significant given the spacing of the transects.
To better illustrate this issue, Figure 3-1 shows a comparison of the 10-percent method for the 2007 and 2000 datasets. The points labeled “Test Data” indicate the 10-percent of data points that were removed for comparison in the 10-percent method for estimating interpolation error. The “Training Data” indicates the remaining 90-percent of the data that was used to create the interpolated surfaces. The 2007 data is high-density, multi-beam data. In this case, the 10-percent method removes and compares points that are spatially distributed fairly evenly and randomly throughout the river channel. The method gives an unbiased estimate of the interpolation error under these circumstances. On the other hand, the 2000 data is low-density, single beam data, with transects generally spaced greater than 100 metres apart. In this case the 10-percent method removes and compares points that fall only on the single-beam transects themselves. No estimate of the interpolation error can be made between the transects, which creates a bias in the interpolation error estimate when using the 10-percent method under these circumstances.

![Figure 3-1: Comparison of 2007 and 2000 data density, including test data and training data used in 10-percent method for estimating interpolation error.](image_url)

The Simulated Single-Beam (SSB) interpolation method overcomes this difficulty. In the SSB method, simulated-single beam datasets were generated from 2007 data by interpolating elevation data from the 2007 surface created by Bennion (2008) at only those geographic locations where data was collected in each of 1971 and 2000. Figure 3-2 shows a portion of the two SSB datasets (i.e. one interpolated at 1971 locations and the other at 2000 locations). The two SSB datasets were then used to interpolate two additional 2007 surfaces using SMS and the same linear interpolation method used to create the original surfaces. A subset of 10-percent of the actual measured 2007 data points (2007 “Test Data”) were then compared to the elevation values obtained at the same locations from the surfaces interpolated from the SSB data. With this method, an unbiased estimate of the mean and standard interpolation error was obtained that included
estimates spatially distributed throughout the river, as opposed to along the single-beam transects only.

The results for the various years and the two different error estimation methods used are shown in Table 3-1. The results illustrate a number of important details. First, the difference between the results from the 10-percent method used for the 1971 and 2007SSB71 model is small. The mean error is the same (i.e. -0.10 metres for both 1971 and 2007 SSB 71) and the standard error differs by only 0.06 metres. A similar result is seen in the differences between 2000 and 2007SSB00. This provides evidence that the interpolation error depends more on the interpolation method and the data density of the dataset as opposed to the data values themselves, which further suggests that the interpolation error estimated using the SSB method for the 2007 simulated-single beam datasets also provides a reasonable estimate of the uncertainty in the 1971 and 2000 datasets.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Method</th>
<th>Mean Error (m)</th>
<th>Standard Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>10%</td>
<td>-0.10</td>
<td>1.03</td>
</tr>
<tr>
<td>2000</td>
<td>10%</td>
<td>-0.01</td>
<td>0.27</td>
</tr>
<tr>
<td>2007</td>
<td>10%</td>
<td>-0.02</td>
<td>0.23</td>
</tr>
<tr>
<td>2007 SSB 71</td>
<td>10%</td>
<td>-0.10</td>
<td>0.97</td>
</tr>
<tr>
<td>2007 SSB 00</td>
<td>10%</td>
<td>-0.01</td>
<td>0.24</td>
</tr>
<tr>
<td>2007 SSB 71</td>
<td>SSB</td>
<td>-0.26</td>
<td>0.89</td>
</tr>
<tr>
<td>2007 SSB 00</td>
<td>SSB</td>
<td>-0.17</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 3-1: Interpolation error estimation results.
In addition, Table 3-1 shows that the mean error tends to be shifted towards negative values, in particular for the low-density datasets. This is primarily the result of an assumption that was made regarding the shoreline elevation when creating the different geometry surfaces. Since shoreline data was not available for any years, it was assumed that the shoreline elevation was equal to the low water datum elevation minus one metre. This has the effect of causing the interpolated values to be biased, such that the interpolated elevation values, in particular those near the shoreline, were often greater than the actual measured values. This bias was most significant in the upper portion of the St. Clair River, and is clearly evident in Figure 3-3, which illustrates the spatial distribution of the interpolation error in this location. Unfortunately, since actual measured shoreline data was unavailable, this problem could not be avoided. Additionally, the location of the measured bathymetry data itself may contribute to the bias in the interpolation error. This bias towards overestimating the elevations is greatest in the low density datasets, and would cause the simulated water surface elevations for these models to be overestimated as well.

![Figure 3-3: Spatial distribution of interpolation error in the St. Clair River below the Bluewater Bridge.](image)

Lastly, Table 3-1 shows the interpolation error estimates from the 10-percent method and the SSB method. Note that the 2007 dataset could only be investigated using the 10-percent method. It was expected that the interpolation error estimated using the 10-percent method would be less than the interpolation error estimated using the SSB method for each of the low density datasets. Surprisingly, the 1971 interpolation error estimated from the 10-percent method was greater than the interpolation error estimated from the SSB method (1.03 metres vs. 0.89 metres, respectively). The 2000 bathymetry, however, gave a significantly greater error estimate when the SSB method was used.
compared to that provided by the 10-percent method (0.77 metres vs. 0.27 metres, respectively). It is unclear why the 1971 interpolation methods did not show a similar result. It is possible that this was caused by the greater spacing between points along each transect in the 1971 dataset (points spaced between 20 and 40 metres, approximately) compared to the 2000 dataset (points spaced between 5 and 10 metres, approximately), or possibly combined with the fact that with far fewer measured data points in total in the 1971 data (11,736 vs. 52,247 in 2000), removing 10-percent in this case had a more significant impact on the interpolation error. Regardless, for the reasons outlined above, it was assumed that the SSB method provided the more accurate estimate of interpolation error in both the 1971 and 2000 datasets.

Table 3-2 shows the final combined estimates of bathymetric uncertainty used for each model in the uncertainty analysis. All mean errors (Column 3) and standard errors (Column 4) are those calculated using the SSB method, except for the 2007 model, for which the error was calculated using the 10-percent method. The Bennion surface standard error (Column 5) accounts for the fact that the simulated single-beam data for 2007 was interpolated from the 2007 surface created by Bennion (2008). Bennion’s 2007 surface had a reported standard error of 0.14 metres, and this error is included in the standard error estimated using the SSB method (Column 4). The Bennion surface standard error must be kept in the total error estimated for the simulated single-beam models (i.e. 2007SSB71 and 2007SSB00) since they use data interpolated from the Bennion surfaces, but must be removed from the 1971 and 2000 models as they use measured data. Survey standard errors (Column 6) were also reported by Bennion. The total error (Column 7) is the sum of all standard errors calculated and reported, and this sum was calculated by adding the variances (squared standard errors) and taking the square root.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Interpolation Error Method</th>
<th>Mean Error (m)</th>
<th>Standard Error (m)</th>
<th>Bennion Surface Standard Error (m)</th>
<th>Survey Standard Error (m)</th>
<th>Total (Std.) Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>SSB</td>
<td>-0.26</td>
<td>0.89</td>
<td>-0.14</td>
<td>0.3000</td>
<td>0.93</td>
</tr>
<tr>
<td>2000</td>
<td>SSB</td>
<td>-0.17</td>
<td>0.77</td>
<td>-0.14</td>
<td>0.3000</td>
<td>0.81</td>
</tr>
<tr>
<td>2007</td>
<td>10-percent</td>
<td>-0.02</td>
<td>0.23</td>
<td>--</td>
<td>0.1524</td>
<td>0.28</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>SSB</td>
<td>-0.26</td>
<td>0.89 (included)</td>
<td>--</td>
<td>0.1524</td>
<td>0.90</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>SSB</td>
<td>-0.17</td>
<td>0.77 (included)</td>
<td>--</td>
<td>0.1524</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 3-2: Full sources of error used in uncertainty analysis.

With the total error in the bathymetry data estimated, a Monte Carlo analysis was performed on the bathymetric data used as input in the RMA2 model geometry files in order to determine how bathymetric data uncertainty translates into uncertainty in the simulated Lake Huron water level. Exploratory data analysis was conducted on the interpolation errors to determine if a normal distribution would be a suitable representation of the bathymetry error for use in the Monte Carlo analysis. Figure 3-4 shows a histogram of the interpolation errors for 2007. The histogram shows a somewhat bell-shaped distribution, indicating the use of a normal distribution for modelling the errors may be appropriate; however, the distribution appears to be narrow and peaked,
indicating a higher than normal kurtosis. Some extreme values, particularly on the negative side of the distribution, are also evident from the histogram.

Figure 3-4: Interpolation error histogram for 2007.

Figure 3-5 shows a comparison of the cumulative distribution functions for the interpolation error values found for 2007 and the normal distribution defined by the mean and standard interpolation error found for 2007. While not a perfect fit, the normal distribution provides a fairly good estimate of the actual interpolation error, and at the very least provides for a conservative estimate. The 2007SSB71 data showed a similar result (Figure 3-6), as did the other datasets. It was assumed that the survey errors were normally distributed, and therefore the combined error could also be described by a normal distribution.

Figure 3-5: CDF comparison of the 2007 data interpolation error and the normal distribution defined by the mean and standard interpolation error values for 2007.
The uncertainty in the bathymetry data for each year was described by a normal distribution with a mean equal to the mean error and a standard deviation equal to the total (standard) error given in Table 3-2. The cumulative normal distribution described by these statistics was then used to randomly perturb each model mesh node in the main channel of the St. Clair River by a realistic error value. That is, for each model year, each model node elevation in the main channel was raised or lowered by a random amount obtained from the cumulative normal distribution of the bathymetric errors for that year. Note that the model nodes downstream of Algonac and into Lake St. Clair were not perturbed in this way, since the only bathymetry data available in this area was collected in 2000, and this was therefore used and kept constant in each model. Figure 3-7 shows the model mesh and the area perturbed. The geometry data was sampled in this way to create a subset of model geometry files for each year.

In this analysis the spatial distribution of the bathymetric uncertainty was not taken into account, and all nodes were perturbed completely at random. This means that adjacent nodes could be perturbed in different directions and by varying amounts, and that this could cause the river bottom to be somewhat saw-toothed, with the result being that the roughness of the channel may be greater than in reality. It is understood that this may be unrealistic, and that this would reduce conveyance for a given model as compared to the original base case model, but due to the method of interpolation used in the RMA2 modelling (linear interpolation) and time constraints, it was unavoidable. However, each model mesh was perturbed in the same way, and because of this the differences in conveyance between models will be preserved. That is to say that while the water levels simulated by the base case models for each year will differ from the mean water levels as simulated in the Monte Carlo analysis for each year, the difference in simulated water
level between years is preserved since the method was consistent. In addition, concerns regarding spatial distribution of bathymetric errors were also addressed in a sensitivity analysis conducted and discussed below.

Each of the model geometry files for a given year was evaluated using the RMA2 model. All other variables were kept constant, and average boundary conditions were assumed for all model runs. The RMA2 model was used to simulate a full set of Fort Gratiot water levels for each year from the subset of perturbed geometry files. The simulated Fort Gratiot levels were statistically analyzed, and the mean and standard deviation of the simulated levels for each year was determined. The standard deviation represents the standard error or uncertainty in the results.

The results of the Monte Carlo analysis are shown in Table 3-3. One difficulty with this analysis was maintaining stability when running the RMA2 model. The result of perturbing the model nodes randomly was that the elevation of some nodes would become higher than the water level, in particular those nodes in shallower areas, such as near the shoreline, islands or shoals. When too many nodes fall above the water level it can lead to excessive wetting and drying, which can cause the model to become unstable.

![Figure 3-7: Model mesh with perturbed nodes indicated.](image-url)
and fail. This was unavoidable, and resulted in a certain number of model simulations failing for each year. The percentage of model simulations that failed depended on the bathymetric uncertainty value used to perturb the nodes (i.e. those with greater uncertainty were more likely to fail than those with less). Since each model has over 60,000 model mesh nodes that were perturbed randomly, it was assumed that there was no particular bias as to which models failed and which did not, and the failed simulations should not affect or cause any bias in the final results of the uncertainty analysis.

As expected, the degree of uncertainty in simulated water level was found to vary with the degree of uncertainty in the bathymetric data. For example, the standard error in the 2007 full-density model is much less than the standard error in the other models created with the low-density data. The error determined from the high-density 2007 model is only 0.6 centimetres, whereas the error in the simulated water levels for all low-density models was close to two centimetres.

As expected, the degree of uncertainty in simulated water level was found to vary with the degree of uncertainty in the bathymetric data. For example, the standard error in the 2007 full-density model is much less than the standard error in the other models created with the low-density data. The error determined from the high-density 2007 model is only 0.6 centimetres, whereas the error in the simulated water levels for all low-density models was close to two centimetres.

### Table 3-3: Monte Carlo analysis results.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Total Simulations</th>
<th>Successful Simulations</th>
<th>Failed Simulations</th>
<th>Simulated Fort Gratiot Water Level Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean (m)</td>
</tr>
<tr>
<td>1971</td>
<td>1000</td>
<td>839</td>
<td>161</td>
<td>176.774</td>
</tr>
<tr>
<td>2000</td>
<td>1000</td>
<td>953</td>
<td>47</td>
<td>176.650</td>
</tr>
<tr>
<td>2007</td>
<td>500</td>
<td>850</td>
<td>150</td>
<td>176.659</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>1000</td>
<td>973</td>
<td>27</td>
<td>176.679</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note that with the exception of the 2007 full-density model the mean simulated water levels from the Monte Carlo analysis differ from the simulated water levels found in Phase 1 (Table 2-1). Specifically, the mean simulated water levels for the four low-density models were less than the simulated water levels from Phase 1. This is a result of the bias in the interpolation error discussed previously, which in general caused the bed surface elevations to be biased towards overestimation. Since all of the low-density models were affected by this, the differences between simulated water levels of equal density do not change. That is, the difference between water levels simulated by the 1971 model and the 2007 simulated single-beam model at 1971 locations is still approximately 12 centimetres, though the simulated water levels themselves are lower. Likewise, the difference between the simulated water levels from the 2000 model and the 2007 simulated single-beam model for 2000 is still approximately negative three centimetres. However, the differences between the full density 2007 model and the two low-density versions of the 2007 model is reduced substantially in the Monte Carlo analysis.

It should also be noted that there is correlation between the data density and the smoothness of the channel bottom. Specifically, when the low-density data is interpolated the resulting surface is rougher than a surface created using high density data. This can be seen upon close inspection of the bed surface profiles for various models between Fort Gratiot and just upstream of Stag Island (Figure 3-8), and can be
more easily seen in the 2007 profiles when zoomed-in on a shorter portion of the river bed profile (Figure 3-9). In addition to the bias towards overestimating the elevations in the low-density models, these discrepancies in roughness also help account for the differences between the simulated results for the various 2007 models. Lastly, the locations of the bathymetric measurements themselves also differ in the various 2007 datasets, which also accounts for some of the discrepancies in the simulated values.

Figure 3-8: Bed surface profile comparison from Fort Gratiot to Stag Island.

Figure 3-9: Expanded portion of bed surface profile showing differences in roughness between various 2007 models as a result of differing data densities.
In addition to the best estimates for the bathymetric uncertainty for each year, the Monte Carlo analysis was also run a number of additional times for each model using different estimates for the bathymetric uncertainty. This provided for a simple sensitivity analysis of the Monte Carlo results. Figure 3-10 shows a plot of bathymetric uncertainty versus the uncertainty in the simulated water level for all model results. The best estimates of the bathymetric uncertainty are shown in the dark blue squares. The results are fairly linear. The spread of the values near the upper end of the plot may be a result of a greater number of failed model simulations due to wetting and drying issues as explained above at these higher uncertainty values.

A number of assumptions went into estimating the bathymetric uncertainty for each model, and the best estimates are by no means perfect. The important thing to note from Figure 3-10 is that even if the bathymetric uncertainty estimates are inexact, the resulting uncertainty in the simulated water levels does not change significantly. For example, even at bathymetric uncertainty values of 1.40 metres, which is much greater than the largest best estimate of 0.93 metres bathymetric uncertainty for the 1971 model, the resulting uncertainty in the simulated water level at Fort Gratiot would be less than three centimetres. Furthermore, if the spatial correlation of the error values was considered, it seems likely that this would have reduced the resulting uncertainty in the simulated water levels at Fort Gratiot, and for this reason and others already discussed, the estimates given here can probably be considered conservative.

![Bathymetry Uncertainty vs Water Level Uncertainty](image.png)

Figure 3-10: Bathymetric uncertainty versus uncertainty in simulated water level.
The change in conveyance over time can be estimated by subtracting the mean simulated water levels from the Monte Carlo analysis for different years, and the uncertainty in this estimate can be calculated by properly summing the standard errors. The results are shown in Table 3-4. They indicate that from 1971 until 2007, if bathymetric data of equal density is used and all other variables remain constant, under average boundary conditions the water level has dropped 11.5 +/- 2.7 centimetres. Conversely, from 2000 until 2007 the water level has increased 2.8 +/- 2.4 centimetres, again given average boundary conditions and bathymetric data of equal density.

<table>
<thead>
<tr>
<th>Conveyance Change Estimate (Water Level)</th>
<th>Mean WL Difference (m)</th>
<th>Standard Error (m)</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971 - 2007 (from 2007SSB71 model)</td>
<td>0.115</td>
<td>0.027</td>
<td>0.053</td>
</tr>
<tr>
<td>2000 - 2007 (from 2007SSB00 model)</td>
<td>-0.028</td>
<td>0.024</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Table 3-4: Conveyance change estimate and uncertainty as a function of water level.

In Section 2 of this report, the change in conveyance was estimated in terms of the change in discharge given average water levels as model boundaries. This was done by simulating a full range of possible boundary conditions in order to build hydraulic performance graphs (HPGs). The discharge required for each year, assuming average water levels, was then interpolated from these graphs. It would not be practical to run a Monte Carlo analysis on the full range of different boundary conditions needed to create the HPGs. Instead, the uncertainty in the change in conveyance as a function of discharge can be estimated using the HPGs already created. The change in conveyance as a function of discharge was estimated in Section 2 by assuming average upstream and downstream water levels for all models and interpolating the discharge values from the HPGs. If the error in the simulated upstream water level is added or subtracted from the average level, the discharge required to simulate an average water level plus or minus the error can again be estimated from the HPGs in this way. The estimated results for discharge are shown in Table 3-5.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Average Lake Huron Water Level (m)</th>
<th>Standard Error (m)</th>
<th>HPG Interpolated Discharge (m³/s)</th>
<th>Difference from Average (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average W.L.</td>
<td>Average + S.E.</td>
<td>Average - S.E.</td>
<td>Average + S.E.</td>
</tr>
<tr>
<td>1971</td>
<td>176.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>176.61</td>
<td>0.019</td>
<td>5118</td>
<td>5164</td>
</tr>
<tr>
<td>2007</td>
<td>176.61</td>
<td>0.006</td>
<td>5653</td>
<td>5668</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>176.61</td>
<td>0.020</td>
<td>5393</td>
<td>5443</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>176.61</td>
<td>0.017</td>
<td>5409</td>
<td>5451</td>
</tr>
</tbody>
</table>

Table 3-5: Uncertainty in simulated discharge for each model as estimated by hydraulic performance graphs.

The difference in simulated discharge for the different years is given in Table 3-6. By treating the differences from average as the standard deviation of the discharge and adding the variances, under average water levels, the discharge in the St. Clair River was
found to have increased by 275 +/- 68 m$^3$/s from 1971 until 2007, assuming data of equal density are used. On the other hand, from 2000 until 2007, the discharge in the St. Clair River was found to have decreased by 74 +/- 61 m$^3$/s, again assuming data of equal density. This again shows that the conveyance has increased since 1971, but after 2000 this decrease has stopped or even reversed.

<table>
<thead>
<tr>
<th>Conveyance Change Estimate (Discharge)</th>
<th>Mean Q Difference (m$^3$/s)</th>
<th>Standard Error (m$^3$/s)</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971 - 2007 (from 2007SSB71 model)</td>
<td>-275</td>
<td>68</td>
<td>133</td>
</tr>
<tr>
<td>2000 - 2007 (from 2007SSB00 model)</td>
<td>74</td>
<td>61</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 3-6: Conveyance change estimate and uncertainty as a function of discharge.

4. Conclusions

In Phase 1 of the St. Clair River RMA2 modelling project, changes in conveyance over time in the St. Clair River as a result of changes in bathymetry were investigated. Assuming all other variables remained constant (i.e. channel roughness, eddy viscosity, temperature, boundary conditions, bathymetric data density, etc.), a deterministic estimate of the change in water level of Lake Huron resulting from changes in channel geometry was given. Assuming data of equal density are compared, it was found that the water level of Lake Huron had decreased by 12 centimetres from 1971 until 2007, but had increased by three centimetres from 2000 until 2007. It can subsequently be inferred from these estimates that the conveyance has increased since 1971 as a result of changes in channel geometry, but that the increase in conveyance has not continued since 2000.

In the first part of Phase 2 of this project, the change in conveyance as a function of discharge was estimated using Hydraulic Performance Graphs (HPGs). The HPGs were used to interpolate discharge values for each of the different years given the same average water levels at the upstream and downstream model boundaries. The results showed that under average conditions, the discharge in the St. Clair River has increased by 275 m$^3$/s from 1971 until 2007, but that since 2000, the discharge has decreased by 74 m$^3$/s.

In the second part of Phase 2, the uncertainty in the bathymetric data was investigated. Specifically, the uncertainty in the model simulation outputs resulting from uncertainty in the bathymetric data was estimated using Monte Carlo analysis. The interpolation error was estimated using two methods and was then combined with the survey error to estimate the total uncertainty in the bathymetric data for each model. A large sample of geometry files was created and simulated to produce a set of model evaluations that could be statistically analyzed.

The model results showed that the uncertainty in the bathymetric data translates to standard errors in the simulated Fort Gratiot water level of between 0.6 and 2.0
centimetres, depending on the model year and the density of the data. By combining the uncertainty values, a probabilistic estimate of the change in conveyance between years was determined. From 1971 until 2007, under average conditions the simulated water level at Fort Gratiot dropped approximately 12 +/- 3 centimetres, or the discharge increased by 275 +/- 68 m$^3$/s, indicating an increase in conveyance. From 2000 until 2007, again under average conditions, the simulated water level at Fort Gratiot increased approximately 3 +/- 2 centimetres, or the discharge decreased by 74 +/- 61 m$^3$/s, indicating a decrease in conveyance over this period. Again, these estimates of uncertainty are likely conservative due to the assumptions made in this analysis, including the facts that the bathymetric uncertainty was approximated by a normal distribution function and that the spatial correlation of the uncertainty values was ignored. Therefore, the uncertainty in the simulated Lake Huron water level may actually be less, but the conveyance change estimates can be considered statistically significant regardless.

Therefore, if we assume all other factors have remained constant over this time period, the conveyance of the St. Clair River has increased since 1971 as a result of changes in bathymetry. However, after 2000 the increase in conveyance has stopped and may have reversed as a result of additional changes in bathymetry since this time. It is impossible to determine from this analysis whether the changes in bathymetry causing the changes in conveyance have been gradual or the result of sudden events. Furthermore, this analysis did not investigate the likely possibility that other changes have occurred in the channel since 1971, including those that could affect conveyance such as changes in channel roughness, shoreline alterations, etc. This study investigated changes in bathymetry and their effect on conveyance only. Further studies would be required to identify whether other changes have occurred in the St. Clair River, and if they have, how these changes have affected the conveyance of the river.
5. References


St. Clair River
Hydrodynamic Modelling Using RMA2

Addendum to Phase 1 and 2

Prepared for the
International Upper Great Lakes Study Team

By

Jacob Bruxer
Environment Canada
April 2009
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1. **Introduction**

As part of the International Upper Great Lakes Study the Hydraulic Modelling Technical Working Group was tasked with investigating changes in conveyance in the St. Clair River over time. It has been proposed by W. F. Baird and Associates (2005) that since the last dredging project in 1962 the St. Clair River has continuously eroded, such that the channel has generally become larger and the conveyance in the river has increased. This increase in conveyance has been suggested as one of the causes of the low water levels experienced on Lakes Michigan-Huron in recent years, as well as the cause of an observed decrease in the fall between Lakes Michigan-Huron and Lake Erie.

2. **Previous Investigations**

The suggested increase in conveyance was investigated in the Upper Great Lakes Study with the aid of a number of hydrodynamic models, including a two-dimensional hydrodynamic model of the St. Clair River developed using Resource Management Associates’s RMA2 code. In Phase 1 of this project (Bruxer and Thompson, 2008a), the RMA2 model was used to simulate water levels at Fort Gratiot given different channel bathymetry data from various years, including 1971, 2000 and 2007, for which bathymetry data for the full river was available. Only the bathymetry was changed, with all other variables (including all calibration parameters such as bed roughness) held constant. A full range of possible boundary conditions (outflow from Lake Huron at the upstream boundary and Lake St. Clair water level at the downstream boundary) were simulated, and it was found that from 1971 to 2007, assuming bathymetry data of equal density, the water level at Fort Gratiot would have dropped approximately 12 cm for the same average boundary conditions. On the other hand, from 2000 to 2007, under the same assumptions, it was found that the water level at Fort Gratiot would have been higher by approximately 3 cm.

In Phase 2 of this project (Bruxer and Thompson, 2008b), the RMA2 model results were used to develop hydraulic performance graphs (HPGs) for the St. Clair River. HPGs relate upstream and downstream water level to discharge, and using these plots the change in conveyance as a function of a change in discharge could be estimated. The HPG results indicated that from 1971 to 2007, assuming data of equal density and given average water levels as boundary conditions, the discharge had increased by approximately 275 m$^3$/s. Conversely, from 2000 to 2007, assuming the same conditions, a decrease in discharge of 74 m$^3$/s was observed.

The second part of Phase 2 involved performing an uncertainty analysis on the RMA2 model results. Model bathymetry data is subject to uncertainty, which is a function of both survey error (i.e. the accuracy of the raw surveyed bathymetry data) and interpolation error (a result of interpolating the raw data to a finite element mesh).
Since bathymetry data was the only model parameter not held constant in this study, in order to give a probabilistic estimate of the conveyance change, it was necessary to estimate the uncertainty in the simulated model results due to uncertainty in the bathymetric data. A Monte Carlo analysis was performed by randomly perturbing each model node in each model mesh by an amount obtained from the cumulative normal distribution of the bathymetric errors for that year. The geometry data was sampled in this way to create a subset of model geometry files for each year. The RMA2 model was then used to simulate a full set of Fort Gratiot water levels for each year from the subset of perturbed geometry files. The results indicated that from 1971 until 2007, under average conditions the simulated water level at Fort Gratiot was found to be lower by approximately 12 +/- 3 cm, or the discharge increased by 275 +/- 68 m$^3$/s, indicating a significant increase in conveyance. From 2000 until 2007, again under average conditions, the simulated water level at Fort Gratiot was found to have increased approximately 3 +/- 2 cm, or the discharge decreased by 74 +/- 61 m$^3$/s, indicating a nearly insignificant decrease in conveyance over this period.

3. Additional Analysis

A meeting was held on January 6-7$^{th}$ in Burlington, ON, with members of the Study management, the Hydraulic Modelling Technical Working Group (TWG) and the Study peer review group. At this meeting a number of questions and concerns were discussed with regard to the hydrodynamic modelling work performed for the St. Clair River. After much discussion, four main topics were identified as requiring further investigation.

The first topic identified was that additional analysis and clarification was required to determine how and why the results of the RMA2 model analysis performed for the Study differed from the results produced by W. F. Baird and Associates (2005). Additional investigations and explanation regarding possible reasons for these differences were requested.

The second topic was a request for additional analysis using RMA2, including additional clarification regarding the results of the uncertainty analysis. This included: a convergence test of the model mesh density; a variogram comparison of model node elevations from the basis of comparison models and the models perturbed in the uncertainty analysis; a normal probability plot of the bathymetry errors; a reconciliation of the disconnect between model boundary conditions and actual conditions controlling flow in the St. Clair River; and an explanation of the differences between the mean water levels simulated during the Monte Carlo uncertainty analysis and the simulated levels from the original deterministic models.

The third topic to come out of the Burlington meeting was a request to rationalize the differences between the two key hydraulic modelling experiments
conducted. In addition to the analysis performed using the RMA2 model, similar analyses were performed by other researchers using additional models, including a one-dimensional HEC-RAS model and a two-dimensional TELEMAC model. In our initial analysis, the model calibration parameters were held constant. Subsequent work carried out using the TELEMAC model led to questions regarding the appropriateness of this assumption, and it was requested that this be investigated further.

The fourth and final topic to come out of the meeting was a request for rationalization of the differences between the results from the different hydrodynamic models used in the Study. The hydrodynamic models used in the Study and their results differ for a number of reasons, including the model itself and the various assumptions that went into creating each. A request was made that these differences be explained or resolved if possible.

This addendum to the work already completed in Phase 1 and 2 contains discussion and additional results that help address each of the first three topics outlined above. The fourth topic (i.e. rectification of differences from the various model results) will be addressed by others, including in the St. Clair River Task Team final report.

4. Comparison of RMA2 Results with Baird Results

As part of W. F. Baird and Associates (2005) report they performed a hydraulic modelling analysis similar to those done for the Study using the same base RMA2 model prepared by Holtschlag and Koschik (2001). During the Burlington meeting, concern was expressed regarding the differences between the results obtained by Baird and those found in our study. In particular, Baird compared simulated Fort Gratiot levels from their 1971 and 2000 models and found the difference to be 23 cm. Our model results indicated the difference between 1971 and 2000 to be only 16 cm, although it was also stressed that this comparison is inappropriate due to significant differences in the density of the bathymetric data available for each of these two years. Regardless, the different results were questioned by those at the Burlington meeting, and it was suggested that the reasons for these differences be resolved.

Hydrodynamic modelling requires a number of assumptions and decisions to be made by the researcher. For example, in the RMA2 model, assumptions were made regarding the bathymetric data interpolation method chosen, the average boundary conditions used, the calibration parameters and the shoreline bathymetry information. During initial model construction, these choices are normally based on the researcher’s best judgment. Later, a thorough analysis of the effect of the various decisions made can be assessed by performing sensitivity analysis on the model inputs, during which the
effects on model results of alternative decisions and assumptions that the researcher could have made are evaluated.

Both we and Baird were required to make decisions and assumptions regarding various model inputs when performing the hydraulic modelling analysis of the St. Clair River. The assumptions and decisions made in our modelling efforts have been fully documented and their sensitivity tested. Without knowing what assumptions and decisions were made in the Baird model, it is impossible to comment with certainty as to the causes of the differences between our results. However, the sensitivity analyses that were performed on our model do suggest the most likely causes for the differences observed.

Five assumptions in particular were hypothesized to be the cause of the differences in model results, including the bathymetric data set used, the interpolation method chosen, the calibration parameters (Manning’s roughness coefficients), the boundary conditions used, and the different shoreline data assumption chosen.

In our work, the bathymetric data used in the various models was subject to detailed review and quality control. A full description of the process undertaken is given by Bennion (2008). In terms of the bathymetric data used in the RMA2 modelling, it is assumed that the raw bathymetric data itself used by both Baird and ourselves originated from the same source, and that the only differences in the data would result from the review and quality control process undertaken. Both we and Baird performed such processes, but it is unlikely that any differences in these processes had a significant impact on the results, and almost certainly these differences would only account for a small fraction of the difference observed between the results of Baird’s and our analyses.

As the raw bathymetric data itself must be interpolated to the finite RMA2 grid, the choice of interpolation method may cause differences in model results. At the Burlington meeting and in subsequent communications, Rob Nairn of W. F. Baird and Associates stated that the natural neighbour method of interpolation was used in their analysis, whereas in our analysis, a linear interpolation method was used. Regardless, prior to the Burlington meeting, the choice of interpolation method was investigated to determine the impact it had on model results, and specifically the differences in simulated Fort Gratiot water level between years. The effect of using the different interpolation methods can be seen in Table 4-1.

It was noted in Phase 1 that bathymetry data of unequal density can cause significant differences in model results. Bathymetry data of unequal density, when interpolated to a finite grid, can cause differences in form roughness (i.e. the roughness of the channel resulting from variations in bed elevation on a relatively small scale). This form roughness can have a significant impact on channel conveyance. As discussed in Phase 1 of this work, the differences between the model results from the three 2007 models created with data of varying density are in large part the result of these
differences in form roughness. These differences are noted in Table 4-1. The 2007 model (full data density) and the two simulated single-beam models, one at 1971 data locations (2007SSB71) and the other at 2000 data locations (2007SSB00), each simulated different Fort Gratiot water levels, regardless of the interpolation method used. In some cases natural neighbour interpolation may create a smoother surface than linear interpolation, but this interpolation method does not substantially reduce form roughness resulting from low-density bathymetric data, and it is still no replacement for real, measured data.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Simulated Fort Gratiot Water Level for each Interpolation Method (m)</th>
<th>Differences (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Linear</td>
<td>Natural Neighbour</td>
</tr>
<tr>
<td>1971</td>
<td>176.85</td>
<td>176.85</td>
</tr>
<tr>
<td>2000</td>
<td>176.69</td>
<td>176.77</td>
</tr>
<tr>
<td>2007</td>
<td>176.62</td>
<td>176.63</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>176.73</td>
<td>176.72</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>176.72</td>
<td>176.80</td>
</tr>
</tbody>
</table>

Table 4-1: Comparison of results from linear and natural neighbour interpolation methods.

As can also be seen in Table 4-1, the resulting simulated water level differed substantially for some model years, in particular the 2000 model and 2007 simulated single-beam model at 2000 locations (2007SSB00). The difference resulting from the interpolation method chosen is actually the opposite of what one might expect, as the natural neighbour method of interpolation appears to have increased the form roughness, and caused the difference between 1971 and 2000 (0.08 m) to be even less than what was estimated with the linear interpolation method (0.16 m). This does not, therefore, account for the differences between our results and Baird’s. Also of note is that the simulated differences between years were the same when data of equal density were used. Regardless of interpolation method chosen, the simulated difference in Fort Gratiot water level was 0.12 m between 1971 and 2007SSB71, and -0.03 m between 2000 and 2007SSB00. This helps reaffirm our original estimates, and provides additional evidence that data of equal density must be used in this type of comparison.

The main calibration parameters in the RMA2 models are the Manning’s roughness coefficients. As noted in Phase 1, since some modifications were made to the original RMA2 model grid, the roughness coefficients were also modified in order to calibrate the model to observed water level and flow data. These roughness coefficients
are almost surely different than those used by Baird. Their report suggests they did not modify the roughness coefficients from the original RMA2 model. Without knowing for sure what roughness coefficients they used, their results could not be reproduced exactly. However, a sensitivity analysis was conducted on Manning’s roughness, and from these results it seems unlikely that the model calibration parameters are a major cause of the observed differences between our results and Baird’s.

The boundary conditions used can also influence the conveyance change results. It was shown in Phase 1 that the difference in simulated Fort Gratiot water level varies according to the model boundary conditions used. The average boundary conditions used in our analysis were a discharge of 5680 m$^3$/s and a Lake St. Clair water level of 175.29 m. These were calculated from coordinated data from 1962 to 1999, using the months of May to November, which represents the ice-free season. Baird used a discharge of 5200 m$^3$/s, but the exact Lake St. Clair water level used could not be found in their report. A discharge of 5200 m$^3$/s was therefore simulated using our model and a number of Lake St. Clair water levels. The results are given in Table 4-2. As can be seen, the simulated results differ depending on the boundary conditions used, but again these differences are not enough to account for the 0.23 cm difference in Fort Gratiot water level observed between 1971 and 2000 that Baird estimated.

<table>
<thead>
<tr>
<th>Lake St. Clair Water Level (m)</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
<th>1971</th>
<th>2000</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>174.50</td>
<td>176.25</td>
<td>176.07</td>
<td>0.176</td>
<td></td>
</tr>
<tr>
<td>174.75</td>
<td>176.36</td>
<td>176.20</td>
<td>0.165</td>
<td></td>
</tr>
<tr>
<td>175.00</td>
<td>176.49</td>
<td>176.33</td>
<td>0.156</td>
<td></td>
</tr>
<tr>
<td>175.25</td>
<td>176.62</td>
<td>176.48</td>
<td>0.145</td>
<td></td>
</tr>
<tr>
<td>175.50</td>
<td>176.77</td>
<td>176.64</td>
<td>0.136</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-2: Simulated Fort Gratiot water level with discharge of 5200 m$^3$/s and various Lake St. Clair water levels as boundary conditions.

The choice of shoreline elevation was also investigated. It was found to be the most sensitive model input, and is suggested as the likely cause of the majority of the differences observed in the model results. As was discussed in Phase 1 of this project, bathymetric data is collected on the St. Clair River by boat, and because of this, portions of the channel that are too shallow to navigate with the survey vessel are missed. Since hydrographic surveys are normally performed for the purpose of creating hydrographic charts for navigation, this is not usually a problem. However, in a hydraulic modelling exercise such as this one, it is necessary to estimate the bathymetry in the near-shore area, despite the inevitable inaccuracies resulting from a lack of data in these portions of the channel. For this reason, three choices of shoreline elevation were used in our study in order to test the sensitivity of the resulting simulated changes in conveyance to
the choice made for the shoreline elevation. Shoreline elevations were assumed to be equal to Low Water Datum (LWD) minus one metre (DM1), LWD minus two metres (DM2), or the shoreline elevations were extrapolated out to the shoreline (ExS) model nodes from the closest measured survey point(s).

DM1 was chosen as the preferred shoreline elevation assumption because it is a reasonable choice and it provided the most stability in the RMA2 model simulations executed. The shoreline delineation of the original St. Clair River model was taken from recreational boating charts (Holtschlag and Koschik, 2001). The shorelines of these charts are normally drawn at the location of the estimated Low Water Datum (LWD) elevation, and it follows that at these locations the bed elevation would also be equal to LWD. The subtraction of one metre from the LWD elevation was necessary to limit wetting and drying issues in the RMA2 model. Furthermore, use of the DM1 shoreline provides a more realistic cross-section shape in the river than extrapolating the shore elevations from the closest survey point(s), since in most locations the channel bed elevation increases gradually as one approaches the shore.

The sensitivity of the shoreline elevation assumption was tested by running the models for each year with each of the three different shoreline elevation assumptions. The results of these tests are given in Table 4-3. It was found that the simulated Fort Gratiot water level was quite close to the chosen shoreline data assumption. For example, the 1971 model with shoreline assumptions of DM1, DM2 and ExS shorelines simulated Fort Gratiot water levels of 176.85 m, 176.81 m and 176.88 m, respectively. Furthermore, when comparing differences in simulated water levels between 1971 and 2000, the differences were found to be 0.16 m, 0.16 m and 0.25 m, respectively. The extrapolated shoreline (ExS) assumption result of 0.25 m is very close to the 0.23 m estimated by Baird. If Baird chose to extrapolate the shoreline elevations or make a similar assumption, which seems probable, these findings indicate that this assumption is the most likely cause of the differences in the results of our analyses.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Simulated Fort Gratiot Water Level for each Shoreline Method (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DM1</td>
</tr>
<tr>
<td>1971</td>
<td>176.85</td>
</tr>
<tr>
<td>2000</td>
<td>176.69</td>
</tr>
<tr>
<td>2007</td>
<td>176.62</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>176.73</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>176.72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Differences (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971-2000</td>
</tr>
<tr>
<td>2000-2007</td>
</tr>
<tr>
<td>1971-2007</td>
</tr>
<tr>
<td>1971-2007SSB71</td>
</tr>
<tr>
<td>2000-2007SSB00</td>
</tr>
</tbody>
</table>

Table 4-3: Results of different shoreline data assumptions.
Knowing that shoreline elevation can affect our results, it should also be noted that when comparing the differences between models of the same data density, the shoreline assumption was found to have a very small effect. For example, when comparing simulated Fort Gratiot water levels from the 1971 model and the 2007 simulated single-beam model at 1971 locations (2007SSB71), the estimated difference in simulated water level was found to be 0.12 m for the DM1 and DM2 models, and 0.13 m for the ExS model, a difference of only 0.01 m. Similarly, when comparing the 2000 model and the 2007 simulated single-beam model at 2000 locations (2007SSB00), the simulated differences in Fort Gratiot water level were -0.03 m for all three shoreline assumptions. These results provide further evidence that data of equal density must be used when comparing the model results from different years.

Without knowing exactly the assumptions that went into the Baird RMA2 model, it is impossible to know for certain the causes of the differences observed in the results from their analysis and ours. However, it seems very likely that the main cause of the differences observed was the assumption made regarding the shoreline elevation, since results of using an extrapolated shoreline assumption gave a 0.25 m difference in simulated Fort Gratiot water level between 1971 and 2000, which is quite close to the 0.23 m estimated by Baird. If this is true, then it is likely that other assumptions would be the cause of the remaining 2 cm difference. In fact, a comparison of the 1971 and 2000 models created using the extrapolated shoreline assumption and natural neighbour interpolation gave a difference of 22.5 cm (Table 4-4), almost exactly the 23 cm reported by Baird.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>176.919</td>
</tr>
<tr>
<td>2000</td>
<td>176.694</td>
</tr>
<tr>
<td>Difference</td>
<td>0.225</td>
</tr>
</tbody>
</table>

Table 4-4: Simulated Fort Gratiot water levels using both the extrapolated shoreline assumption and natural neighbour interpolation.

What is most strongly indicated by these results is the need to use data of equal density, since the assumptions chosen affect the final result otherwise. Both the shoreline and interpolation method assumptions affected the final comparison results unless data of equal density was used. Baird performed their hydraulic modelling analysis prior to 2007 when the high-density multi-beam data used in our analysis was collected. Therefore, they could not have performed the same types of analyses that were done in our study in which the 2007 bathymetric data was reduced to the same density as the 1971 and 2000 data. Regardless, they should have questioned the validity of comparing data sets of unequal density in hydrodynamic modelling.
5. Additional Discussion Regarding RMA2 Results

The second topic to come out of the Burlington meeting was a request for additional analysis using RMA2, including additional clarification regarding the results of the uncertainty analysis. This included: a convergence test of the model mesh density; a reconciliation of the disconnect between model boundary conditions and actual conditions controlling flow in the St. Clair River; a variogram comparison of model node elevations from the original models and the models perturbed in the uncertainty analysis; a normal probability plot of the bathymetry errors; and an explanation of the differences between the mean water levels simulated during the Monte Carlo uncertainty analysis and the simulated levels from the original deterministic models.

5.1 Convergence Test

A convergence test of the model mesh density was requested by the peer reviewers at the Burlington meeting in January of 2009. The peer reviewers were concerned with the sensitivity of the RMA2 model results to differences in model mesh density. If our model results were found to be sensitive to mesh density, our estimate of whether conveyance has changed over time and by how much might be affected. Specifically, they asked that a convergence test be conducted to determine the minimum mesh density at which the simulated model results were found to be consistent.

The dimensionality of the RMA2 code and the limits of available computer resources made this a difficult task. Even if Lake St. Clair was omitted, one refinement of the model mesh increased the number of elements from 22175 to 61272, and the number of nodes from 68941 to 186994. The RMA2 model used in this study with a 32-bit processor computer could not handle the computations of the resulting solution matrix due to limitations in physical memory (with a 32-bit processor any one process is limited to 2 gigabytes of memory). The option of reducing the model mesh size was investigated by moving the model boundaries closer together; however, in order to refine the mesh more than once, the model boundaries had to be so close together that the results were essentially meaningless.

Instead, the model mesh for the entire St. Clair River was relaxed and the results compared to the results of the refined model mesh. In Phase 1 of this project the model mesh density was increased from the original mesh density used by Holtschlag and Koschik (2001). This was accomplished by using the “Refine” tool in SMS. In this analysis, the original mesh density used by Holtschlag and Koschik was tested and compared to the refined mesh used in Phase 1 and 2 of this study to estimate the effects of mesh density on simulated water level results and differences in simulated
water level over time. The Peclet number had to be modified to ensure model stability when using the less dense model mesh, therefore the Peclet number was reduced to 15 for all runs. Manning’s roughness was held constant for all model runs as well. The results of this analysis are given in Table 5-1. As can be seen, the simulated water levels at Fort Gratiot differed by up to 0.121 m. However, when comparing the 1971 minus 2007SSB71 model results, the difference is equal to 0.123 m, regardless of which mesh density was used. This was not true when comparing the models involving the high-density 2007 data.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1 and 2 Density</td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>176.89</td>
<td>-0.121</td>
</tr>
<tr>
<td>2007</td>
<td>176.656</td>
<td>-0.108</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>176.767</td>
<td>-0.121</td>
</tr>
<tr>
<td></td>
<td>Holtschlag and Koschik Density</td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>177.011</td>
<td>-0.121</td>
</tr>
<tr>
<td>2007</td>
<td>176.764</td>
<td>-0.108</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>176.888</td>
<td>-0.121</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td></td>
</tr>
<tr>
<td>1971-2007</td>
<td>0.234</td>
<td>-0.013</td>
</tr>
<tr>
<td>1971-2007SSB71</td>
<td>0.123</td>
<td>0</td>
</tr>
<tr>
<td>2007-2007SSB71</td>
<td>-0.111</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Table 5-1: Comparison of simulated water levels at Fort Gratiot for different mesh densities.

So while a full convergence test could not be performed, the previous test indicates that the mesh density used does not affect the results of the conveyance change analysis so long as data of equal density are used. Furthermore, the most dense model mesh density that was computationally feasible was used in this study, and since this mesh has more nodes (locations where elevation of the channel bottom is defined) than the number of soundings in both the 1971 or 2000 bathymetry datasets themselves, it is unlikely that a denser mesh is required for these two datasets. The mesh is, however, less dense than the 2007 multi-beam data. That being said, the 2007 data is the only multi-beam dataset, and for many reasons comparisons of the single beam datasets with the full 2007 multi-beam dataset have already been shown to be inappropriate.

### 5.2 Concerns Regarding Model Boundary Conditions

This section involves reconciliation of the apparent disconnect between the RMA2 model boundary conditions and the actual conditions controlling flow in the St. Clair River. The RMA2 model of the St. Clair River uses a specified discharge at the upstream boundary (Lake Huron at Fort Gratiot) and a specified water level at the downstream boundary (Lake St. Clair at St. Clair Shores). The model was run under these boundary conditions, and the resulting simulated upstream water level at Fort Gratiot was the variable used to infer changes in conveyance over time. In reality,
however, for the most part it is the water levels of Lake Huron and Lake St. Clair that drive the flow in the St. Clair River at any point in time. This apparent disconnect between model boundary conditions and actual boundary conditions has been questioned.

However, though the flow in the St. Clair River at any particular point in time is driven by the levels of Lake Huron and Lake St. Clair, over the long term the flow in the St. Clair River is driven by the net basin supplies to the lakes themselves. For example, if we assume that the net basin supplies to Lake Huron and Lake St. Clair remain at average levels indefinitely, and if we also assume that during this time all other factors affecting flow in the St. Clair River remain constant (e.g. channel geometry, roughness, meteorological factors, etc.), the discharge through the St. Clair River would eventually equal its average discharge and remain at this value indefinitely, regardless of what the water levels of Lake Huron and Lake St. Clair were at the start of the experiment. If, for example, the water levels at the start of the experiment were lower than normal, then the flow through the St. Clair River would initially be below average as well. However, given average net basin supplies, over time the water levels of both lakes would increase, which would in turn cause the discharge to increase, until the water levels of the two lakes and the discharge through the St. Clair River all reached average values.

Furthermore, if at some point during this period of average levels and flow, the geometry of the St. Clair River channel bed were to change substantially, the water levels of the two lakes, being initially at the same level as prior to the change in channel geometry, would cause the flow in the St. Clair River to change in order to accommodate the changed conveyance capacity of the river. However, immediately after the conveyance change event the new flow through the channel would begin to cause the water levels of the two lakes to change as well. If we are still assuming constant, average net basin supplies to the lakes, eventually the water levels of the two lakes would change to accommodate the new channel configuration, such that over time the flow through the channel would return to an average value, but this average flow would be driven by a new water level regime. To give a more specific example, if at a point in time the St. Clair River became deeper, the conveyance capacity of the channel would be increased. Given the water levels of Lake Huron and Lake St. Clair at the time of the change, the discharge in the channel would initially increase due to the increased channel conveyance capacity. Immediately after the change in conveyance, however, the water levels of the lakes would also begin to change as a result of the increased flow through the channel. The flow through the channel would begin to slowly decrease as the water level of Lake Huron slowly dropped due to the increased outflow, and the water level of Lake St. Clair slowly rose due to the increased inflow. Eventually, again assuming net basin supplies remained at average levels, the flow through the St. Clair River would reach an average value, the water level of Lake St. Clair would return to its average value, but the water level of Lake Huron would be lowered due to the deeper channel.
In effect the RMA2 model experiments performed simulated this same scenario. By assuming the boundary conditions as steady, average flow and Lake St. Clair water level, we have assumed that a change in conveyance has occurred at some point between 1971 and 2007, and simulated the change in Lake Huron water level resulting from this assumed change in conveyance. We have simulated the long-term, average change in Lake Huron water level that would result from a change in the St. Clair River channel geometry. To understand the continuous changes in water levels and flows in the Lake Huron to Lake St. Clair corridor would require a full routing model and a continuous simulation of all factors affecting water levels and flows, but this is not necessary to estimate the impact of changes in conveyance in the St. Clair River specifically on the flow regime. We have instead captured snapshots that indicate whether changes have occurred in Lake Huron’s water level due to changes in the river that have occurred at some point in time.

In addition, a similar analysis as was conducted with RMA2 was also conducted by a different researcher using HEC-RAS (Giovannettone, 2008). HEC-RAS is a one-dimensional hydrodynamic model. It tends to be more stable than RMA2, and can be used to simulate water levels as both upstream and downstream boundary conditions. The simulated variable used to infer changes in conveyance in this case was the calculated discharge. This analysis showed similar results to those found using the RMA2 model.

### 5.3 Variogram Analysis

A variogram comparison was also requested by the peer reviewers during the Burlington meeting. A variogram is a quantitative description of the spatial dependence of a dataset. Empirical and model-fitted variograms were created for each model year, and for both the original deterministic model mesh and an example of the perturbed probabilistic model meshes. A spherical equation was fitted to the empirical variogram data to create the model-fitted variograms, and alternative model choices showed comparable results. Examples of the empirical and model-fitted variograms for the 1971 model are shown in Figure 5-1 and Figure 5-2, respectively. The variograms from other model years showed similar characteristics. As can be seen, the probabilistic model variograms show an upwards shift in nugget and sill, indicating greater variation between node pairs in the probabilistic model. This indicates the probabilistic model surfaces are rougher, having greater variation in elevation between nodes than in the original model, which is expected. A shift to the right or left is not apparent in the probabilistic model variograms. A horizontal shift would indicate that the distance between nodes and the distance at which spatial correlation is observed has changed, but this was not the case. Therefore, spatial correlation has not changed. In both the original and probabilistic models, the range is approximately 375 m, indicating that there is little if any spatial correlation beyond this distance.
Figure 5-1: Empirical variogram comparison of 1971 RMA2 model mesh node elevations from original deterministic and probabilistic models.

Figure 5-2: Model-fitted variogram comparison of 1971 RMA2 model mesh node elevations from original deterministic and probabilistic models.

In summary, the variograms indicate that spatial correlation has not changed, but the probabilistic model surfaces are rougher than the original deterministic model surfaces. This increase in form roughness can affect model results. The effects of form roughness are discussed further in subsequent sections.
5.4 Normal Probability Plot

A normal probability plot of the interpolation errors was requested by the peer reviewers. This is a more appropriate means of examining the suitability of using a normal distribution to approximate the observed interpolation errors for each model year. An example normal probability plot shown for the 2007SSB71 model is seen in Figure 5-3. Other models showed similar results.

![Normal Probability Plot of 2007SSB71 Interpolation Error](image)

**Figure 5-3:** Normal probability plot of interpolation error for 2007 simulated single-beam model at 1971 locations (2007SSB71).

The large departure of the tails of the interpolation errors from the fitted line indicates that a normal distribution does not fit the data well. An alternative distribution, such as a logistic distribution, would likely fit the data better, or alternatively, a random bootstrap sampling technique was also suggested as a more appropriate, non-parametric method for this type of analysis. The uncertainty analysis could not be repeated with either of these types of approaches within current project deadlines, but consideration will be given to these types of methods in any future work. Regardless, as was discussed in Phase 2 of this work, the choice of a normal distribution to represent the interpolation errors overestimates the interpolation error somewhat, providing a more conservative estimate of the error values. Furthermore, the survey errors, which are added to the interpolation error to make up the total bathymetric
error in the model geometry, were assumed to be normally distributed. By assuming a normal distribution for the interpolation errors as well, the total error could be found by combining the two normal error distributions directly.

### 5.5 Difference between Mean Levels from the Uncertainty Analysis and the Original Deterministic Results

During the Burlington meeting the question was raised as to why the mean simulated water levels from the uncertainty analyses differed so significantly from the simulated water levels from the original deterministic models. Recall that during the RMA2 model uncertainty analysis, Monte Carlo simulations were performed for each model year, during which the model geometry node elevations were raised or lowered by a random value obtained from a normally distributed representation of the bathymetric error. Hundreds of simulations were run for each model year with randomly generated geometry data, with the distribution of these results giving an estimate of the uncertainty in the simulated Fort Gratiot water level for each year resulting from bathymetric errors. Table 5-2 shows a comparison of the water levels simulated at Fort Gratiot using the deterministic model and the probabilistic mean water level simulated in the Monte Carlo analysis. As can be seen there are fairly significant differences between these results, which may seem unexpected. An explanation regarding these differences was requested by the peer reviewers.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original Deterministic Model</td>
</tr>
<tr>
<td>1971</td>
<td>176.85</td>
</tr>
<tr>
<td>2000</td>
<td>176.69</td>
</tr>
<tr>
<td>2007</td>
<td>176.62</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>176.73</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>176.72</td>
</tr>
</tbody>
</table>

Table 5-2: Comparison of deterministic model results and mean probabilistic results.

There are two main causes for the differences observed in the deterministic model results and the mean probabilistic model results. First, a bias in the mean bathymetric error was included in the probabilistic modelling. Second, an increase in form roughness results from the random perturbation of model node elevations. As will be discussed, these two factors actually shift the mean model results in opposite directions.

A bias was found in the mean interpolation error, and this was included in the probabilistic modelling. This was discussed in detail in Phase 2 of this work, but to explain once more, in general, the mean interpolation error tends to be shifted towards
negative values, in particular in the low-density datasets. This is primarily the result of an assumption that was made regarding the shoreline elevation when creating the different geometry surfaces. As discussed in Chapter 4 of this report, since shoreline data was not available for any years, it was assumed that the shoreline elevation was equal to the Low Water Datum elevation minus one metre. This has the effect of causing the interpolated values to be biased, such that the interpolated elevation values, in particular those near the shoreline, were often greater than the actual measured values. This bias was most significant in the upper portion of the St. Clair River, and more so during years, such as 1971 and 2000, for which only low-density bathymetric data is available.

![Figure 5-4: Comparison of interpolation error (actual elevation minus interpolated elevation, in metres) from 2007 and 2007SSB bathymetries.](image)

Figure 5-4 shows a comparison of 2007 and 2007SSB00 interpolation errors in the Upper St. Clair River, which indicates the greater error associated with the 2007SSB00 bathymetry, in particular in the near-shore areas. Figure 5-5 also shows an example of how the interpolation error can be greater in the near-shore areas, especially between transects in the low-density datasets. Additionally, the location of the measured bathymetry data itself may contribute to the bias in the interpolation error. In both cases, this bias towards overestimating the elevations will be greatest in the low density datasets, and would cause the simulated water surface elevations for these models to be overestimated as well.
This apparent bias in the interpolation errors was included in the Monte Carlo analysis as it would account for much of the differences between the three different 2007 models (i.e. 2007, 2007SSB71 and 2007SSB00), as well as some of the differences in the 1971 and 2000 models when compared to the 2007 full-density model. In all four of the low-density models (i.e. 1971, 2000, 2007SSB71 and 2007SSB00) the interpolation error bias causes the simulated water levels at Fort Gratiot to be overestimated, since the interpolated bed elevation used in the model is, in general, higher than in reality. Since the mean bias in the 2007 full-density model is much less than in the other two models (Table 5-3), the simulated Fort Gratiot water level for this model will not be overestimated to the same degree. However, if bathymetric data of equal density is used, the differences resulting from the mean bias is cancelled out, since the bias was determined to be equal for these models. For example, the difference in simulated Fort Gratiot water level between the 1971 and 2007SSB71 models is the same (approximately 12 cm) in both the deterministic and probabilistic analysis, with or without the mean bias included. On the other hand, the differences between the three 2007 models is reduced somewhat, since the interpolation error bias, which is part of the cause of these differences, has been accounted for.

Figure 5-5: Spatial distribution of interpolation error at near-shore areas.
<table>
<thead>
<tr>
<th>Model Year</th>
<th>Mean Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>-0.26</td>
</tr>
<tr>
<td>2000</td>
<td>-0.17</td>
</tr>
<tr>
<td>2007</td>
<td>-0.02</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>-0.26</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>-0.17</td>
</tr>
</tbody>
</table>

Table 5-3: Mean error for each model.

The second cause of the difference between the deterministic and mean probabilistic model results was an increase in form roughness resulting from the random perturbation of model node elevations in the uncertainty analysis. As discussed in Chapter 4, small scale changes in bed elevation can cause an increase in form roughness. Higher form roughness will reduce the conveyance of the channel, such that the simulated water level at Fort Gratiot will be higher given the same boundary conditions. This is another reason that data of equal density must be used in a conveyance comparison such as this.

Similarly, by randomly perturbing the model node elevations during the uncertainty analysis, the form roughness of the probabilistic models was artificially made greater than the form roughness of the original deterministic model. This resulted in two related issues. First, the resulting distribution of the probabilistic model results becomes skewed towards higher simulated water levels since the increased form roughness tends to cause a decrease in conveyance (Figure 5-6). Second, it follows that the mean simulated water level from the probabilistic modelling analysis will be higher than it would have been had form roughness not been increased.

![1971 Uncertainty Results](image1.png)

**Figure 5-6:** Histogram of 1971 probabilistic modelling results from Monte Carlo analysis.
This increase in form roughness is the second reason for the differences between the simulated Fort Gratiot water levels from the deterministic model and the mean simulated water levels from the probabilistic modelling. The mean bias in the interpolation errors causes the mean probabilistic results to be shifted lower than the original deterministic model, while the form roughness acts in the opposite direction, causing the mean probabilistic results to be shifted back to slightly higher water levels. An approximation of the net result can be seen in the boxplot shown in Figure 5-7. The models were each run by lowering all node elevations by the mean error amount. For example, all model node elevations from the original deterministic model for 1971 were lowered by the same amount of 0.26 m, which is the mean bathymetric error found for this model. The difference between the water level simulated with the original geometry and that simulated with the original geometry lowered by the mean error gives an estimate of the result of the mean error on simulated water levels. Since the increased form roughness shifts the model results in the opposite direction, the difference between the lowered model and the mean from the uncertainty analysis is an estimate of the effect of form roughness. As can be seen in Figure 5-7, the effects of these two forces, which act in opposite directions, varies depending on the mean error and the standard error used for each model. For example, the 2007 mean and standard errors used in the probabilistic modelling (-0.02 m and 0.23 m, respectively) were much less than the 1971 model (-0.26 m and 0.89 m, respectively), and therefore the effect of these errors on the model results was smaller.

Figure 5-7: Boxplot of probabilistic model results from Monte Carlo analysis with results of mean error and form roughness indicated.
This analysis also helps quantify the effect of form roughness on the probabilistic model results. The estimated effect of increased form roughness on the mean probabilistic results is given in Table 5-4. As can be seen, the increased form roughness caused the mean probabilistic results to differ from the original deterministic results by a maximum amount of approximately 2.3 cm. The results are also skewed towards higher values, as was already shown in both Figure 5-6 and Figure 5-7.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Estimated Average Effect of Increased Form Roughness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>0.023</td>
</tr>
<tr>
<td>2000</td>
<td>0.017</td>
</tr>
<tr>
<td>2007</td>
<td>0.002</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>0.021</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Table 5-4: Estimated average effect of increased form roughness for each model year.

6. Rationalization of Differences between the Two Key Hydraulic Modelling Experiments

The final topic to come out of the Burlington meeting that will be discussed in this addendum was a rationalization of the differences between the two key types of hydraulic modelling experiments conducted. In addition to the original analysis performed using the RMA2 model, similar analyses were performed by other researchers using additional models, including a one-dimensional HEC-RAS model and a two-dimensional TELEMAC model. In each of these initial analyses the model calibration parameters were held constant, with the only variable being the channel geometry. Subsequent work carried out using the TELEMAC model led to questions regarding the appropriateness of this assumption. Specifically, the TELEMAC models for 1971 and 2007 were recalibrated using water level and flow data from each of the respective eras. A full description of this work is given in Faure (2008). The results of this study indicated that in addition to the channel geometry the channel roughness may have increased over time, such that the estimated change in conveyance from this analysis was found to be only 0.03 m, much less than the 0.12 m estimate found by holding the calibration parameters constant. This being said, the method of calibration and the uncertainty in this estimate was questioned, and it was requested that this analysis be reinvestigated using the RMA2 model.
As discussed, in Phase 1, the parameters in hydrodynamic modelling normally having the greatest influence on computed water levels and velocities are the roughness coefficients. Manning’s roughness coefficient, $n$, is used in the St. Clair River RMA2 model to specify the roughness of the channel. Turbulence parameters, specified in this model using a Peclet number, have lesser influence and are normally adjusted to ensure model convergence rather than for calibration purposes. Therefore, for the recalibration of the St. Clair River model the Peclet number was held constant and the Manning’s roughness coefficients were employed as the only calibration parameters. Regardless, a sensitivity analysis was conducted on both of these parameters initially to determine their effect on water levels and flows, and specifically their effect on observed changes in conveyance over time.

### 6.1 Sensitivity Analyses

Manning’s $n$ originates from Manning’s equation for steady, uniform flow. Manning’s equation is an empirical formula that was derived from other equations, experimental data and observations. There is no exact method for measuring Manning’s roughness coefficient, and Manning’s $n$ is affected not only by the bed surface roughness, but also by channel irregularities, channel alignment, stage and discharge, among other factors that are unaccounted for in the equations governing flow in open channels. For these reasons and others, in addition to representing channel roughness, Manning’s $n$ is often used as a calibration parameter in hydraulic modelling, and because of this it often partly accounts for additional factors affecting water level and flow in open channels.

To test the sensitivity of the RMA2 model to changes in the Manning’s roughness coefficients, a number of experiments were performed. First, a constant Manning’s $n$ value was assumed for the entire St. Clair River. A number of constant roughness coefficient values were tested to observe their effect on simulated model results. The results of this analysis are shown in Table 6-1. The missing values indicate failed model simulations. It can be seen from this table that the simulated water level at Fort Gratiot increases as roughness increases, which was expected, but also that the difference between different models increases as roughness increases as well. For example, the 1971 versus 2007SSB71 comparison shows that the difference between these two model years increases from 0.128 m to 0.187 m as the roughness coefficient is increased from 0.03 to 0.05. From this it must be concluded that Manning’s $n$ can affect the estimated change in conveyance over time.
The sensitivity of the Peclet number was also tested. The Peclet number is used in RMA2 to control turbulence and the stability of the numerical solution. The Peclet number is normally adjusted in RMA2 to ensure model convergence rather than for calibration purposes. Regardless, the sensitivity of the simulated results to changes in Peclet number was tested by running the model with different values of this parameter. The results are shown in Table 6-2. As can be seen, the simulated Fort Gratiot water level changed for each year depending on the Peclet number chosen. The difference between models of different density also changed depending on the Peclet number. However, the differences in simulated water levels for the various models of equal data density (i.e. 1971 vs. 2007SSB71) showed almost no variation (only 0.001 m) when the Peclet number was varied. Therefore, it can be concluded that Peclet number does not affect the estimated change in conveyance over time, so long as models created with data of equal density are compared.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 0.01</td>
</tr>
<tr>
<td>1971</td>
<td>--</td>
</tr>
<tr>
<td>2000</td>
<td>--</td>
</tr>
<tr>
<td>2007</td>
<td>--</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>--</td>
</tr>
<tr>
<td>2007SSB00</td>
<td>--</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971-2000</td>
</tr>
<tr>
<td>1971-2007</td>
</tr>
<tr>
<td>2000-2007</td>
</tr>
<tr>
<td>1971-2007SSB71</td>
</tr>
<tr>
<td>2000-2007SSB00</td>
</tr>
</tbody>
</table>

Table 6-1: Constant Manning’s n sensitivity analysis results.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peclet = 15</td>
</tr>
<tr>
<td>1971</td>
<td>176.890</td>
</tr>
<tr>
<td>2007</td>
<td>176.656</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>176.767</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971-2007</td>
</tr>
<tr>
<td>1971-2007SSB71</td>
</tr>
<tr>
<td>2007-2007SSB71</td>
</tr>
</tbody>
</table>

Table 6-2: Peclet number sensitivity analysis results.
6.2 **Comparison and Analysis of Measured Flow Data**

Measured flow data were analyzed for use in the model recalibration analysis that follows. At the time of this analysis flow data for the St. Clair River was available for the post-dredging period from 1962 to 2006. In this analysis, flow measurements made prior to 1996 are conventional current-meter measurements, whereas measurements from 1996 onwards are Acoustic Doppler Current Profiler (ADCP) measurements. In a number of years no data was collected, in particular during periods of the 1980s and 1990s, and in some years more data was collected than in others. A plot of year versus measured flow is shown in Figure 6-1.

![Figure 6-1: Measured flow versus year in the St. Clair River.](image)

All flow measurement data, including water levels at the time of measurement, were sorted in order of their time of collection. Each flow measurement was then compared to all other measurements taken at some time after it, and similar 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 and a difference in measured discharge of less than 100 m$^3$/s were identified (“Dataset 1”); second, all pairs of flow measurements separated by more than one year and having a difference in downstream water level at St. Clair Shores of less than 5 cm and a difference in upstream water level at Fort Gratiot of less than 5 cm were also identified (“Dataset 2”). Each of these two resulting sets of paired measurements can be considered to have the same boundary conditions, and the difference in their measured Fort Gratiot water level or measured discharge,
respectively, can be used to help identify possible changes in conveyance over time, without the use of a hydrodynamic model.

For “Dataset 1”, since the difference in water level at St. Clair Shores between each pair of measurements is within 5 cm and the difference in measured discharge is within 100 m$^3$/s, a difference in Fort Gratiot water level during these measurements could be used to indicate a change in conveyance. There are a number of additional factors that could impact the results of this analysis. These include: the water levels at the time of measurement, since it has been observed that the fall between Lake Huron and Lake Erie is greater during periods of high water levels than during periods of low water levels; the time of year, since weed growth could affect the measured flows (note that flow measurements are not normally conducted in the St. Clair River during periods of potential ice effects, so ice is not a factor in this analysis); meteorological factors, such as wind in particular, are known to cause differences in water level and flow in large channels such as the St. Clair River; and the differences in flow measurement methods and technologies used themselves (i.e. conventional versus ADCP measurements). It is difficult to separate these factors from the analysis of conveyance change, but these factors can cause a lot of noise in the comparison results, and possibly even cause an apparent change in conveyance to be observed where in fact none exists.

Similar to “Dataset 1”, the second set of paired observations, “Dataset 2”, was also used to infer changes in conveyance over time. Since in “Dataset 2” the difference in water level at St. Clair Shores and at Fort Gratiot between each pair of measurements was within 5 cm, a difference in measured flow could be used to indicate a change in conveyance over time in terms of discharge. Note that the same additional factors as outlined previously could impact the results of this analysis as well. Regardless, an attempt was made to identify possible changes in conveyance over time from the measured data pairs having similar boundary condition.

Descriptive statistics for the two datasets are given in Table 6-3 and Table 6-4. From the onset, it must be noted that these statistics are almost certainly biased due to the additional factors outlined above that affect the flow measurements. Nonetheless, the statistics give some indication that conveyance changes have occurred over time. The mean difference in Fort Gratiot water level for “Dataset 1” (Table 6-3) of 0.086 m indicates that, in general, the conveyance has increased over time. That is, given similar Lake St. Clair water levels and measured discharge values, the Fort Gratiot water level was, on average, 0.086 m higher in the earlier measurement than during the more recent measurement. The median value of 0.099 m is similar. However, the standard deviation of 0.101 m shows that there is a great deal of uncertainty in these estimates resulting from the additional factors outlined.
### Table 6-3: Difference in Fort Gratiot water level statistics for “Dataset 1”.

<table>
<thead>
<tr>
<th>Difference in Fort Gratiot Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Max</td>
</tr>
<tr>
<td>Min</td>
</tr>
</tbody>
</table>

Similarly, the mean difference in measured discharge for “Dataset 2” (Table 6-4) of -111 m³/s again indicates that, in general, the conveyance has increased over time. That is, given similar Lake St. Clair and Fort Gratiot water levels, the measured discharge was, on average, -111 m³/s lower in the earlier measurement than during the more recent measurement. The median value of -128 m³/s is similar, but again, the standard deviation of 244 m³/s shows that there is a great deal of uncertainty in these estimates.

### Table 6-4: Difference in measured discharge statistics for “Dataset 2”.

<table>
<thead>
<tr>
<th>Difference in Measured Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Max</td>
</tr>
<tr>
<td>Min</td>
</tr>
</tbody>
</table>

Since, as mentioned previously, these numbers are likely biased due to the additional factors affecting measured water levels and flows, an additional non-parametric assessment of the two datasets is given in Table 6-5. In this analysis, all pairs of measurements separated by more than one year or greater from both datasets were divided into three groups: those showing an increase in conveyance, those showing a decrease, and those showing no change. More specifically, in “Dataset 1”, where the downstream water level and measured discharge are approximately equal, all water level differences over time at Fort Gratiot of greater than 5 cm were assumed to show an increase in conveyance, all differences of less than -5 cm were assumed to show a decrease in conveyance, and all differences between these two values were assumed to show no change in conveyance. Similarly, in “Dataset 2”, where the downstream water level and measured discharge are approximately equal, all measured discharge differences over time of greater than 100 m³/s were assumed to show a decrease in conveyance, all discharge differences of less than -100 m³/s were assumed to show an increase in conveyance, and all differences between these two values were assumed to show no change.
Table 6-5: Non-parametric analysis of Datasets 1 and 2.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary Conditions</td>
<td>Difference in Lake St. Clair Water Level &lt; 5 cm</td>
<td>Difference in Lake St. Clair Water Level &lt; 5 cm</td>
</tr>
<tr>
<td>Total Pairs of Measurements</td>
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<td>909</td>
</tr>
<tr>
<td>One Year or Greater Apart</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Pairs Indicating</td>
<td>929</td>
<td>494</td>
</tr>
<tr>
<td>Increase in Conveyance over</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Pairs Indicating</td>
<td>169</td>
<td>163</td>
</tr>
<tr>
<td>Decrease in Conveyance over</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Pairs Indicating No</td>
<td>248</td>
<td>252</td>
</tr>
<tr>
<td>Change</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Indicating Increase in</td>
<td>69.0</td>
<td>54.3</td>
</tr>
<tr>
<td>Conveyance over Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Indicating Decrease in</td>
<td>12.6</td>
<td>17.9</td>
</tr>
<tr>
<td>Conveyance over Time</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It can be seen from this analysis that the majority of the pairs from both datasets indicate an increase 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. Likewise, up to 54.3-percent of all pairs indicated an increase in conveyance in “Dataset 2”, with only 17.9-percent showing a decrease. While not quantitative measures of conveyance changes, these statistics support both the hypothesis that the conveyance in the St. Clair River has changed, and the hypothesis that the change has been an increase in conveyance over time.

Note again, however, that these statistics can also be biased due to the reasons outlined. For example, if a number of measurements in either dataset are all taken from one year, and for whatever reason these all appear to show an increase in conveyance (which may be a real change in conveyance, or might be the result of a bias due to additional factors), then the results in Table 6-5 would also be biased to some degree. This possible bias has not been investigated further during this study.

Figure 6-2 shows the difference in discharge between pairs of measurements for each year given similar upstream and downstream water levels (i.e. the second set of paired observations). Each series in the plot is a year from 1962-1977 (labeled “Comparison Year 1”). The abscissa, labeled “Comparison Year 2”, is the year that each series is compared to. The left ordinate is the difference in discharge between the two years. There is obviously a great deal of uncertainty in these compared values, as
indicated by the scatter of measured values for each comparison. This is caused by the factors affecting flow measurements outlined above. However, it seems reasonable that if the majority of measurements fall below the zero difference in discharge line, this would indicate an increase in conveyance over time, whereas if most measurements fall above the zero line this would indicate a decrease in conveyance. The average difference in discharge (“Avg Q Dif”) for each set of paired measurements is also shown, as is the Fort Gratiot water level, which was plotted to help detect correlation with Lake Huron water level.

![Figure 6-2: Comparison of pairs of measured flows having similar upstream and downstream water levels (1962-1977 start year).](image)

The plotted results indicate that conveyance has changed from the 1962-1977 period, and that in general the change appears to be an increase in conveyance, as all but three average discharge differences fall below the zero difference line. Two notable exceptions are evident. The 1963 measurements, when compared to 1966, appear to show a decrease in conveyance. Likewise, the 1977 measurements, when compared to 1998, also show a decrease in conveyance, although this second comparison is based on only seven measurements. These discrepancies may be explained by additional factors. Otherwise nearly all measurements from the 1962-1977 period show an increase or no change in conveyance as evidenced by their average differences falling near or below the zero difference line. Once again, while any particular measurement or group of measurements may be biased, the fact that the majority of measurements appears to show an increase in conveyance lends evidence to this hypothesis. Also note that the apparent changes in conveyance are evident regardless of measurement technology.
used. For example, the 1968 conventional measurements show an increase in conveyance when compared to the 1977 conventional measurements, and a similar increase in conveyance when compared to the 1998 and 1999 ADCP measurements. From this plot there does not appear to be any relation between changes in conveyance and Fort Gratiot water level, though it may be hidden by other factors not considered, such as weed growth or wind effects on measurements. The correlation coefficient for average change in discharge versus Fort Gratiot water level was -0.16.

Figure 6-3 shows the same type of comparison, only the start year period ranges from 1981-1985. Note that there are not nearly as many measurements during this period, and subsequently not as many pairs for comparison. In any case from this plot there is little evidence supporting a conveyance change in one direction, as the average change is scattered fairly uniformly around the zero line. In addition, the average differences in discharge appear correlated with Fort Gratiot water level (correlation coefficient equal to 0.69). Lastly, Figure 6-3 shows the same type of comparison, only the start year period ranges from 1996-2005. Correlation between average discharge difference and water level is not as evident in this case (correlation coefficient equal to 0.17). In this plot, an increase in conveyance is again somewhat more evident than in the 1981-1985 plot (Figure 6-3), though certainty not conclusive and not nearly as obvious as in the 1962-1977 plot (Figure 6-2).

![Figure 6-3: Comparison of pairs of measured flows having similar upstream and downstream water levels (1981-1985 start year).](image-url)
Figure 6-4: Comparison of pairs of measured flows having similar upstream and downstream water levels (1996-2005 start year).

These plots are meant to illustrate a number of points. First, the scatter in the data is clearly evident. This is the result of biases caused by the additional issues described above, or measurement error, or both. Regardless, the noise in the measurement data will have a significant impact on the results of any hydrodynamic model calibration, and this will be discussed further in subsequent sections. Second, all three plots indicate that the system is very dynamic, as apparent changes in conveyance occur in both directions, whether they are the result of actual conveyance changes or otherwise. Lastly, regardless of the many issues and potential biases, it may be possible for this data to help identify the potential timing of conveyance changes. For example, Figure 6-2 appears to indicate that any changes in conveyance occurred early in the post-dredging period, since nearly all comparisons of years from 1962-1977 to later years tend to show an increase in conveyance. Such a trend is not as evident in the other plots. It is suggested that the possible use of this data to determine the timing of changes should be investigated further.

In addition, comparisons of measured flows and water levels may be used to help identify areas of the river where conveyance changes have occurred. Similar to the plots of compared flows and comparisons of water levels at Fort Gratiot as shown above, water levels can be compared at other gauge locations. The differences in water levels at these locations can be used to determine where changes in conveyance have occurred over time. Water surface profiles can also be plotted and compared to
estimate location of changes. An example is given in Figure 6-5. In this the changes in conveyance observed appear to have occurred throughout the river. Note that as explained above, there would be uncertainty in any type of analysis such as this due to the noise in the measured data itself, as well as the additional factors affecting the results. Nonetheless, further investigations of the locations of changes in the river using this data may be worthwhile.

![Water Surface Profile Comparison from Measured Flow Data](image)

**Figure 6-5:** Example comparison of water surface profiles having similar boundary conditions.

### 6.3 Model Recalibration

Following the analysis of measured data, an attempt was made to recalibrate the 1971, 2007 and 2007SSB71 models to measured water levels and flows. The goal was to use measured water level and flow data collected around 1971 to calibrate the 1971 model, and additional measured water level and flow data collected around 2007 to calibrate each of the two 2007 models (i.e. 2007 full density and 2007SSB71). It was suggested that the results from the recalibrated models could be compared under average boundary conditions to determine changes in conveyance, taking into account both changes in channel geometry and roughness over time. As discussed, Manning’s roughness coefficient $n$ was used as the calibration variable. Peclet number was held at the original value of 21.9011 determined by Holtschlag and Koschik (2001). The model mesh density was also held constant for all calibrations.
In the previous section, Figure 6-1 showed measured flows versus the year they were collected. As was seen in this plot, measured flow data is not available for 1971. The two closest years for which measurements were collected are 1968 and 1973. Though measured flow data was collected in 2007, it was unavailable at the time of this analysis; however, data was available and collected for a number of years immediately prior to 2007.

Initially data from 1968 and 1973 was going to be used to calibrate the 1971 model, while data from 2004 to 2006 was going to be used to calibrate the 2007 models. That being said, it quickly became apparent that significant differences exist between these two eras and their measurements. These differences could affect the calibrations, and would certainly affect any comparison of the models from the two eras. First, these eras correspond to different water level and flow regimes, with the 1971 era corresponding to relatively higher water levels and flows, and the 2007 era corresponding to relatively lower water levels and flows. A model calibrated at one regime may not be applicable at a different regime, and therefore any comparison of models calibrated at different regimes would be biased due to these differences alone. Second, the method of data collection is different between the two eras, as the measurements prior to 1996 were taken with a conventional current metre, while those taken from this point on were collected with ADCP technology. In this analysis it was assumed that the conventional and ADCP measurements were for the most part unbiased, but this caveat should be noted.

An attempt was instead made to calibrate the models from each era to measurements taken during similar water level and flow regimes. In order to calibrate each model to a broad range of comparable water levels and flows, it was assumed that all conventional measurements (1962 to 1985) were applicable to the 1971 model, and all ADCP measurements (1996-2006) were applicable to the 2007 model. Measurements from each era having comparable model boundary conditions (i.e. Lake St. Clair water level within 5 cm and measured discharge within 100 m³/s) as identified in the previous section were sorted in order of discharge. Three sets of five paired measurements were then chosen from this list arbitrarily, but with an effort to cover a full range of water levels and flows. Each model was then calibrated three times using the three sets of measurements. The measurements used for each calibration are given in Table A1 in the Appendix. Note that some measurements had to be used in more than one calibration in order to cover the full range of water levels and flows. This was especially true at the higher water levels and flows, for which there were fewer measurements having similar boundary conditions.

All calibrations were performed using Universal Parameter Estimate Code (UCODE) as developed by Poeter et al (2005). UCODE can be used to automatically compare measured observations to model-simulated equivalents. The sensitivities of the model-simulated values to changes in model calibration parameters are also calculated, and the parameters are subsequently modified in an iterative fashion until a
solution is reached that minimizes the objective function equal to the sum of squared weighted residuals within user-specified criteria. For this study involving the RMA2 model of the St. Clair River, the measured observations and model-simulated equivalents were water levels at gauge stations located along the river. Model calibration parameters were Manning’s roughness coefficients, $n$. The convergence criteria were specified as a maximum fractional change in parameter values of less than 0.01 (1%).

Manning’s roughness coefficients are specified in the RMA2 model for a number of zones. For this analysis the roughness zones in Lake St. Clair and much of the St. Clair River Delta were kept constant. Only the roughness zones in areas of the main river channel and the main shipping channel of the St. Clair delta were allowed to change. Furthermore, the number of available water level stations and their locations limited the number of different Manning’s roughness zones that could be modified in the calibration. Given the available calibration data, it was found that the model parameter estimation would not converge for any more than four Manning’s $n$ zones. In comparison, the original RMA2 model developed by Holtschlag and Koschik (2001) used seven roughness coefficient zones in the main river and shipping channel of the delta, but they also used additional calibration data, including velocity and flow distribution around islands, which was unavailable for this analysis. The four roughness zones used in this analysis were discretized based on the locations of the gauges themselves and assumptions made regarding the geometry of the channel. The locations of the roughness zones and the gauge stations are shown in Figure 6-6.

Each calibration was run on multiple processors running in parallel, yet each still took anywhere from 8 to 24 hours to converge on a solution. A total of nine calibrations were attempted (three each for the 1971, 2007 and 2007SSB71 models). Of these, two calibrations failed to converge on a solution under the specified convergence criteria (Calibration 3 for the 1971 model, and Calibration 1 for the 2007SSB71 model). It is possible that by relaxing the convergence criteria or by making additional minor modifications that these calibrations could also have been made to converge. However, given the time required for each calibration run and the deadlines of the study, this was not possible.

The final sum of squared weighted residuals for each calibration scenario are shown in Table 6-6. The two calibrations that failed to converge are noted, but they have been kept in this analysis by accepting the successful iteration having the lowest sum of squared weighted residual objective function. As can be seen, the objective function results of these two scenarios fall within the range of the other successful scenarios, indicating that the errors in these calibrations are similar to those scenarios that did converge.
Figure 6-6: Location of roughness zones and water level gauge stations.
### Table 6-6: Sum of squared weighted residuals for all calibration scenarios (highlighted scenarios failed to converge).

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Sum Squared Weighted Residuals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calibration 1</td>
</tr>
<tr>
<td>1971</td>
<td>319.43</td>
</tr>
<tr>
<td>2007</td>
<td>82.298</td>
</tr>
<tr>
<td>2007SSB71</td>
<td><strong>89.24</strong></td>
</tr>
</tbody>
</table>

It can also be seen in Table 6-6 that the two 2007 models gave very similar results. This is an indication that the calibration data itself influences the calibrated model results. Furthermore, the 1971 model had higher error values than the two 2007 models. This is likely a reflection of the differences in measurement technologies used in each era (i.e. conventional versus ADCP measurements). It generally takes longer to complete a single conventional measurement than it does to complete an ADCP measurement. The steady state assumption over a longer period of measurement may be less valid, which likely results in greater error in the measured water levels and subsequently greater error in model calibration results for the conventional measurements than the ADCP measurements.

An analysis of the residuals for each specific gauge was also performed. The results for the 1971, 2007 and 2007SSB71 models are given in Table 6-7, Table 6-8 and Table 6-9, respectively. The average and standard error values of the residuals from the calibrations, as well as the maximum and minimum errors, are given for each set of five calibration measurements. In general, the simulated water level errors increase as one moves up the channel from Lake St. Clair to Lake Huron. This is primarily the result of moving further away from the downstream boundary, which was fixed as a water level value at the St. Clair Shores gauge. In addition, it was found to be difficult to calibrate simulated water levels to measured water levels at the most upstream gauge locations, in particular at Fort Gratiot, Dunn Paper and Point Edward. These three gauges are located very close together, yet this area of the river also corresponds to a very steep drop in the river bed, a significant restriction of the channel as Lake Huron enters the St. Clair River, and a sharp curvature or bend in the river. It is likely that the close proximity of these gauges, the geometric features of the channel in this area, and the limitations and assumptions characterizing the RMA2 model code prevent the model from properly capturing the hydraulics in this area of the river. The result is that during calibration, errors in the simulated water level at the Fort Gratiot gauge were found to be on average -1 or -2 cm, while average errors in the simulated water level at Dunn Paper and Point Edward ranged from -6 to 4 cm. Standard errors ranged between 3 and 7 cm for the three gauge stations. This provides an indication of the uncertainty in both the measured and simulated water levels for these three gauges.
<table>
<thead>
<tr>
<th>Gauge</th>
<th>Average Cal. 1</th>
<th>Average Cal. 2</th>
<th>Average Cal. 3</th>
<th>Standard Error Cal. 1</th>
<th>Standard Error Cal. 2</th>
<th>Standard Error Cal. 3</th>
<th>Maximum Cal. 1</th>
<th>Maximum Cal. 2</th>
<th>Maximum Cal. 3</th>
<th>Minimum Cal. 1</th>
<th>Minimum Cal. 2</th>
<th>Minimum Cal. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fort Gratiot</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>0.06</td>
<td>0.04</td>
<td>0.05</td>
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<td>0.04</td>
<td>0.04</td>
<td>-0.07</td>
<td>-0.07</td>
<td>-0.07</td>
</tr>
<tr>
<td>Dunn Paper</td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
<td>0.06</td>
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<td>0.10</td>
<td>0.11</td>
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<td>-0.01</td>
<td>-0.02</td>
</tr>
<tr>
<td>Point Edward</td>
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<td>-0.06</td>
<td>-0.06</td>
<td>0.06</td>
<td>0.03</td>
<td>0.04</td>
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<td>-0.02</td>
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</tr>
<tr>
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<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
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<td>-0.05</td>
<td>-0.05</td>
</tr>
<tr>
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<td>0.02</td>
<td>0.06</td>
<td>0.04</td>
<td>0.05</td>
<td>0.11</td>
<td>0.06</td>
<td>0.07</td>
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<td>-0.16</td>
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</tbody>
</table>

Table 6-7: Residual statistics from 1971 model calibrations.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Average Cal. 1</th>
<th>Average Cal. 2</th>
<th>Average Cal. 3</th>
<th>Standard Error Cal. 1</th>
<th>Standard Error Cal. 2</th>
<th>Standard Error Cal. 3</th>
<th>Maximum Cal. 1</th>
<th>Maximum Cal. 2</th>
<th>Maximum Cal. 3</th>
<th>Minimum Cal. 1</th>
<th>Minimum Cal. 2</th>
<th>Minimum Cal. 3</th>
</tr>
</thead>
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<tr>
<td>Fort Gratiot</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
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<td>0.03</td>
<td>-0.07</td>
<td>-0.09</td>
<td>-0.07</td>
</tr>
<tr>
<td>Dunn Paper</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.09</td>
<td>0.08</td>
<td>0.10</td>
<td>-0.02</td>
<td>-0.04</td>
<td>-0.02</td>
</tr>
<tr>
<td>Point Edward</td>
<td>-0.02</td>
<td>-0.03</td>
<td>-0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.06</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
<td>-0.08</td>
<td>-0.10</td>
<td>-0.09</td>
</tr>
<tr>
<td>M. Black River</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
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<td>0.09</td>
<td>-0.03</td>
<td>-0.06</td>
<td>-0.04</td>
</tr>
<tr>
<td>Dry Dock</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.06</td>
<td>0.08</td>
<td>-0.02</td>
<td>-0.03</td>
<td>-0.03</td>
</tr>
<tr>
<td>St. Clair Police</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
<td>0.05</td>
<td>-0.03</td>
<td>-0.05</td>
<td>-0.04</td>
</tr>
<tr>
<td>Port Lambton</td>
<td>0.01</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.07</td>
<td>-0.04</td>
<td>-0.04</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Table 6-8: Residual statistics from 2007 model calibrations.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Average Cal. 1</th>
<th>Average Cal. 2</th>
<th>Average Cal. 3</th>
<th>Standard Error Cal. 1</th>
<th>Standard Error Cal. 2</th>
<th>Standard Error Cal. 3</th>
<th>Maximum Cal. 1</th>
<th>Maximum Cal. 2</th>
<th>Maximum Cal. 3</th>
<th>Minimum Cal. 1</th>
<th>Minimum Cal. 2</th>
<th>Minimum Cal. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fort Gratiot</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
<td>0.05</td>
<td>0.07</td>
<td>0.03</td>
<td>-0.07</td>
<td>-0.08</td>
<td>-0.07</td>
</tr>
<tr>
<td>Dunn Paper</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>0.09</td>
<td>0.07</td>
<td>0.08</td>
<td>-0.03</td>
<td>-0.05</td>
<td>-0.03</td>
</tr>
<tr>
<td>Point Edward</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
<td>-0.09</td>
<td>-0.11</td>
<td>-0.09</td>
</tr>
<tr>
<td>M. Black River</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.09</td>
<td>-0.03</td>
<td>-0.06</td>
<td>-0.04</td>
</tr>
<tr>
<td>Dry Dock</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.08</td>
<td>-0.02</td>
<td>-0.03</td>
<td>-0.03</td>
</tr>
<tr>
<td>St. Clair Police</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>0.01</td>
<td>0.04</td>
<td>0.05</td>
<td>-0.02</td>
<td>-0.05</td>
<td>-0.04</td>
</tr>
<tr>
<td>Port Lambton</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.05</td>
<td>0.05</td>
<td>0.00</td>
<td>-0.03</td>
<td>-0.02</td>
</tr>
<tr>
<td>Algonac</td>
<td>0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.00</td>
<td>-0.04</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Table 6-9: Residual statistics from 2007SSB71 model calibrations.

The roughness coefficients for each calibration scenario are given in Table 6-10, and a comparative plot is shown in Figure 6-7. For any given model the calibrated roughness coefficients for Zones 1, 2 and 3 did not vary significantly; however, the coefficients for Zone 4, in the St. Clair delta, did show significant variation, as can be seen below. This likely reflects the fact that the simulated water levels were found to be
least sensitive to changes in this roughness coefficient of this zone than the other zones. Furthermore, the simulated water level at Algonac was found to be sensitive to this zone almost exclusively, and therefore the differences in roughness coefficients likely reflect the uncertainty in the observed water levels at this gauge.

![Calibrated Manning’s roughness coefficients for each model.](image)

Table 6-10: Calibrated roughness coefficients for each model.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Calibration #</th>
<th>Calibrated Manning’s Roughness Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zone 1</td>
<td>Zone 2</td>
</tr>
<tr>
<td>1971</td>
<td>0.0289</td>
<td>0.0241</td>
</tr>
<tr>
<td>2</td>
<td>0.0293</td>
<td>0.0238</td>
</tr>
<tr>
<td>3</td>
<td>0.0293</td>
<td>0.0238</td>
</tr>
<tr>
<td>2007</td>
<td>0.0311</td>
<td>0.0261</td>
</tr>
<tr>
<td>2</td>
<td>0.0315</td>
<td>0.0270</td>
</tr>
<tr>
<td>3</td>
<td>0.0311</td>
<td>0.0263</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>0.0285</td>
<td>0.0244</td>
</tr>
<tr>
<td>2</td>
<td>0.0289</td>
<td>0.0252</td>
</tr>
<tr>
<td>3</td>
<td>0.0285</td>
<td>0.0244</td>
</tr>
</tbody>
</table>
It is also notable that the roughness coefficients for the 2007 model are generally higher than those for the 1971 and 2007SSB71 models. This is likely a result of the differences in bathymetric data density and subsequent differences in form roughness. As described previously, the low-density models have higher form roughness than the 2007 high-density multi-beam model. The roughness coefficients in the 2007 full-density model were therefore found to be higher than those in the two low density models. In effect the differences in the roughness coefficients are in part compensating for the differences in form roughness between the different models.

Lastly, a comparison of the roughness coefficients between the two low-density models (i.e. 1971 and 2007SSB71) shows them to be similar (Table 6-11). Since these two models were created with bathymetry data of equal density, the effects of form roughness on the comparison should be negligible. The similarity of the calibrated roughness coefficients for these two models is evidence that the model roughness has likely not changed significantly over time despite the observed changes in channel geometry.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Calibrated Manning's Roughness Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zone 1</td>
</tr>
<tr>
<td>1971</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.0291</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.0002</td>
</tr>
<tr>
<td>2007SSB71</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.0286</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.0002</td>
</tr>
<tr>
<td>Difference in Average</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Table 6-11: Comparison of calibrated roughness coefficients for 1971 and 2007SSB71 models.

Each calibrated model was then simulated under average water level and discharge conditions to estimate changes in conveyance over time given the same boundary conditions. The results are given in Table 6-12. The 1971 simulated water levels were similar for all three calibrations. Also, when comparing the same calibration in the 2007 and 2007SSB71 model (e.g. Calibration 1 for both), the results are also similar (Table 6-13). This is expected since these models were calibrated to the same data, and recall that the calibrated roughness coefficients will compensate for differences in form roughness. However, it can be seen that for both 2007 models the water levels simulated with Calibration 2 were higher than those simulated with the other two calibrations, especially in the upper portion of the river. A closer look at the roughness coefficients for Calibration 2 (Figure 6-7, shown previously) indicates that they are higher than those determined for Calibrations 1 and 3, and hence the higher simulated water levels.
### Table 6-12: Simulated model result under average boundary conditions.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Calibration #</th>
<th>Fort Gratiot</th>
<th>Dunn Paper</th>
<th>Point Edward</th>
<th>Black River</th>
<th>Dry Dock</th>
<th>St. Clair Police</th>
<th>Port Lambrton</th>
<th>Algonac</th>
<th>St. Clair Shores</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>1</td>
<td>176.61</td>
<td>176.44</td>
<td>176.43</td>
<td>176.35</td>
<td>176.23</td>
<td>175.86</td>
<td>175.50</td>
<td>175.46</td>
<td>175.29</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>176.61</td>
<td>176.44</td>
<td>176.42</td>
<td>176.34</td>
<td>176.23</td>
<td>175.86</td>
<td>175.49</td>
<td>175.44</td>
<td>175.29</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>176.61</td>
<td>176.45</td>
<td>176.42</td>
<td>176.35</td>
<td>176.23</td>
<td>175.87</td>
<td>175.47</td>
<td>175.42</td>
<td>175.29</td>
</tr>
<tr>
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<td>176.36</td>
<td>176.35</td>
<td>176.29</td>
<td>176.17</td>
<td>175.85</td>
<td>175.48</td>
<td>175.43</td>
<td>175.29</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>176.58</td>
<td>176.41</td>
<td>176.39</td>
<td>176.34</td>
<td>176.21</td>
<td>175.88</td>
<td>175.51</td>
<td>175.45</td>
<td>175.29</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>176.54</td>
<td>176.37</td>
<td>176.35</td>
<td>176.30</td>
<td>176.18</td>
<td>175.86</td>
<td>175.50</td>
<td>175.45</td>
<td>175.29</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>1</td>
<td>176.52</td>
<td>176.36</td>
<td>176.35</td>
<td>176.28</td>
<td>176.17</td>
<td>175.85</td>
<td>175.48</td>
<td>175.43</td>
<td>175.29</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>176.57</td>
<td>176.41</td>
<td>176.39</td>
<td>176.33</td>
<td>176.22</td>
<td>175.88</td>
<td>175.50</td>
<td>175.45</td>
<td>175.29</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>176.53</td>
<td>176.37</td>
<td>176.35</td>
<td>176.29</td>
<td>176.18</td>
<td>175.86</td>
<td>175.50</td>
<td>175.45</td>
<td>175.29</td>
</tr>
</tbody>
</table>

### Table 6-13: Comparison of simulated results for 2007 and 2007SSB71 Models

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Fort Gratiot</th>
<th>Dunn Paper</th>
<th>Point Edward</th>
<th>M. Black River</th>
<th>Dry Dock</th>
<th>St. Clair Police</th>
<th>Port Lambrton</th>
<th>Algonac</th>
<th>St. Clair Shores</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>3</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 6-14, Table 6-15 and Table 6-16 show comparisons of the differences in simulated water levels over time (1971 to 2007) for Calibration 1, 2 and 3, respectively. At Fort Gratiot, Calibration 1 indicates a difference in water level of 0.08 or 0.09 m from 1971 to 2007, depending on the 2007 model used. Calibration 2, however, only shows a difference of 0.03 or 0.04 m, while Calibration 3 shows a difference of 0.07 or 0.08 m.
<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Comparison</th>
<th>Difference in Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fort Gratiot</td>
</tr>
<tr>
<td>Difference in WL simulated by calibrated models</td>
<td>1971-2007</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>1971-2007SSB71</td>
<td>0.04</td>
</tr>
<tr>
<td>Avg. difference in WL from observed data</td>
<td>1971-2007</td>
<td>0.04</td>
</tr>
<tr>
<td>Residual (Simulated – Observed)</td>
<td>1971-2007</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>1971-2007SSB71</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 6-15: Comparison of simulated versus observed water level differences over time for Calibration 2.

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Comparison</th>
<th>Difference in Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fort Gratiot</td>
</tr>
<tr>
<td>Difference in WL simulated by calibrated models</td>
<td>1971-2007</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>1971-2007SSB71</td>
<td>0.08</td>
</tr>
<tr>
<td>Avg. difference in WL from observed data</td>
<td>1971-2007</td>
<td>0.08</td>
</tr>
<tr>
<td>Residual (Simulated – Observed)</td>
<td>1971-2007</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>1971-2007SSB71</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 6-16: Comparison of simulated versus observed water level differences over time for Calibration 3.

The differences in these simulated results (and also the differences in simulated Fort Gratiot water level for Calibration 2) can be explained by the flow measurement and water level data used in each of the calibrations. The average differences in observed water level over time from the calibration data itself are also given in each table above. As can be seen, the difference in simulated results tends to match the difference in the average observed water levels used to calibrate the models (i.e. the difference in simulated water level at each gauge was very close to the observed average difference in water level seen in the measurements). The residuals in this comparison can be explained by error in the calibrated models and minor differences in boundary conditions (i.e. discharge and St. Clair Shores water level are similar but not exact). As was discussed in Section 6.2, given very similar Lake St. Clair water level and measured discharge, the measured Fort Gratiot water level was seen to vary significantly, such that any observed changes in conveyance depended on the measurements chosen. This also explains the observed differences in the simulated
results from Calibration 2 for the two 2007 models. On average, the arbitrarily chosen calibration data for Calibration 2 shows higher water levels in the upper river than the other two calibrations for this year. The model, when calibrated to this data, results in an increased Manning’s roughness in order to match the simulated water levels to the observed values.

These results reveal the major problem with this analysis. What they suggest is that even if the models could be calibrated perfectly to observed water levels and flows (i.e. all errors being negligible), a comparison of conveyance change over time as simulated by the calibrated hydraulic models under average conditions would depend entirely on the data chosen for calibration, and would therefore provide us with no additional information than the measured data itself. That is, the modelled differences reflect the differences observed in the calibration data only, and not necessarily differences related to changes in conveyance. The calibration parameters, in this case roughness coefficients, are modified during calibration to fit the observed data. Therefore, even if both the observations themselves and the model calibrations fitting those observations were perfect, the models would give us no additional information in terms of whether conveyance has changed. Since in reality neither the data itself nor the calibration is free of error, this analysis is even more questionable.

With additional time and resources, a more thorough analysis, including more detailed investigations of calibration uncertainty, could be performed. However, given the results shown, it seems unlikely that further analysis using the RMA2 model would provide any additional information about whether conveyance in the St. Clair River has changed. An investigation of the measured water level and flow data indicates that the conveyance has changed, and that the change is likely an increase. Hydrodynamic models can be used to test different factors causing conveyance changes and give an estimate of the magnitude of these changes given known characteristics of the river, such as information on the channel geometry, for example, as was done in Phase 1 and 2 of the St. Clair RMA2 analysis.

### 6.4 Additional Analysis Regarding Manning’s Roughness Coefficient

As seen, little additional information regarding conveyance change could be garnered from the recalibration analysis. However, it was also shown in Section 6.1 that, in addition to the channel geometry, the conveyance change estimate is sensitive to the choice of Manning’s $n$. The measured data itself also indicates changes in conveyance have occurred, though of an unknown magnitude. The effects of changes in channel geometry on conveyance were investigated in Phase 1 and 2. To refine the estimate of
conveyance change over time due to potential changes in Manning’s roughness, further sensitivity analyses were performed on this variable.

A sensitivity analysis was performed using the roughness coefficients as found from the recalibrated St. Clair RMA2 models described above. Specifically, each model was run using both the maximum calibrated roughness coefficients found for each zone during the recalibration analysis, and the minimum roughness coefficients found for each zone. The models were also run with the maximum and minimum roughness coefficients increased or decreased in magnitude by 5-percent, respectively. Lastly, the 1971 model was run using the 2007SSB71 model coefficients, and vise versa, in order to compare results assuming no change in roughness has occurred, similar to the assumptions of Phase 1 and 2 of this study, but given the new roughness coefficients as calibrated. The roughness coefficients used are seen in Table 6-17.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Scenario</th>
<th>Calibrated Manning’s Roughness Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Zone 1</td>
</tr>
<tr>
<td>1971</td>
<td>Max</td>
<td>0.02931</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.02886</td>
</tr>
<tr>
<td></td>
<td>Max + 5%</td>
<td>0.03078</td>
</tr>
<tr>
<td></td>
<td>Min - 5%</td>
<td>0.02742</td>
</tr>
<tr>
<td>2007</td>
<td>Max</td>
<td>0.03147</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.03106</td>
</tr>
<tr>
<td></td>
<td>Max + 5%</td>
<td>0.03304</td>
</tr>
<tr>
<td></td>
<td>Min - 5%</td>
<td>0.02951</td>
</tr>
<tr>
<td>2007SSB71</td>
<td>Max</td>
<td>0.02886</td>
</tr>
<tr>
<td></td>
<td>Min</td>
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</tr>
<tr>
<td></td>
<td>Max + 5%</td>
<td>0.03030</td>
</tr>
<tr>
<td></td>
<td>Min - 5%</td>
<td>0.02710</td>
</tr>
</tbody>
</table>

Table 6-17: Maximum and minimum roughness coefficients used in sensitivity analysis.

The simulated results of all model runs are given in Table 6-18, and a comparison of the results for the two low-density models is shown in Table 6-19. As can be seen, if the assumption that no change in Manning’s roughness coefficient is made (as was done in Phase 1 and 2 of this study), given coefficients as determined from the recalibrated single-beam models, the resulting change in water level was found to be 0.11 m, regardless of the coefficients chosen. This is close to the 0.12 m found in Phase 1.
<table>
<thead>
<tr>
<th>Model Year</th>
<th>Scenario</th>
<th>Simulated Fort Gratiot Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>Max</td>
<td>176.645</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>176.573</td>
</tr>
<tr>
<td></td>
<td>Max + 5%</td>
<td>176.734</td>
</tr>
<tr>
<td></td>
<td>Min - 5%</td>
<td>176.489</td>
</tr>
<tr>
<td></td>
<td>Max (2007SSB71)</td>
<td>176.682</td>
</tr>
<tr>
<td></td>
<td>Min (2007SSB71)</td>
<td>176.619</td>
</tr>
<tr>
<td>2007</td>
<td>Max</td>
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</tr>
<tr>
<td></td>
<td>Min</td>
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</tr>
<tr>
<td></td>
<td>Max + 5%</td>
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</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>Min - 5%</td>
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</tr>
<tr>
<td></td>
<td>Max (1971)</td>
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</tr>
<tr>
<td></td>
<td>Min (1971)</td>
<td>176.465</td>
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Table 6-18: Simulated water levels for Manning’s roughness scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Difference in Simulated Fort Gratiot Water Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>1971-2007SSB71</td>
</tr>
<tr>
<td>No Change</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max (2007SSB71) - Max (2007SSB71) 0.11</td>
</tr>
<tr>
<td></td>
<td>Min (2007SSB71) - Min (2007SSB71) 0.11</td>
</tr>
<tr>
<td></td>
<td>Max (1971) - Max (1971) 0.11</td>
</tr>
<tr>
<td></td>
<td>Min (1971) - Min (1971) 0.11</td>
</tr>
<tr>
<td>Observed</td>
<td></td>
</tr>
<tr>
<td>(Calibration Change)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max (1971) - Max (2007SSB71) 0.08</td>
</tr>
<tr>
<td></td>
<td>Min (1971) - Min (2007SSB71) 0.06</td>
</tr>
<tr>
<td></td>
<td>Max (1971) - Min (2007SSB71) 0.14</td>
</tr>
<tr>
<td></td>
<td>Min (1971) - Max (2007SSB71) 0.00</td>
</tr>
<tr>
<td>Hypothetical</td>
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<tr>
<td>Extreme</td>
<td>Change</td>
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<tr>
<td></td>
<td>Max (1971+5%)-Max (2007SSB71+5%) 0.08</td>
</tr>
<tr>
<td></td>
<td>Min (1971-5%)-Min (2007SSB71-5%) 0.06</td>
</tr>
<tr>
<td></td>
<td>Max (1971+5%)-Min (2007SSB71-5%) 0.31</td>
</tr>
<tr>
<td></td>
<td>Min (1971-5%)-Max (2007SSB71+5%) -0.17</td>
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</table>

Table 6-19: Manning’s roughness coefficient sensitivity analysis comparison.

Furthermore, if the maximum and minimum observed calibration parameters are used in the two low-density models, various comparison combinations give different results for the difference in simulated Fort Gratiot water level over time. For example, if the maximum coefficients found for both models are used, the difference in Fort Gratiot water level is 0.08 m. If the minimum coefficients found for each model are used, the
difference is only 0.06 m. If the maximum from the 1971 model and the minimum from the 2007SSB71 model are used, the difference is 0.14 m, whereas if the reverse is true the difference is zero. None of these scenarios is considered any more likely than the others, yet while these estimates all differ in magnitude, other than the final parameter combination all showed an increase in conveyance over time. Furthermore, even if one looks at the unlikely but hypothetical extreme changes in roughness coefficients, only one hypothetical scenario (Min (1971-5%)-Max (2007SSB71+5%)) showed a decrease in conveyance, whereas all other scenarios showed an increase.

None of these scenarios specifically can be identified as likely to have occurred, and as noted from the recalibration analysis, there is little evidence to suggest that Manning’s roughness has changed over time. A comparison of the average roughness coefficients from the three calibrations performed on the low-density 1971 and 2007SSB71 models (Table 6-11) showed that the calibration parameter Manning’s $n$ differed at only the fourth decimal place for Zones 1, 2 and 3, and the third decimal place in Zone 4 (though Zone 4 was also found to be sensitive to uncertainties in the measured water level at Algonac). However, what this sensitivity analysis does show is the possible range in estimates of the change in conveyance over time. It also suggests that even if one assumes changes in roughness coefficient have occurred, however unlikely, the result is that these changes combined with changes in channel geometry have likely caused an increase in conveyance over time. Without additional evidence to suggest a real change in roughness, the results of Phase 1 and 2 must be assumed to provide our best estimate of the magnitude of these changes.

7. Summary

This addendum to Phase 1 and 2 of the RMA2 analysis for the International Upper Great Lakes Study was completed in response to issues raised by peer reviewers and Study management. Hopefully it has addressed many of the questions and concerns peer reviewers and Study management may have had regarding the meaning and significance of the RMA2 modelling results, and hopefully it also shows the diligence and attention that was given to many of the issues identified by both the authors and others during this study.

The results of the RMA2 modelling completed by Baird differed from the results presented in Phase 1 of this study. Investigation of these differences has shown that the most significant cause of the differences between the 1971 and 2000 model comparisons is the shoreline assumption used. Additional factors, including interpolation method, roughness coefficients and boundary conditions used make up the remaining differences. That being said, it was also found that the assumptions made regarding these factors only affect the results when data of unequal density are compared. When data of equal density are used, the effect of the different assumptions is negligible.
Additional discussion was presented regarding the RMA2 model results, including the results of the uncertainty analysis. A convergence test showed that results were not likely sensitive to mesh density used. Model boundary conditions are consistent with conditions on the St. Clair River itself. Variogram comparisons and Monte Carlo analysis results indicate that the probabilistic model meshes have greater form roughness than the original model. The result of this increase in form roughness is likely an increase in simulated water level of only a few centimetres at Fort Gratiot, and so long as data of equal density is compared, the results of increased form roughness on comparisons over time are negligible.

The comparison and analysis of measured flow data pairs having similar boundary conditions shows that the system is dynamic. The data appears to indicate that the conveyance has changed over time, and also that this change is likely an increase. With further analysis, this data may be able to help identify the time of changes in conveyance, and also the location in the river where possible changes have occurred.

The measured flows available and the noise observed in the measured data itself makes it impossible to compare calibrated RMA2 models from the two eras, 1971 and 2007, for which bathymetric data is available. The error in the measured water levels and flows and the model calibration error make it difficult to make any meaningful comparisons. Furthermore, and most importantly, any comparison of modelled results would be biased by the arbitrary choice of measurements used. Even a model perfectly calibrated to measured data would be biased by the measured flows and water levels chosen, and would therefore tell us nothing more than the data itself. Therefore, recalibrated hydrodynamic models are inappropriate for this type of analysis.

On the other hand, a hydrodynamic model is appropriate for helping estimate the magnitude of changes based on known characteristics of the channel in time. The Phase 1 and Phase 2 analyses estimated that the geometry by itself may be responsible for approximately 12 +/- 3 cm of the apparent change in fall between Lake Huron and Lake Erie over time. The additional sensitivity analysis on Manning’s roughness conducted in this addendum indicates that when possible roughness changes are combined with changes in channel geometry, the final result is still likely an increase in conveyance over time. However, given little if any evidence of a change in roughness over time, the estimated magnitude of these changes can not be refined further.
8. References


9. Appendix
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<th>End Time</th>
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<th>ADCP (2007 Models)</th>
<th>Conventional (1971 Model)</th>
<th>Water Level (m)</th>
<th>Water Level (m)</th>
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<td>175.700</td>
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Table A1: Measured flows and water levels used for calibration analysis
St. Clair RMA2 Modelling - Peer Review Response

Jacob Bruxer and Aaron Thompson, P. Eng.

Overview

The authors would like to first thank Dr. Colin Rennie and Dr. Brian Barkdoll for their reviews of the reports by Bruxer and Thompson regarding the RMA2 modelling of the St. Clair River performed for the International Upper Great Lakes Study (IUGLS) as part of the St. Clair River Task Team (Bruxer and Thompson, 2008a; Bruxer and Thompson, 2008b; Bruxer, 2009). The authors would also like to apologize to the reviewers for not consolidating the three reports into one final version, but we hope the reviewers understand that this was necessary given Study deadlines and the evolving nature of both the Study and our work as part of it.

This document is in response to the reviewer’s comments and concerns as outlined in their reports. Part One is in response to the comments received from Dr. Rennie (Rennie, 2009), while Part Two is in response to those comments received from Dr. Barkdoll (Barkdoll, 2009).

Part One: Response to Dr. Colin Rennie’s Review

Dr. Rennie (the reviewer) made suggestions in a number of areas and under a number of subheadings. Responses to these suggestions are discussed in the same sequence below.

1) Calibration Data

The reviewer asks for confirmation as to whether monthly flows and water levels were used in the calibration of the revised St. Clair RMA2 model. As the reviewer understands, the model used in the study was derived from an existing model of the entire St. Clair – Detroit River system developed by Holtschlag and Koschik (2001). After making a number of revisions to this original model, validation was performed on the revised model using monthly flows as derived from stage-fall-discharge equations and measured average monthly water levels. While the flow in the St. Clair River is considered unsteady on a shorter time scale, over the course of a month the flow is likely sufficiently steady such that these assumptions are appropriate. Furthermore, in this study the RMA2 model was not used in a transient mode, but rather it was only run under steady conditions in order to determine the difference in conveyance capacity of the channel between years. Under these circumstances the authors argue that the model need only be calibrated to a reasonable degree of accuracy, so long as sensitivity
analysis is conducted on model calibration parameters in order to estimate how uncertainties in these parameters affect model-simulated differences in water levels and flows over time. Such a sensitivity analysis was performed by the authors, and it was observed that given a realistic range of possible calibration parameters, the simulated water level and flows of one model may change, but the differences in water level and flows between different models developed for different years, which was the primary question being answered, did not change significantly.

2) Error Analysis

The reviewer asks for additional statistics and clarification regarding the model validation performed in Bruxer and Thompson (2008a). Specifically, the reviewer asked for mean absolute error statistics and clarification regarding the sum squared error statistic shown in Bruxer and Thompson, 2008a, pg. 12, Table 3-2.

To address the first point, mean absolute errors from the model re-validation are shown in Table 1 and Table 2 below. As can be seen in both tables, the modified model mesh having Manning’s roughness coefficients increased by 3-percent generally showed the best results. Furthermore, Table 2 shows that there are no longitudinal trends in the residuals at gauges along the St. Clair River.

To address the second point, the label in the original table was correct; the “Sum Sq. Error” stands for sum of the squared errors. This statistic could be compared to show which models performed best. The root mean squared error from all gauges (RMSE) has been added to Table 1 below, as has the root mean squared error at Fort Gratiot (RMSE (FG)) as per the reviewer’s request. If we choose either of these statistics for making comparisons, the results in terms of which model performed best remain the same.

<table>
<thead>
<tr>
<th>Observed – Simulated WL (m)</th>
<th>Modified High Density Mesh</th>
<th>Low Density Mesh</th>
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<tr>
<td>Max. Error</td>
<td>0.122</td>
<td>0.092</td>
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<tr>
<td>Min. Error</td>
<td>-0.065</td>
<td>-0.071</td>
</tr>
<tr>
<td>Average Error</td>
<td>0.030</td>
<td>0.009</td>
</tr>
<tr>
<td>Sum Error</td>
<td>1.876</td>
<td>0.545</td>
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<tr>
<td>Sum Sq. Error</td>
<td>0.170</td>
<td>0.082</td>
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<tr>
<td>RMSE</td>
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<td>0.036</td>
</tr>
<tr>
<td>RMSE (FG)</td>
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<td>0.029</td>
</tr>
<tr>
<td>Mean ABS Error</td>
<td>0.040</td>
<td>0.027</td>
</tr>
<tr>
<td>Mean ABS Error (FG)</td>
<td>0.054</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Table 1: Summary of model validation results (revised).
### Mean Absolute Error (m) at Gauges

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Man. N + 2%</th>
<th>Man. N + 3%</th>
<th>Man. N + 4%</th>
<th>Man. N + 5%</th>
<th>Low Density Mesh</th>
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<tr>
<td>Fort Gratiot</td>
<td>0.054</td>
<td>0.025</td>
<td>0.017</td>
<td>0.019</td>
<td>0.035</td>
<td>0.019</td>
</tr>
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<td>Dunn Paper</td>
<td>0.049</td>
<td>0.019</td>
<td>0.015</td>
<td>0.025</td>
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<td>Point Edward</td>
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<td>0.025</td>
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<td>0.022</td>
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<tr>
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<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 2: Mean absolute error values at all gauges from model validation results.

However, it should again be noted here that, regardless of model performance, sensitivity analysis was performed on the model parameters to show that uncertainties in these had little effect on the model simulated differences in water level and flow between years.

#### 3) Bathymetry and Interpolation Procedure

The reviewer asks that plots of the interpolated bathymetry be provided for each year in order to help interpret model results. The reviewer also suggests colour-coding the 1971 survey dots in Bruxer and Thompson, 2008a, p.14, Figure 4-1, so that changes in surveyed elevation between 1971 and 2007 can be visually identified. In addressing these comments, recall first that the hydrodynamic modelling using RMA2 was done in parallel with another study performed by Bennion (2008), which provided an in depth statistical analyses and comparison of bathymetric datasets collected over time for the St. Clair River. The authors would refer the reviewer and others to Bennion’s report for a more detailed account of the differences in bed geometry between years than that which is presented here or in the other modelling reports. Bennion showed that, according to available bathymetry data, the river bed was generally slightly shallower in 1971 than in 2007 (indicating degradation over this period). Conversely, Bennion also showed that the bed was generally slightly deeper in 2000 than in 2007 (indicating accretion over this period). This helps explain the increase in conveyance observed in the RMA2 modelling between 1971 and 2007, and the decrease in conveyance observed between 2000 and 2007.

That being said, the raw survey data was interpolated independent of Bennion’s work for the RMA2 modelling study. The general conclusions outlined by Bennion regarding the differences in the bathymetry over time apply equally here, but the interpolation procedures used differ and this could affect the interpretation of model results, as indicated by the reviewer. Unfortunately, the differences between the
interpolated data sets over time are not significant enough to be able to observe obvious causes for the changes in conveyance in the plots of model bathymetry, but Figure 1 shows a comparison of stream centerlines for the 1971 and 2007 models, and it appears from this plot that the main channel of the river is for the most part deeper in 2007 than it was in 1971, though in some areas the reverse is true. Nevertheless, to better understand the differences in bathymetry over time, the reviewer is referred to Bennion (2008), and these differences are the cause of the changes in conveyance observed in the RMA2 modelling work.

![Stream Centreline Comparison](image)

**Figure 1**: Stream centerline comparison of bed surfaces from 1971 and 2007 simulated single-beam (2007SSB71) model.

The reviewer next discusses the interpolation procedure used in the RMA2 modelling, namely linear interpolation, and suggests an alternative to the method chosen, specifically kriging. The authors chose to use linear interpolation since this method is commonly used in hydrodynamic modelling, it preserves the elevations of the surveyed bathymetric measurements, and it was used in the original RMA2 model developed by Holtschlag and Koschik (2001). Other interpolation methods supported in the Surface-Water Modelling System (SMS), which was used in pre- and post-processing for the RMA2 model, include Inverse Distance Weighted (IDW) and Natural Neighbour (NN) interpolation methods. In addition to linear interpolation, the authors also chose to test NN interpolation, and found that the results from the two methods were generally consistent (Bruxer, 2009).
The authors also recognize that there are many additional interpolation methods available beyond those supported in SMS, and some of these are more sophisticated than linear interpolation, including kriging, which was suggested as an alternative by the reviewer. Bennion (2008) used kriging to prepare surfaces for the St. Clair River for each year that bathymetric data was available. These surfaces were then compared in detail by Bennion, and also used in the 1-D HEC-RAS modelling work performed for the International Upper Great Lakes Study. It should be noted that these surfaces do not preserve measured elevations (Bennion, personal communication, 2009) and that due to differences in data resolution and accuracy the methods were not necessarily consistent between years. While Bennion took these differences into consideration in his work, the appropriateness of these interpolated surfaces for use in the 2-D hydrodynamic modelling application would need to be assessed independently.

Regardless, the authors of the RMA2 modelling feel there is no one preferred method for data interpolation. Rather, it is more important to test the choice of interpolation method and the sensitivity of the model results to the choice made. We tested the sensitivity of the interpolation method by using both linear and NN interpolation methods and found that the results were for the most part consistent. We can not know for sure without performing additional analyses, but we suspect from our initial results that the results generated using kriging would not differ significantly from those generated using the other interpolation methods.

The reviewer also suggests that the interpolation errors generated using kriging could be used as indications of local interpolation error. Both the authors and the reviewer acknowledge that there are spatial trends to the interpolation error. Specifically, interpolation error is greatest in areas of sparse data coverage, such as between transects or in the near-shore areas. Kriging could help identify these areas and the error associated with them. This may have provided a significant improvement to the uncertainty analysis conducted, since spatial correlation of the errors could have been accounted for. The authors acknowledge that the uncertainty analysis performed using the RMA2 model may be limited in its usefulness due to this issue and other issues related to increases in form roughness. The analysis was meant primarily to illustrate that the changes in conveyance observed were statistically significant, with the exact numbers themselves being secondary in terms of importance. Given time and resources required, it is currently infeasible to redo the uncertainty analysis using kriging standard errors, but the authors will certainly consider this should the need arise in the future, and they suggest that the results from the uncertainty analysis as conducted be used with caution.

The reviewer next discusses the survey data available for the St. Clair River Delta region. The reviewer correctly notes that survey data was only available from the 2000 survey, and that this data was necessarily used in all models (1971, 2000 and 2007). The reviewer states that it is not surprising that the model results only started diverging upstream of the delta, and asks whether there is any evidence for aggradation or
degradation in the delta, since changes in this area were not accounted for in our modelling. First, the authors understood that because the geometry of the delta was the same for all models that this was the reason no changes were observed in the results between the different models in this area. Perhaps, this should have been made clearer. It should also be noted that this relates to one of the methods the authors used to show that changes in conveyance were the result of changes taking place throughout the river, and not in any particular area. In Bruxer and Thompson, 2008a, p.23, Figure 5-6, we showed a plot of the difference in water surface profiles between 1971 and 2007 simulated single-beam, and indicated that the near constant slope of the line above Algonac indicated that changes had taken place throughout the river. If a certain area of the river had shown no change in the difference in water surface profiles (as in the delta region, for example), as noted by the reviewer, this would indicate that the bathymetry was the same and that no significant change had occurred in this region. Second, we can not comment on whether there have been changes in the St. Clair River Delta over time, because we do not have sufficient bathymetric data available for this area prior to 2000. If data in the Delta was available and included in our modelling it would certainly affect our hydrodynamic modelling results, since it is likely that changes of some degree have occurred in the Delta over time, whether they be aggradation or degradation or both. The authors also understand that changes in the Detroit River may also have occurred, and that these would also affect the conveyance capacity of the corridor between Lake Huron and Lake Erie. Therefore, while the reviewer brings up valid points of concern regarding possible changes in other areas of the river, the scope of our work was necessarily confined to the main channel of the St. Clair River due to the availability of data.

4) Variogram Analysis

The reviewer states that it is unclear why the deterministic model produced so many variogram data points (see Bruxer (2009), p. 17, Fig. 5-1). The figure is just an example comparison, with an empirical variogram developed for both the deterministic model mesh and one example of the probabilistic model meshes generated. Since the deterministic and probabilistic models use the same model mesh, the number of nodes is also the same for each, though the elevation of the nodes differs. The number of variogram data points is a result of the number of lags selected when creating the empirical variograms with ArcGIS. A lower number of lags would have produced less variogram data points, but the results in terms of assessing spatial correlation and model mesh roughness remain essentially the same.

5) Actual Flow Data

The reviewer states that the analysis of change in actual flows over time for similar boundary conditions was appreciated (see Bruxer, 2009). The reviewer then
suggests that additional tests and diagrams could be useful in providing further and more direct evidence for a change in conveyance over time. The authors agree with this, and that is why further analysis was suggested in the “Summary” section of the report. The analysis presented in Bruxer (2009) was already beyond the initial scope of the hydraulic modelling work the authors were tasked with, and unfortunately given study deadlines these additional analyses could not be explored further prior to submittal of the final report. The inclusion of the initial results was meant to provide an indication of possible conveyance changes over time with the effects of the hydrodynamic models removed, as well as provide an illustration of what might be possible with further analysis of the raw measured flow data. Certainly additional analyses may help shed more light on the question of possible conveyance changes over time.

One additional point of clarification that must be made though is the misunderstanding regarding Figure 6-5. The reviewer believes that this figure is the most direct evidence of change in conveyance in the St. Clair River. While the figure does indeed appear to show a significant change in conveyance over time, it was meant as an example only. The author stressed that comparisons of any two measurements could be biased by any number of additional factors, including flow regime, time of year, measurement uncertainty, etc. While Figure 6-5 (also shown below as Figure 2) shows an increase in conveyance of approximately 20 cm (note the differences at each gauge also indicates that changes are a result of changes throughout the river, including the delta, which was not investigated with the hydrodynamic models), a different comparison could show a completely different result. For example, Figure 3 provides a similar comparison of water surface profiles over time, but with the result that the apparent change in conveyance is only about 7 cm at Fort Gratiot. So while the figures appear to show direct evidence for a change in conveyance over time, due to the uncertainty and additional factors affecting measured flows and water levels, only non-parametric indicators of conveyance change over time were used by the authors.
Figure 2: Example of water surface profiles having similar boundary conditions (Figure 6-5 from Bruxer, 2009). Fort Gratiot difference is approximately 20 cm.

Figure 3: Additional example of water surface profiles having similar boundary conditions. Fort Gratiot difference is approximately 7 cm.
6) Roughness Calibration

The reviewer states that he appreciated the re-calibration analysis performed by the authors. The reviewer suggests that a 2-D model need not be freely calibrated for roughness if the grid is of sufficient resolution to capture form roughness. However, the authors would like to point out that this is only true if the raw survey data itself is also of sufficient resolution to capture the form roughness. The St. Clair River data used in this study, in particular the data available for 1971 and 2000, is not nearly dense enough to capture form roughness, regardless of the resolution of the RMA2 model grid, which as the reviewer states is 75 m x 25 m.

The reviewer next suggests that a longitudinal trend in the change in Manning’s roughness coefficients is evident in Bruxer, 2009, p. 41, Table 6-11. A slight trend is suggested, but with changes in roughness coefficients occurring at only the fourth decimal place, with the exception of Zone 4, which showed changes at the third decimal place. This trend may or may not be real, as it would depend on the measured flows and water levels chosen for calibration, as discussed in Bruxer (2009). It is possible that had different measurements been chosen, the trend would not have been obvious. Regardless, what is more important is the effect that possible changes in roughness combined with changes in bed geometry have had on channel conveyance. The reviewer indicates that Table 6-12 suggests the change in water level between 1971 and 2007 at Fort Gratiot was only 7 cm under average conditions; however, the authors would rather direct the reader to Tables 6-14 to 6-16 in Bruxer (2009), which indicate the change in water level to be between 3 and 8 cm, depending on the calibration chosen. Furthermore, a sensitivity analysis was performed on the roughness coefficients given the results of the recalibration (Bruxer, 2009, p. 46, Table 6-19). Given realistic assumptions regarding roughness changes over time, as estimated from the recalibration analysis, sensitivity analysis indicated the change in water level to be anywhere between 0 and 14 cm.

Lastly, the reviewer understands that the re-calibrated models are fully determined by the data used to calibrate them. The reviewer suggests that, rather than reject model recalibration to account for changes in roughness, a more complete data set be used to calibrate the 1971 and 2007 models. Note that while the wording of the final summary in Bruxer (2009) may have led the reviewer to believe that the authors rejected model recalibration outright, this was not the case. Rather, the authors tried to show that while the recalibrated models gave revised estimates of the change in conveyance as a function of water level over time, these estimates were fully-determined by the data chosen for calibration. That is, the change in conveyance estimated by the recalibrated models was nearly identical to the average change in conveyance observed from the measured data itself. Therefore, the recalibration of the models was unnecessary, since the estimated change in conveyance could be determined prior to recalibration directly from the measured flow and water level data.
The reviewer’s suggestion that a more complete data set be used to calibrate the models is understandable; however, the reviewer may not be familiar with the availability of measured flow and water level data in the St. Clair River. Specifically, there are long periods of time when flow measurements were not taken (see Bruxer, 2009, p. 27, Figure 6-1). This is particularly true during the late 1980’s and early 1990’s, when no data was collected, and to a lesser degree prior to this period. Only in recent years have flow measurements been collected more consistently. More specifically, no flow measurements were collected in 1971. The closest years for which measurements are available are 1968 and 1973, and these measurements occurred during a period of relatively high water levels and flows. On the other hand, measurements collected around 2007 occurred during a period of relatively low water levels and flows. Since the difference in conveyance as inferred from changes in water level is partly related to the water level and flow regime being compared, it is necessary to calibrate the models to a full range of similar conditions. Unfortunately, in the St. Clair River this is not easily done, since it may take several years before a full range of flow and water level conditions are observed. Lastly, even if a full range of water levels and flows were available for 1971 and 2007, the authors again argue that the change in conveyance over time could be estimated from the data itself, and recalibrated models would not provide any additional information under these circumstances.

**Part Two: Response to Dr. Brian Barkdoll’s Review**

Dr. Barkdoll (the reviewer) gave some general comments regarding the strengths and weaknesses of the modelling work. Two points in particular from this section require additional discussion. First, the reviewer identifies the weakest aspects of the modelling to be the “justification of assumptions and lack of finer grid simulation capabilities”. Second, the reviewer states that while the study focused on conveyance, it is not made clear how it is defined and how it would answer the question if dredging caused lower water levels. These two points are discussed in greater detail by the authors below in addressing the reviewer’s general comments. Specifically the assumptions regarding shoreline elevation are justified, the lack of finer grid simulation capabilities is addressed, and conveyance is defined. The authors would also direct the reviewer and others to the St. Clair River Task Team draft report (IUGLS, 2009) for detailed discussion regarding the methods used to determine whether dredging has caused the lower water levels.

The reviewer also gave a list of general comments for consideration by the authors. While some of these comments are editorial in nature and will be dealt with as suggested, other comments deemed to require an additional response are discussed in greater detail below. Note that comments from the reviewer are in *italics*. 
1) ‘Tie all three phases together into one coherent report...’ The authors again apologize to both reviewers for not being able to tie the three reports together into one coherent report at the time of submittal. As time permits, we will combine the volumes into one report should the IUGLS managers deem it necessary.

2) ‘In Fig. 3-2, please explain what the orange arrows and numbers represent’. The figure in question (Bruxer and Thompson, 2008a, p. 11, Figure 3-4) is shown again below in Figure 4. It was used to show the model mesh extent and boundary conditions. The orange arrows and numbers indicate discharge boundary conditions, specifically the outflow from Lake Huron into the St. Clair River at Fort Gratiot, as well as local inflows from a number of larger streams that drain the surrounding watersheds into the St. Clair River system. In addition, the blue line, number and triangle, though difficult to see, indicate the downstream water level boundary at St. Clair Shores. All of these boundary conditions were kept constant for all comparisons between years.

Figure 4: Model mesh extent and boundary conditions (discharge boundaries shown in orange with arrows, water level boundaries shown in blue with line and triangle.)
3) ‘In Section 3.4, in the following statement: “Specifically, when mesh density was increased the model underestimated both the observed water levels and the water levels simulated by the original, lower density model”. Did the model underestimate from observed values or from the lower-density-mesh simulation?’ As it says in the statement, the revised model having increased mesh density, among other minor revisions, underestimated both the observed water level values and the water levels simulated by the original, lower density mesh model. The authors do not understand where the confusion lies.

4) ‘Ideally, the simulations should be repeated on a computer that is capable of a finer mesh.’ The authors would have liked to have access to greater computer resources in order to use a finer grid resolution and further test the effect of grid resolution on model results. However, as explained above, tests previously completed by the authors indicated that grid resolution did not change the differences in simulated water level over time so long as data of equal density were used. Furthermore, the resolution of the model mesh used in the study is a good deal greater than the resolution of the raw bathymetry soundings from both 1971 and 2000, so the use of a higher resolution grid for at least these datasets is likely unnecessary.

5) ‘In Figure 3-4, please explain what the thick red lines are and how they show the mismatch between boundaries and bathymetry data’. The figure in question (Bruxer and Thompson, 2008a, p. 11, Figure 3-4) is shown again below in Figure 5. The image shows the differences between the model mesh boundaries and the measured bathymetry soundings available for Chenal Ecarte, a relatively small distributary of the St. Clair River. The “thick red lines” are in fact not lines at all, but rather they are the measured bathymetric point soundings collected in Chenal Ecarte. Their density makes them appear as a thick line. As can be seen in the figure, in this are the soundings fall just outside and mostly to the left of the model grid, which is shown in black with brown outline.
6) ‘Justify the use of RMA2 and not other 2D models.’ RMA2 was used for a number of reasons in this study. First, RMA2 is a respected two-dimensional hydrodynamic model. It was used to develop the original St. Clair-Detroit River model by Holtschlag and Koschik (2001), which was readily available and had been fully calibrated and validated by the authors. This original model was adapted and applied for this study. Furthermore, the RMA2 modelling performed for the IUGLS was not done independently, but was performed in coordination with other hydrodynamic modelling work, including the use of additional 1-D (HEC-RAS) and 2-D (TELEMAC 2D) models. These were applied in a similar manner and gave comparable results.

7) ‘Justify the use of linear interpolation for various mesh sizes as described in Table 4-1.’ As discussed above, linear interpolation was used since this method is commonly used in hydrodynamic modelling, it preserves the elevations of the surveyed bathymetric measurements, and it was used in the original RMA2 model developed by Holtschlag and Koschik (2001). In addition to linear interpolation, natural neighbour interpolation was also tested using the RMA2 model. The results in terms of differences in conveyance over time were for the most part consistent.

8) ‘In Figure 5-5, please tell how the difference is calculated...’ The figure in question (Bruxer and Thompson, 2008a, p. 22, Figure 5-5) is shown again below in Figure 6. The figure shows the difference in water surface profiles between
years. For example, the “1971-2000” line indicates the difference in water surface elevation generated by the 1971 model and that generated by the 2000 model (i.e. $Z_{1971} - Z_{2000}$, where $Z$ = elevation, in metres) at points along the stream centerline.

Figure 6: Difference between water surface profiles generated for various years (e.g. “1971 - 2000” is equal to the 1971 water surface elevation minus the 2000 water surface elevation at points along the river centerline).

9) ‘Please show with discrete symbols where the simulations results are. The continuous lines shown suggest that it is a continuous function.’ It is unclear to the authors as to which figure this comment refers to. Clarification is needed.

10) ‘Define “conveyance” at its first use and tell how you can induce its trend by water levels and discharge...’ The term “conveyance” is defined in detail in the draft report of the St. Clair River Task Team (IUGLS, 2009), and in part for this reason was not defined specifically in the RMA2 reports prepared by the authors. The authors do, however, appreciate that a formal definition would have been useful, and so one is given here. As defined in IUGLS (2009), “conveyance is a measure of discharge or the water-carrying capacity of a river or channel.” The RMA2 modelling study inferred changes in conveyance by comparing simulated water levels and discharge given the same boundary conditions. Specifically, if the downstream water level and the discharge in the channel are held constant, a decrease in upstream water level over time would imply that the conveyance has increased, since it can be shown that a lower head difference is required to drive the flow in the river. On the other hand, an increase in upstream water level implies a decrease in conveyance over time, since under this scenario a higher head difference would be required to drive the flow. Alternatively, if
instead of fixing channel discharge as constant over time, both the upstream and downstream water levels are held constant, a change in discharge over time can be used to infer changes in conveyance. Specifically, if water levels at the upstream and downstream boundaries are held constant, and the discharge is seen to increase over time, this implies that conveyance has increased, since for the same head difference the discharge is greater than it was in the past. Contrarily, if the water levels are held constant and the discharge is seen to decrease over time, this implies that conveyance has decreased, since for the same head difference the discharge is less than it was in the past.

11) ‘Provide a schematic diagram to visually explain why the following was done: “Since shoreline data was not available for any years, it was assumed that the shoreline elevation was equal to the low water datum elevation minus one metre.”’ To briefly reintroduce the methods used by the authors, the shoreline elevations were assumed to be equal to either Low Water Datum (LWD) minus one metre (DM1), LWD minus two metres (DM2), or the shoreline elevations were extrapolated out to the shoreline (ExS) model nodes from the closest measured survey point(s). DM1 was chosen as the preferred shoreline elevation assumption because it is a reasonable choice and it provided stability in the RMA2 model simulations executed. The shoreline delineation of the original St. Clair River model was derived from recreational boating charts (Holtschlag and Koschik, 2001). The shorelines of these charts are normally drawn at the location of the estimated LWD elevation, and it follows that at these locations the bed elevation would also be equal to LWD (Figure 7). The subtraction of one metre from the LWD elevation was necessary to limit wetting and drying issues in the RMA2 model. Furthermore, use of the DM1 shoreline provides a more realistic cross-section shape in the river than extrapolating the shore elevations from the closest survey point(s). For example, Figure 8 shows a sample cross-section developed from the survey points shown in Figure 7. With the shorelines extended to the Low Water Datum elevation, the flow is for the most part contained in the channel. If the elevations of the shorelines are extrapolated from the closest survey points, the model will extend a vertical, frictionless surface to contain the flow, which the authors felt was less desirable. Regardless, the authors tested the three different methods for shoreline data that we chose, and the results indicated that the choice of shoreline method had a negligible effect on the differences in conveyance observed over time, so long as data of equal density is used (Bruxer, 2009). However, it should also be noted once more that we can not make assumptions about changes in conveyance beyond the extent of the measured data, since we do not have sufficient data in these areas of the river.
Figure 7: Illustration of sample cross-section surveyed points from 1971, plus model shoreline, which was delineated at the approximate location of the Low Water Datum elevation.

Figure 8: Sample cross-section from 1971 showing the surveyed elevation points, the Low Water Datum, and the assumption made regarding the elevation of the near-shore areas.
Define equations used for each kind of error reported.’ Mean error $\bar{Y}$ was calculated as:

$$\bar{Y} = \frac{1}{N} (y_1 + ... + y_N)$$

Where $y_N$ = the error estimated at point N using one of the methods described in Bruxer and Thompson (2008b). For the Monte Carlo analysis, a subset of probabilistic geometry files was created and simulated with the model. The standard error of each subset is the sample standard deviation, $s$, defined by the equation:

$$s = \sqrt{\frac{\sum (X - \bar{X})^2}{(N-1)}}$$

Where $X =$ simulated water level, $\bar{X} =$ the mean simulated water level, and $N$ = the total number of simulations. The error reported at the 95-percent confidence level was calculated as two times the standard deviation.

When combining the errors to determine the error in the differences in simulated water levels between years, the standard errors were calculated as follows:

$$s_{Year1=Year2} = \sqrt{(s_{Year1}^2 - s_{Year2}^2)}$$

Justify the number of trials used for the Monte Carlo simulation described in Table 3-3...’ The authors ran a total of 500 simulations for the high-density 2007 model and 1000 simulations for each of the low-density models. The standard error from all simulations for each model, as calculated above, was compared to the standard error as calculated from the results split in two separate subsets (Subset 1 and 2). The results are shown below in Table 3. As can be seen, while the results differ to a small degree, they are equivalent to two decimal places (i.e. 1 cm) and nearly equivalent to three decimal places (i.e. 1 mm). The Monte Carlo analysis as performed required a great deal of time and computational resources in itself. It is likely that additional probabilistic simulations would refine the answer to some degree, but given rounding errors and the relative need for precision in this analysis, these results were believed to be sufficient.
Table 3: Comparison of standard error calculations from Monte Carlo simulation for all simulations and subsets.

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Total Simulations</th>
<th>Successful Simulations</th>
<th>Failed Simulations</th>
<th>Standard Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>All Simulations</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Subset 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Subset 2</td>
</tr>
<tr>
<td>1971</td>
<td>1000</td>
<td>839</td>
<td>161</td>
<td>0.019</td>
</tr>
<tr>
<td>2000</td>
<td>1000</td>
<td>953</td>
<td>47</td>
<td>0.017</td>
</tr>
<tr>
<td>2007</td>
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<td>500</td>
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<td>0.006</td>
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<tr>
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<tr>
<td>2007SSB00</td>
<td>1000</td>
<td>973</td>
<td>27</td>
<td>0.017</td>
</tr>
</tbody>
</table>

14) ‘Please give changes in water level, discharge and conveyance relative to the change in bed elevation from dredging operations. It seems counter-intuitive to say that water levels dropped but discharge increased. For fixed bed levels the opposite is true….’ The authors regret that there may be some confusion due to the counter-intuitive nature of the conveyance change issue. The authors inferred conveyance change from changes to water level or discharge given constant boundary conditions, as described above. Since the St. Clair River was found to be reach controlled, as opposed to section controlled as in the case of a weir, the changes in water level, discharge and conveyance cannot be given relative to the bed elevation, since changes in bed elevation throughout the channel have been the cause of the observed conveyance change over time.

15) ‘Define what “value” is on the vertical axis of the variograms.’ The “value” on the vertical axis of the variogram in Bruxer, 2009, p. 17, Figures 5-1 and 5-2, indicates the difference in elevation squared between RMA2 model nodes for the 1971 deterministic model and an example of the 1971 probabilistic models.

16) ‘Modify the statement “Lastly, Figure 6-3 shows the same type of comparison….” To read “Lastly, Figure 6-4 shows the same type of comparison…”’ Noted and modified as appropriate.

17) ‘The following statement is unclear: “This likely reflects the fact that the simulated water levels were found to be least sensitive to changes in the roughness coefficient of this zone than the other zones.”’ As discussed in Bruxer (2009), Universal Parameter Estimate Code (UCODE) was used in the model recalibration analysis described. In addition to automatically comparing measured observations to model-simulated equivalents, UCODE can be used to calculate sensitivity coefficients, which give an indication of the sensitivity of the model outputs to the model calibration parameters. For example, for the RMA2 modelling the model outputs are the simulated water levels at water level gauge locations, and the model calibration parameters are the Manning’s roughness coefficients, which were specified and allowed to vary in four different zones. The calculated sensitivity coefficients indicated that simulated water levels at all
gauge stations other than Algonac were relatively insensitive to changes to the roughness coefficient of Zone 4, but sensitive to the other three zones. Simulated water levels at Algonac, however, were found to be sensitive to the roughness coefficient of this zone, but relatively insensitive to the other three zones. For these reasons, the roughness coefficient of Zone 4 was automatically modified by UCODE to reduce the difference between the observed and simulated water level at Algonac almost exclusively, whereas the roughness coefficients of the other zones would be modified to reduce the differences between observed and simulated water levels at a greater number of gauges. The final calibrated roughness coefficient of Zone 4 was therefore found to have greater variability than calibrated coefficients of the other three zones, since Zone 4 would have been affected by uncertainties in the observed water level at Algonac. We can assume that uncertainties in the water levels at the other gauges would be balanced out to some degree, such that the calibrated roughness coefficient of the other three zones would have been less affected and subsequently showed less variability.

**Summary**

The authors would again like to thank Dr. Colin Rennie and Dr. Brian Barkdoll for their detailed and insightful reviews. The authors hope that the responses they have provided above have at the very least clarified any outstanding issues for the reviewers.

In addition to the more general comments, the reviewers suggested some alternative and additional analyses. In particular, the reviewers suggested additional interpolation methods and shoreline assumptions that could be used in the RMA2 modelling of the St. Clair River, as well as additional calibration scenarios, among other suggestions. The decisions and assumptions made in the hydrodynamic modelling, including RMA2, were arrived at by a group of experts forming the Hydraulics Technical Workgroup of the St. Clair River Task Team. The authors of the RMA2 modelling have been careful to apply all assumptions correctly and consistently between the different years being modelled. Furthermore, the authors previously performed a number of sensitivity analyses on the different assumptions made in the RMA2 modelling, and showed that they generally made little difference to the final result in terms of changes in conveyance over time. The authors feel that while the alternative and additional analyses suggested by the reviewers may help refine the final estimates of conveyance changes over time derived from the RMA2 models, further refinement is unnecessary because the St. Clair River Task Team has provided a range of estimates for changes in conveyance from a number of sources in their draft report (IUGLS, 2009). It is likely that any further refinements and analyses performed with the RMA2 model would result in estimates falling within or very close to this range as well. For these reasons the authors
do not feel that additional analyses using RMA2 are warranted at this time, but if deemed necessary by the International Upper Great Lakes Study management, they could be pursued at a later date, time and resources permitting.

References


