Hydrodynamic model of St. Clair River with Telemac-2D: phase 2 report

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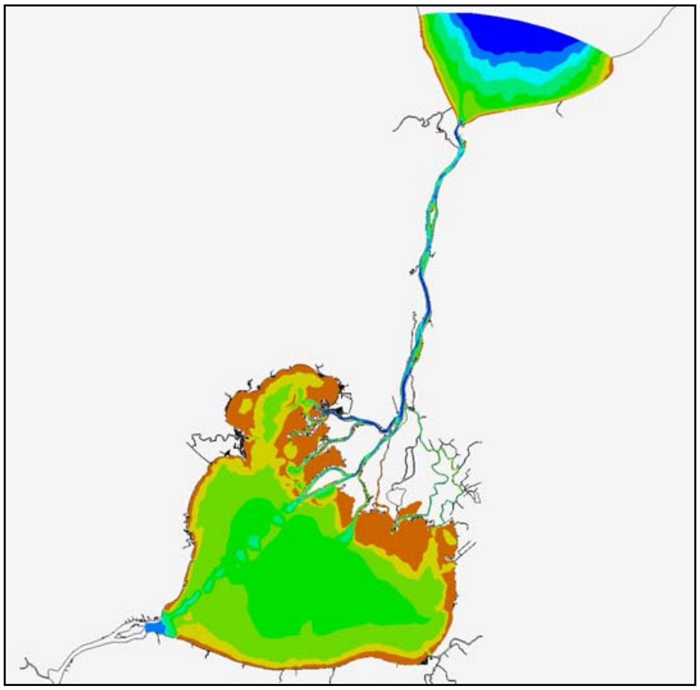
Phase 2 report



Controlled Technical Report CHC-CTR-084

October 2008

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Phase 2 report

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1. Introduction

As part of the International Upper Great Lakes Study, a two dimensional numerical model of St. Clair River was developed using Telemac software (ref 1).

This model was well calibrated with the multi-beam 2002 bathymetry survey in the upper portion of the River, the 2000 single-beam survey for its lower portion, and the existing stage-discharge relationships. It has a very fine grid mesh in the upper portion of the river (15 m) which allows the proper description of small bottom irregularities. It was used extensively to simulate changes, such as bathymetry, morphology, and bed material content or its bottom friction, which may have occurred in the last 35 years, and to assess the impacts of these changes on the river hydrodynamics.

In order to improve the model range of applicability, the following modifications were performed:

- Check the model transect velocity profiles, with ADCP velocity measurements in cross-sections downstream from Blue Water Bridge, in order to verify the size and strength of current recirculation.
- Recalibrate using the 2007 multi-beam bathymetric survey

The model was then used to

- Verify model range of applicability using monthly average data, in a wider range of flows and levels.
- Re-calibrate the model with measurement data available from the 1971 era, (flow and levels).
- Compare 1971/2007 river hydrodynamics using the two 1971 and 2007 models.
- Assess sensitivity of the quality of the input data on the results

2. Model Modification

2.1 Turbulence model

In the numerical model, the velocity gradient across the river is defined by the turbulence algorithm used. This turbulence will specify the local fluid viscosity or diffusivity to best simulate the velocity gradient.

In the original model, the K-Epsilon algorithm was chosen to simulate the turbulence in the flow. It is one of the standard algorithms in 2D numerical modeling.

In order to verify the model turbulence, the large recirculation in the bend of the St. Clair River downstream from the Blue Water Bridge was investigated in detail. ADCP measurements from July 2003 were used to compare model with measurements.

Several sets of ADCP were collected by the USGS and the US Army Corps of Engineers at the same period of time (Reference 4).

The 3D measurements were reduced by Environment Canada, vertically averaged, and processed on a regular square grid at 1m intervals for the USACE data, and 5m for the USGS. Figure 1 shows the vertically averaged velocity vectors, derived from their two horizontal components, as measured on July 2, 2003 by the two organizations.

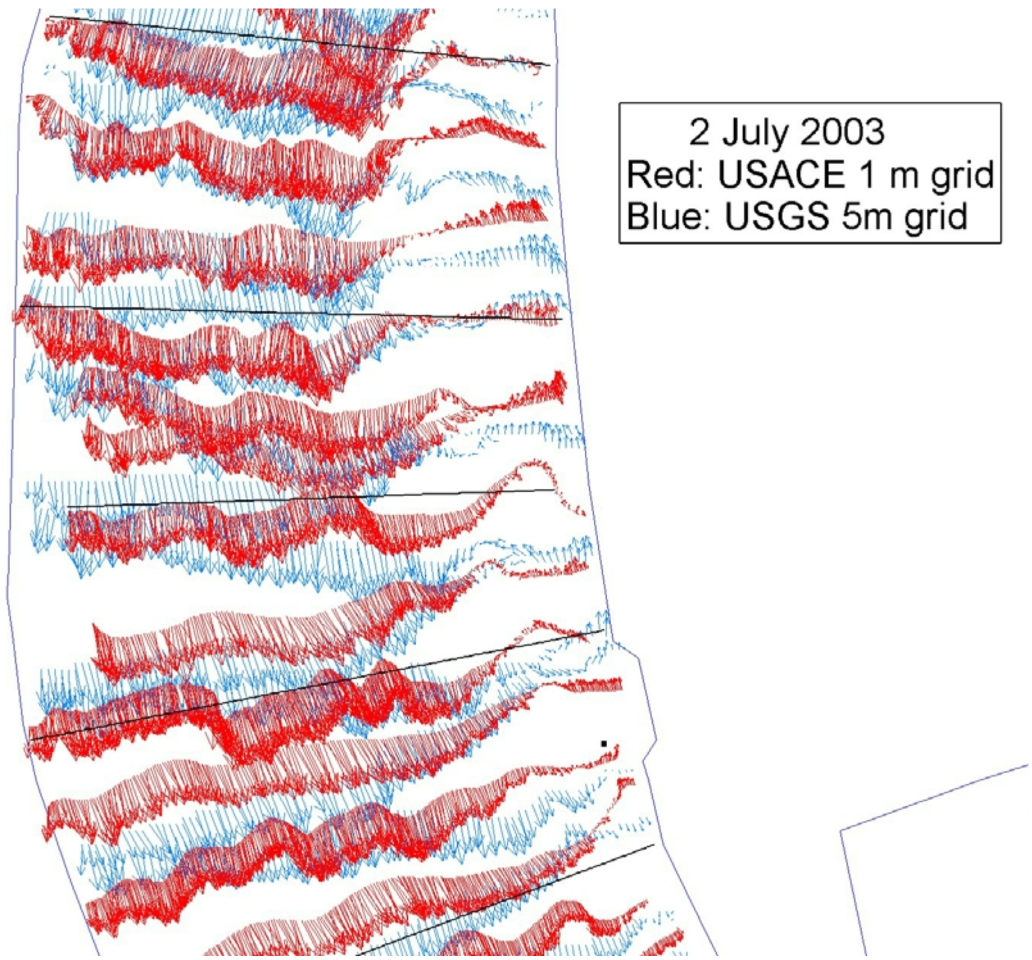

Figure 1 - Velocity vectors from 2003 survey (vertically averaged)

As a comparison, the Telemac model was run with thee different turbulence algorithms: K-epsilon, Elder, and Smagorinsky. They are shown in Figures 2 to 4 which indicate that the K-epsilon model provides a narrower recirculation zone whereas the other two models provide a better representation of the flow pattern.

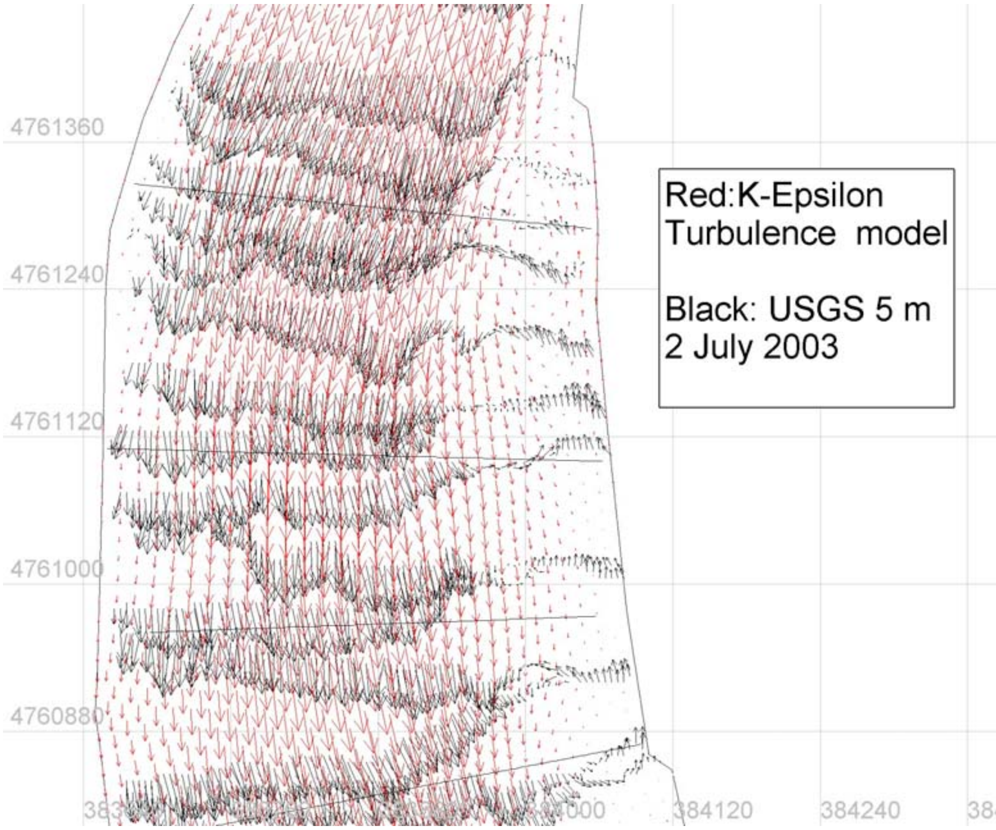

Figure 2 - Comparison: survey with K-epsilon model

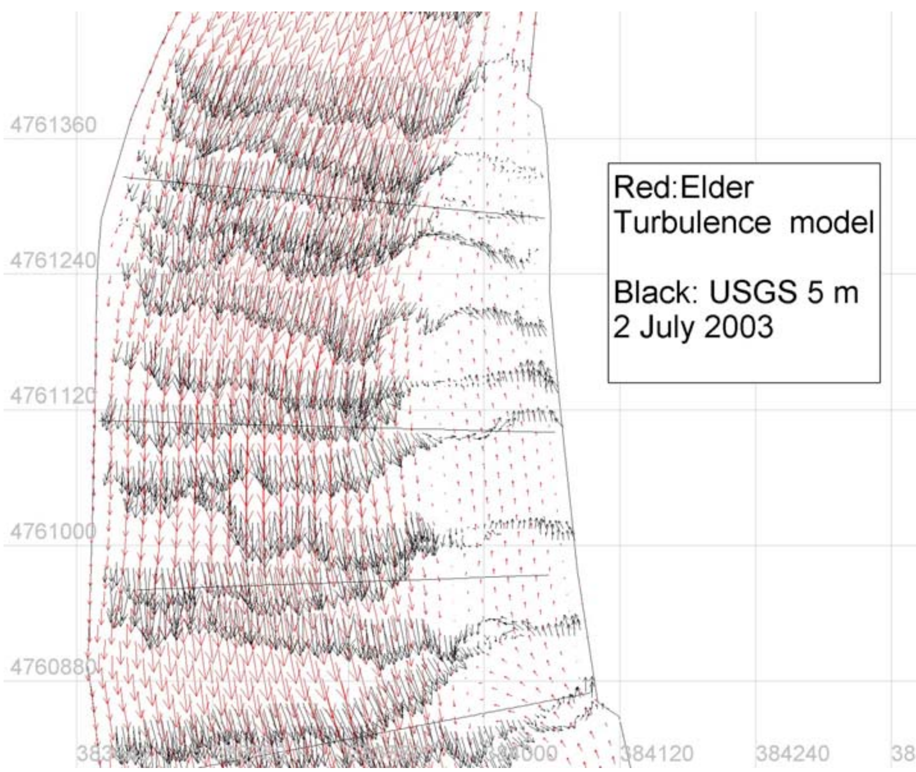

Figure 3 - Comparison: survey with Elder model

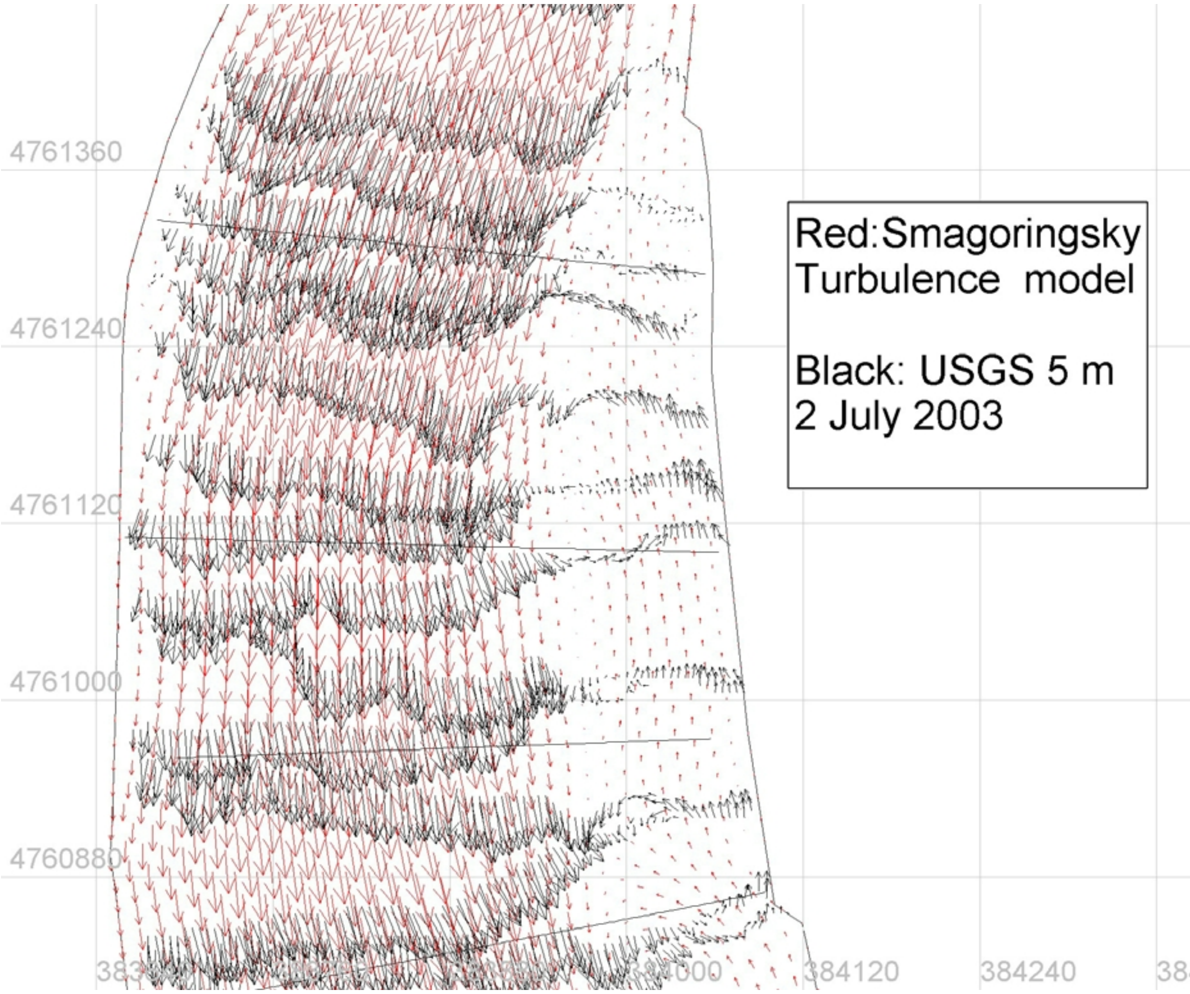

Figure 4 - Comparison: survey with Smagorinsky model

The velocity profiles in several cross-sections of the river bend (shown in figure 5) were prepared. Figure 6 shows that at section 1, where the flow in the river has not started to turn, the three turbulence algorithms give the same velocity profile. Further downstream, there is a strong three-dimensional component to the velocity vector and each turbulence algorithm (all of which are two dimensional) reacts differently to non-2D hydrodynamics, as seen in Figure 7 for the sections 4 and 5.

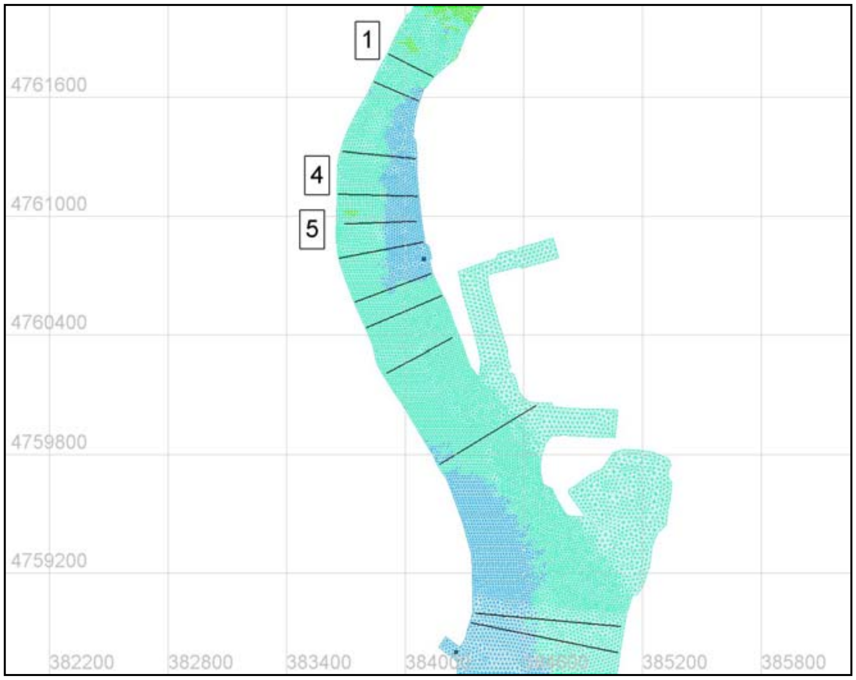

Figure 5 - Cross-section location

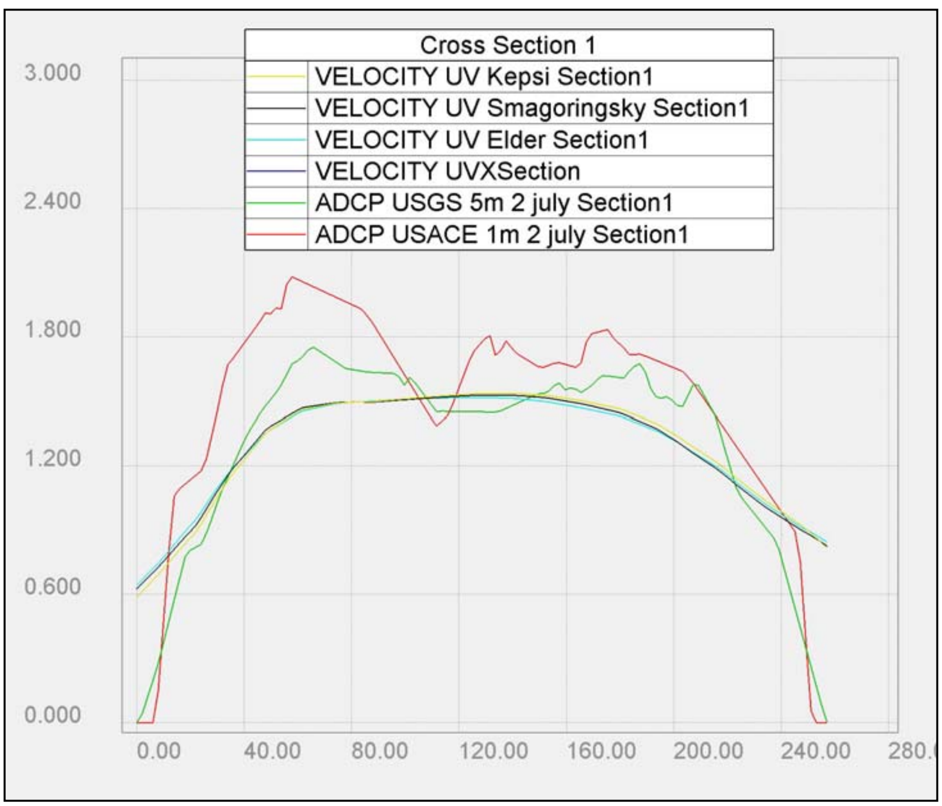

Figure 6 - Cross-sectional velocity profile - Comparison for the upstream section before fluid starts to turn

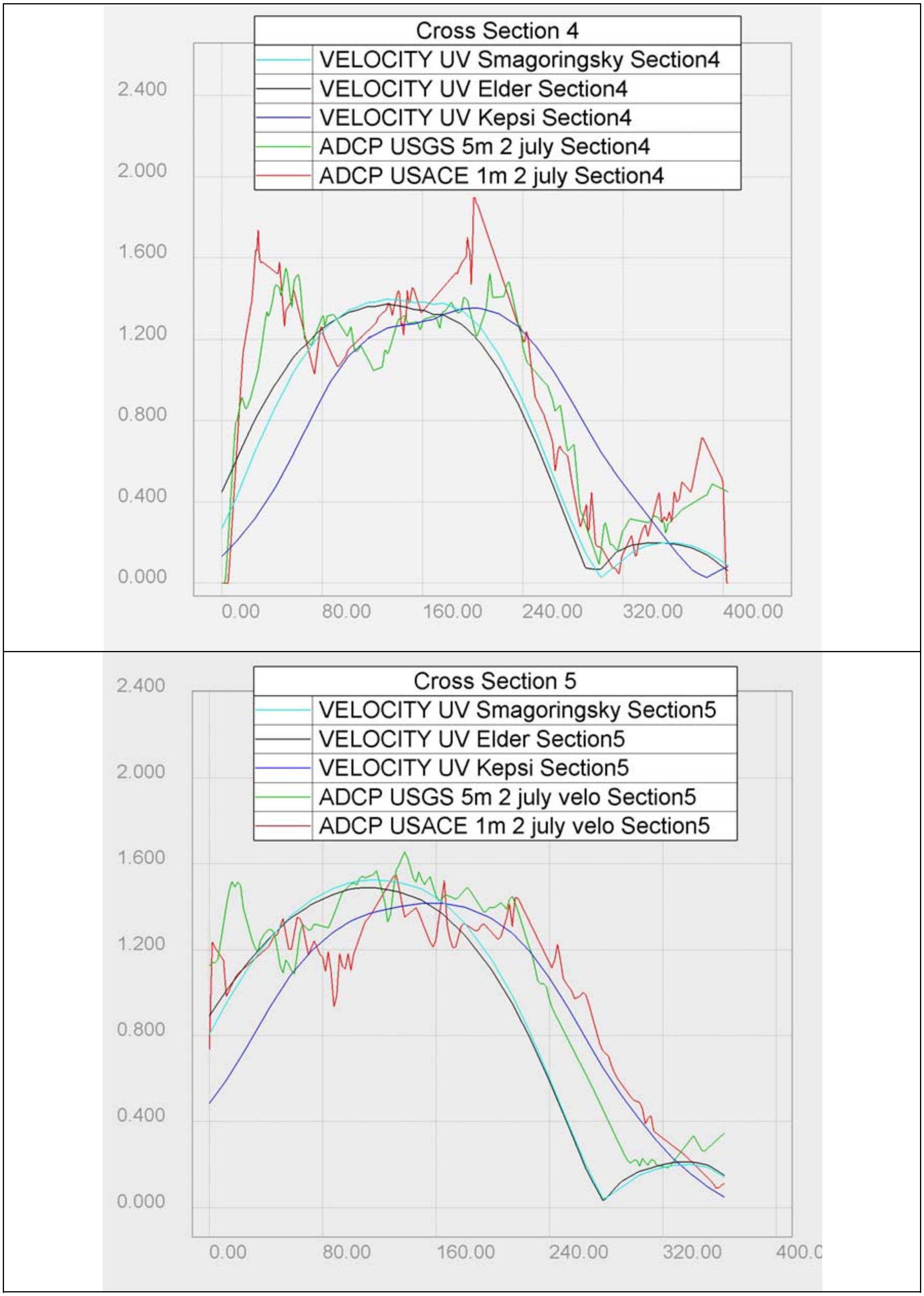

Figure 7 - Cross-sectional velocity profile comparison in the river bend

A few notes of explanation for the graphs in Figure 7:

- The apparent drop to zero velocity on the ADCP surveys on the edges of the section is due to the lack of data close to the shore.
- The difference between the two surveys may come from the interpolation process. The cross-sections are in a straight line whereas the surveys were collected along meandering boat paths (fig 1). The curves shown in Figure 7 are an interpolation between several boat paths. This interpolation has not been performed along stream lines.
- The Elder and Smagorinsky models provide a better match to the overall cross-sectional profile than the K-epsilon model.
- In general the velocities from the model are smaller than the ADCP measurements because the model was calibrated from existing flow-level relationships.

- A preliminary investigation has been performed on the flows obtained during these simulations. Figure 8 shows the instantaneous cross section flows as estimated by the Telemac model when it was run with hourly levels prescribed at Lakeport and at St. Clair Shores. In this figure the beginning of the plots corresponds to 30 June 2003, 18h00. (The model was started a week earlier to insure proper dynamic set-up).

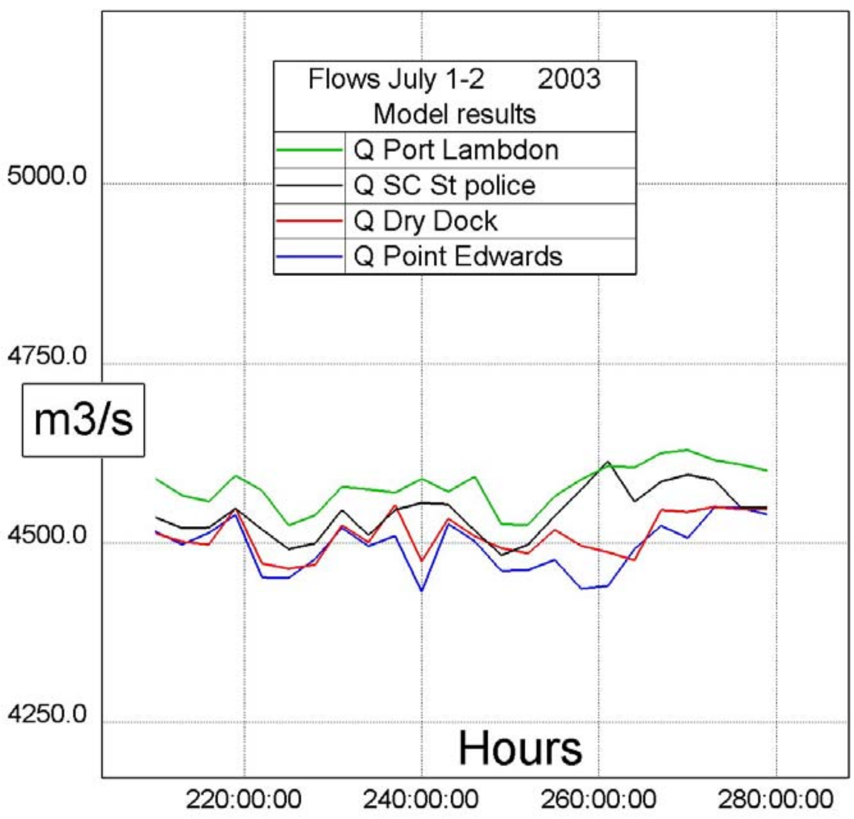

Figure 8 - Model Flows in various locations along St. Clair River during July 1-2, 2003 period

Figure 8 shows flows of the order of 4530 m^3/s. These flows can be compared with measurements taken on July 1st 2003:

- the ADCP measurements of the order of 5000 m^3/s,
- the Environment Canada estimates of the order of 4700 m^3/s, based on stage relationships
- the USACE estimates of the order of 4500 m^3/s, based on stage relationships

This shows that this aspect of flow estimate needs more in-depth analysis, which was not part of this study.

Following these investigations, it was decided to use the Elder turbulence algorithm in future simulations, since it gives a better representation of the velocity profile, and it has a better representation of dispersion.

2.2 Calibration with 2007 bathymetry

The original model was calibrated with the 2002 bathymetric data for the upper section of the St. Clair River, and the 2000 data for the lower section from downstream of the mouth of the Black River to Algonac.

Using the 2007 survey would provide a more accurate model which would better represent the actual morphology of the St. Clair River, since it was a multibeam survey from Fort Gratiot to Algonac.

The 2007 high-density bathymetric surveys used a very large number of data points which were difficult to handle in the pre-processing phase of the modelling. It also provided information which was not required by the model since it was about 10 times more dense than the density of the elements in the Telemac grid. A coarser bathymetric grid was therefore prepared with a spacing of 6 m in the upper portion of the River, and 10 m in the lower portion. The new data points were obtained by averaging the high-density elevation points. Figure 9 shows the high-density set of data and the coarser set of data represented by the black dots.

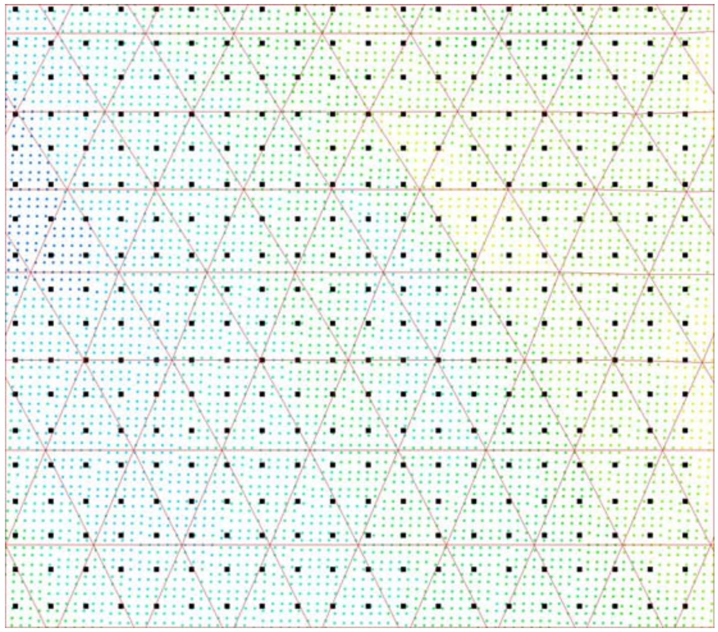

Figure 9 - Definition of the coarser bathymetric set of points, derived from the high density data

In addition to the 2007 survey points, the Fort Gratiot portion of the 2002 survey was used, along with some horizontal paths from the 2000 survey as shown in Figure 10.

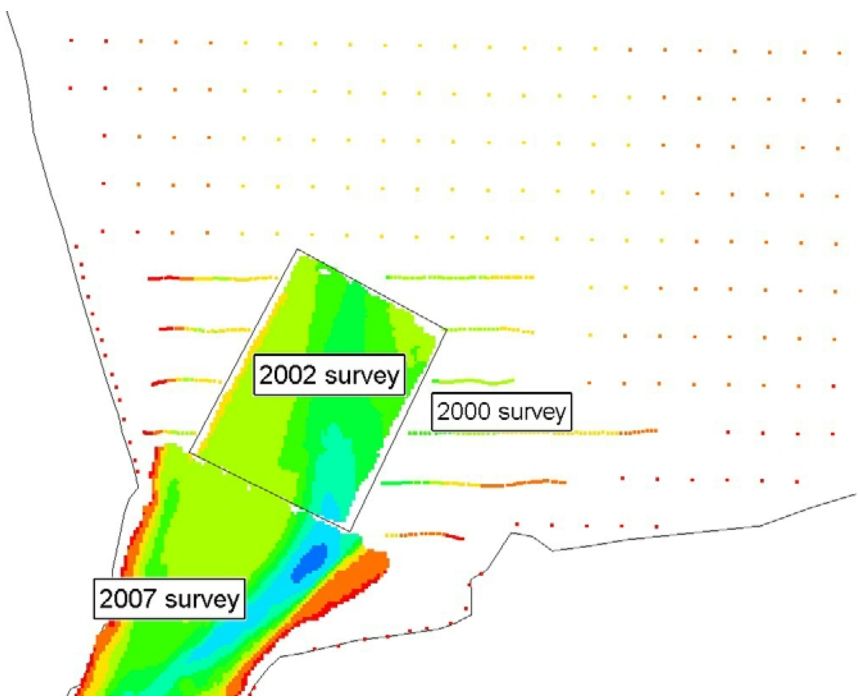

Figure 10 - Bathymetry data used in the upper portion

The calibration/verification was done over the same three time periods as in the original Telemac model, during which the levels and the flow could be considered steady for several days. This ensured that the flows were the same at the upstream and downstream ends of the St. Clair River and at the exit of St. Clair Lake. (See ref 1). The flows were obtained from the existing stage-discharge relationships provided by Environment Canada (Reference 5). Their derivation is explained in more detail in Ref. 1.

Table 1 shows the levels simulated by the model, as compared to the measured level at the various gauging stations. The maximum difference was 18 mm and the minimum was -17 mm, both occurring at the Dunn Paper gauge. In this calibration the bottom friction coefficients for the estuary channels (lower St. Clair River) were maintained in the same ratio as found in the original calibration in order to keep the same flow distribution among the channels.

					Calibration 2007 bathymetry					
					EC existing relationships					
Flow			**4295 m^3/s**			**5020 m^3/s**			**5660 m^3/s**	
run number			124			123			122	
Year		2001			2002			1998		
Days		90-96			194-199			170-176		
		measured	simul	diff	measured	simul	diff	measured	simul	diff
Lakeport (m)		175.770	175.771	0.001	176.35	176.335	-0.015	176.88	176.892	0.012
Fort Gratiot (m)		175.740	175.731	-0.009	176.28	176.29	0.010	176.83	176.844	0.014
Dunn Paper (m)		175.650	175.633	-0.017	176.18	176.171	-0.009	176.69	176.708	0.018
Point Edward (m)		175.580	175.581	0.001	176.11	176.099	-0.011	176.62	176.621	0.001
Mouth Of Black (m)		175.560	175.553	-0.007	176.09	176.076	-0.014	176.59	176.603	0.013
Dry Dock (m)		175.460	175.461	0.001	175.98	175.969	-0.011	176.48	176.489	0.009
St. Clair SP (m)		175.170	175.172	0.002	175.65	175.643	-0.007	176.14	176.145	0.005
Point Lambton (m)		174.880	174.88	0.000	175.30	175.302	0.002	175.78	175.775	-0.005
Algonac (m)		174.830	174.842	0.012	175.26	175.26	0.000	175.73	175.731	0.001
St. Clair Shores (m)		174.690	174.687	-0.003	175.10	175.097	-0.003	175.58	175.57	-0.010

Table 1 - Comparison between measured and simulated levels after 2007 calibration

The 2007 calibration roughness coefficients showed a slight increase. This increase could be due to a change in the bottom since 2000, but it is felt that this change is mainly due to the change in the representation of the bottom in the numerical mesh. The 2007 data is much more dense, and therefore provides a smoother numerical representation in the model which must be compensated for by higher friction factors.

It is to be noted that this calibration was performed using the Stage-fall-discharge relationships from Environment Canada to obtain the flows during steady state periods, with flows at 4295, 5050 and 5660 m^3/s.

Actual flow measurements have also been utilized to calibrate the model in a separate calibration, by using the flows and levels from the RMA model calibration (Ref 2). When trying to calibrate, using scenarios 1, 7 and 4 (from Ref 2), with flows 4905, 5604 and 6302 m^3/s, levels at the same gauging stations showed errors from 3 to 13 cm, with an average error of 6 cm. For the 5604 m^3/s "medium" flow, the average error was smaller, 4 cm, with a maximum error at Dunn Paper of 8 cm.

These errors are much higher than those indicated in Table 1. It is thought that this comes from the fact that the flows and levels in Ref 2 do not correspond to steady state, and that weeds may have come into effect with the seasonal change of the roughness. This calibration was therefore not retained.

3. Comparison with monthly average data

In order to assess the range of applicability of the new model, with the 2007 bathymetry, the flows from Table 2 were simulated in a steady state situation. These correspond to average monthly flows and levels as provided by Ref. 3. The average monthly levels were obtained from NOAA, while Environment Canada calculated the flows using its level-gauge relationships. It can be seen from Table 2 that for the higher flows, an error of the order of 7 cm can be expected for the level at Fort Gratiot. As seen in figure 11, this would correspond to an error in flows of 175 m^3/s or 2.6%.

			AVERAGE MONTHLY DATA			
		level SC Shores	**Q from Huron**	**level Fort Gratiot observed**	**level Fort Gratiot simulated**	**difference**
Year	Month	m	m^3/s	m	m	m
1986	8	175.89	6630	177.34	177.41	0.07
1997	9	175.68	6280	177.09	177.15	0.06
1998	5	175.63	5800	176.86	176.94	0.08
1995	10	175.08	5310	176.38	176.40	0.02
2004	7	175.15	5080	176.34	176.35	0.01
2006	6	175.00	4750	176.11	176.12	0.01
2001	4	174.74	4340	175.79	175.79	0.00

Table 2 - Steady-state simulated flows over a wider range

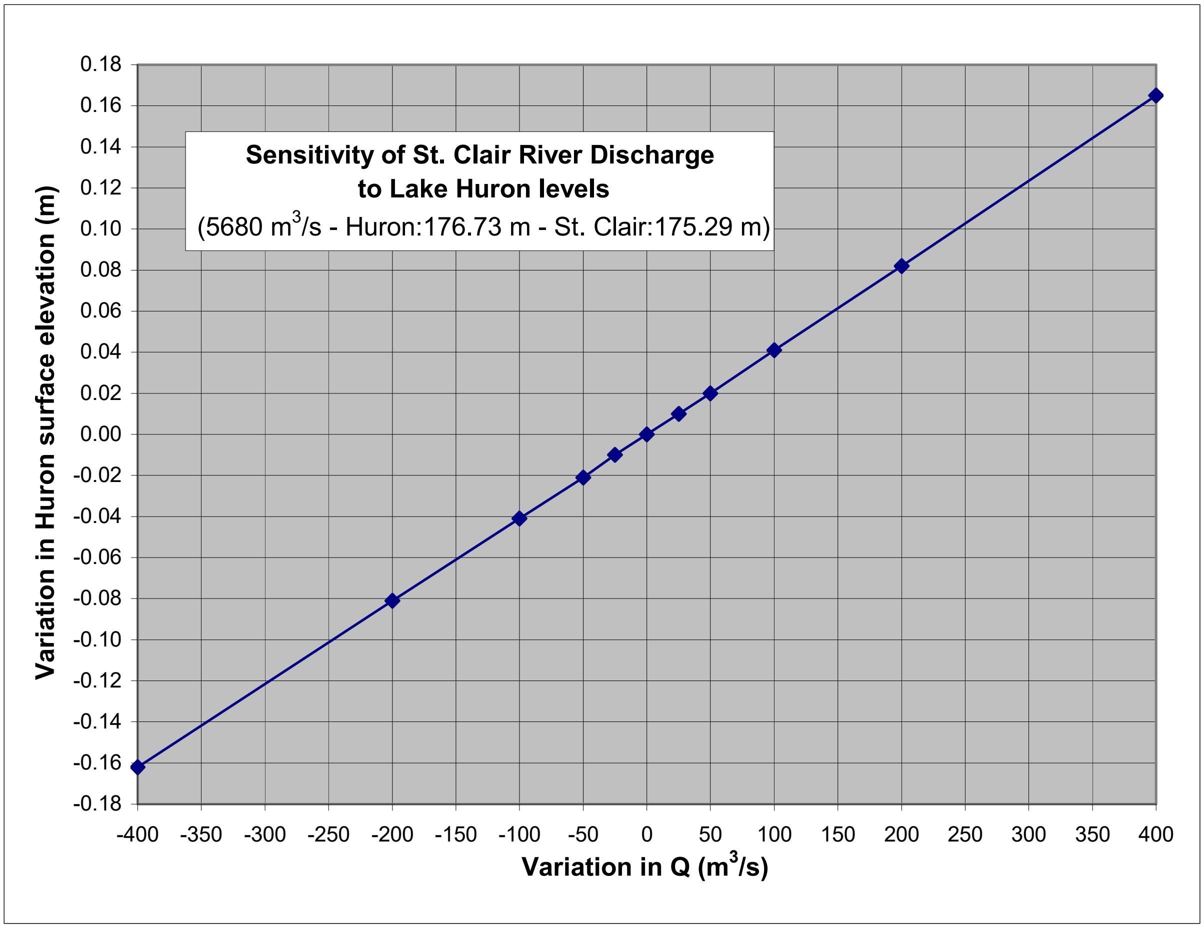

Figure 11 - Sensitivity of St. Clair River discharges to changes in Lake Huron levels

4. Preparation of a new model based on 1971 data.

In the previous study (ref 1), the Telemac model was run with the bathymetry as it was surveyed in 1971, and a comparison with today's data showed that Lake Huron levels would drop by 13 cm if nothing else changed between 1971 and 2007. This important finding was based on the assumption that the bottom roughness did not change during this period.

In order to verify this assumption, a Telemac model of the St. Clair River was prepared using all information available from the 1971 era. Flows had been recorded in various cross-sections in 1968 and 1973 using conventional survey methods.

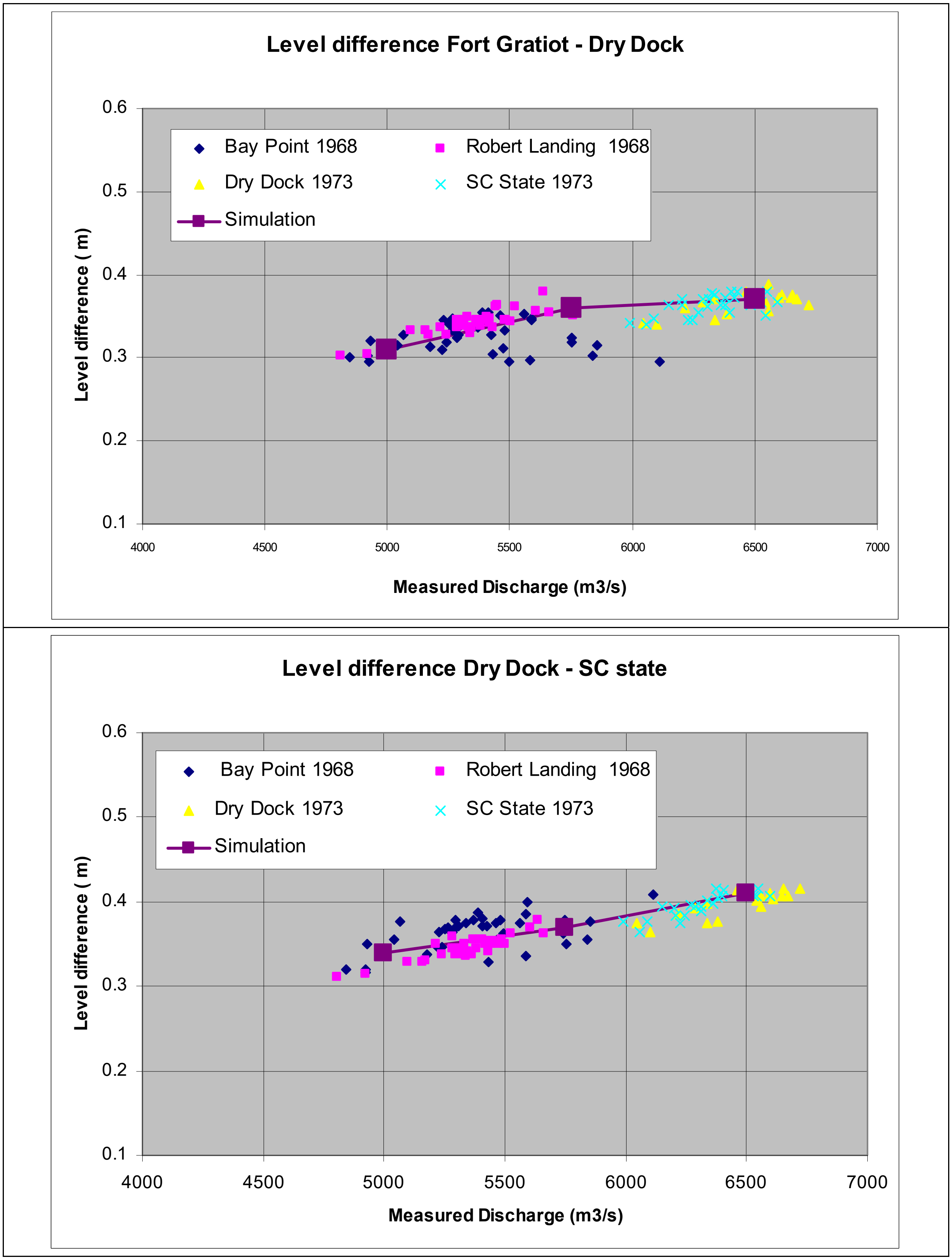

Figure 12 - Head difference measured during 1968 and 1973 flow surveys

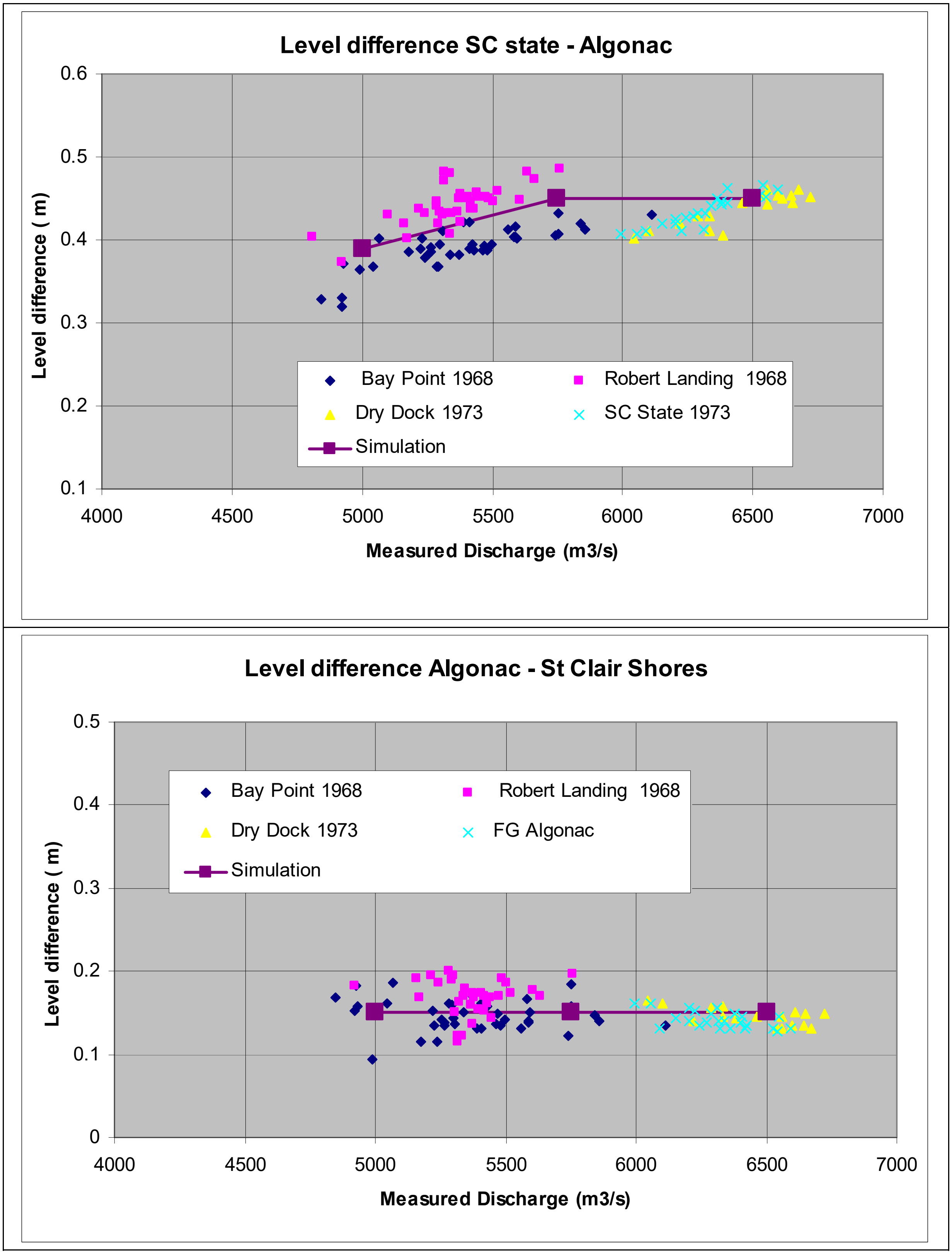

Figure 13 - Head difference measured during 1968 and 1973 flow surveys

Figures 12 and 13 show the level differences between the various gauge stations for the corresponding recorded flow. Figure 14 shows that the 1968 and 1973 surveys were made at two different St. Clair lake levels.

In the preparation of these graphs, all surveys where the levels or flows were questionable have not been used.

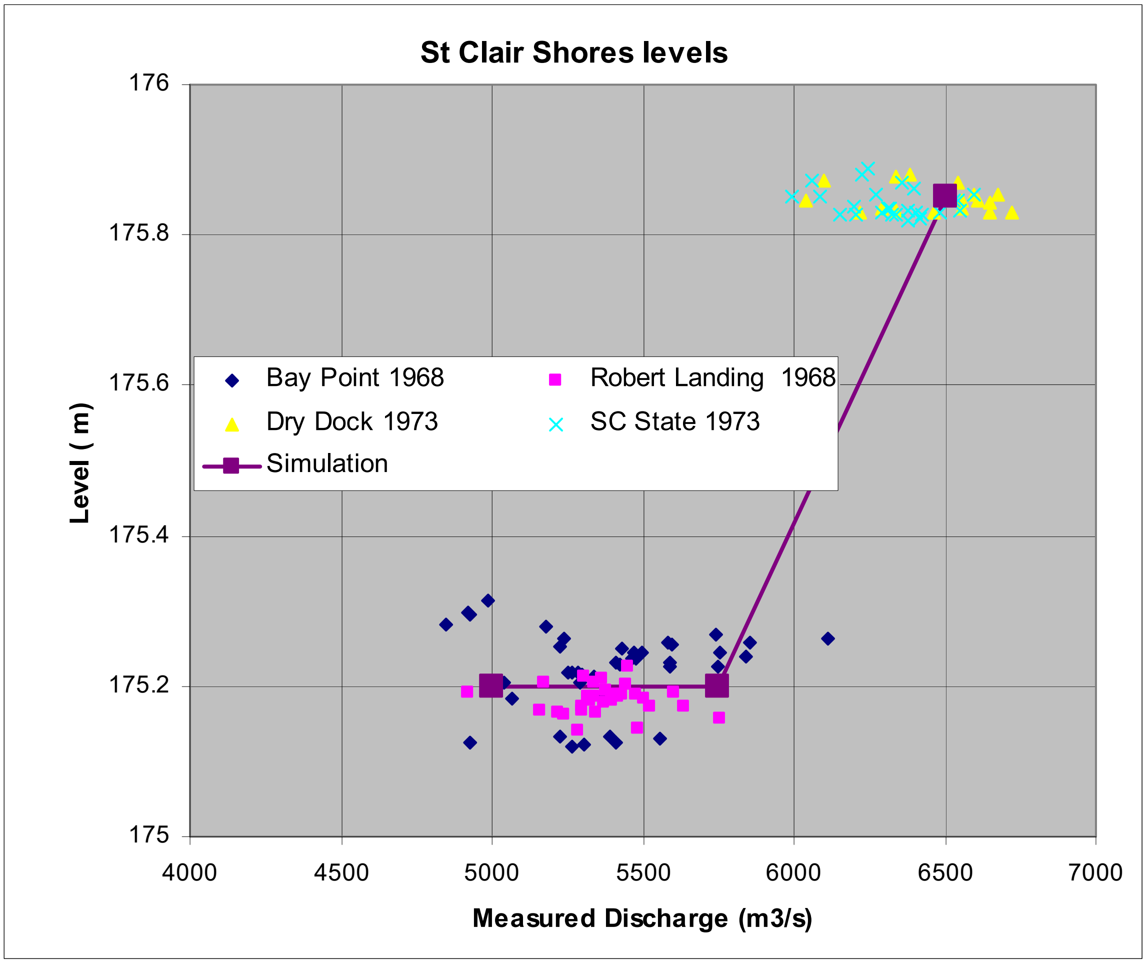

Figure 14 - St. Clair Shore levels during the 1968,1973 surveys

In order to reproduce these conditions with the Telemac model, three scenarios represented by the three large square dots on Figures 12, 13, and 14 were assumed. These would correspond to three “average” situations with discharges of 5000, 5750 and 6500 m^3/s.

The model was calibrated so as to minimize the errors in levels at four gauging stations for these three discharges. The maximum errors were of the order of ±7 cm as shown in Table 3.

	CONDITION 1			CONDITION 2			CONDITION 3		
	5000 m3/s			5750 m3/s			6500 m3/s		
	Estimated	simulated	diff	Estimated	simulated	diff	Estimated	simulated	diff
Fort Gratiot	176.39	176.32	-0.07	176.53	176.61	0.08	177.23	177.29	0.06
Dry Dock	176.08	176.02	-0.06	176.17	176.24	0.07	176.86	176.88	0.02
St.Cl State Police	175.74	175.70	-0.04	175.80	175.84	0.04	176.45	176.49	0.04
Algonac	175.35	175.33	-0.02	175.35	175.37	0.02	176.00	176.01	0.01
St. Clair Shores	175.20	175.20	0.00	175.20	175.20	0.00	175.85	175.85	0.00

Table 3 - Overall calibration of 1971 model

It is to be noted that this error of 7 cm is of the same order of magnitude as the one found when trying to calibrate the model with the RMA2 data (section 2.2). Both the RMA data and the 1971 data are based on actual level and flow information averaged over many hours.

5. Calibration with the modified 2007 bathymetric survey, and modified flows

As mentioned in section 2.2, the model was calibrated with the bathymetric information derived from the multibeam survey, which describes the bottom with a grid density of 6 to 10 m.

The 1971 bathymetric survey describes the bottom with cross-sections spaced at approximately 150 m. When these data points are mapped onto the Telemac grid to provide the node elevations, they present some oscillations in the numerical grid. These oscillations of the model bottom increase its roughness.

To compare the river's ability to carry the flow from one year to the next, it is important for the model to represent the bottom of the river the same way, so that during the mapping process of the bathymetric information onto the grid, the interpolation and extrapolation operate the same way.

To that end, the 2007 bathymetry was reconstructed to get the same density of information as the 1971; the elevations of 2007 survey were assigned only on the locations of the 1971 survey points.

Furthermore, recent studies seem to indicate that the existing stage-discharge relationships provide flows which are lower than those from the recent ADCP measurements. In order to provide a model which better represents today’s situation, 125 m^3/s have been added to the three calibration flows. This amount corresponds to the mean residual between the measured flows using ADCP and the computed flows based on the stage-fall-discharge curves utilized by Environment Canada and the U.S. Army Corps of Engineers.

The model was recalibrated with the three discharges and the same levels shown on Table 1. The friction coefficients were adjusted to provide a modified 2007 calibration based on these revised flows. Table 4 shows the new levels simulated by the model, as compared to the measured level at the various gauging stations. The error in levels is of the order of 1.3 cm except at the Dunn Paper gauge where it is close to 3 cm. This small error indicates that this modified 2007 calibration is very satisfactory.

					Calibration 2007 bathymetry on 1971 survey location					
					Modified EC relationship					
Flow			**4295 +125 m^3/s**			**5020 +125 m^3/s**			**5660 +125 m^3/s**	
run number			138			139			140	
Year		2001			2002			1998		
Days		90-96			194-199			170-176		
		measured	simul	diff	measured	simul	diff	measured	simul	diff
Lakeport (m)		175.770	175.784	0.014	176.350	176.336	-0.014	176.880	176.889	0.009
Fort Gratiot (m)		175.740	175.735	-0.005	176.280	176.282	0.002	176.830	176.832	0.002
Dunn Paper (m)		175.650	175.655	0.005	176.180	176.183	0.003	176.690	176.717	0.027
Point Edward (m)		175.580	175.588	0.008	176.110	176.099	-0.011	176.620	176.619	-0.001
Mouth Of Black (m)		175.560	175.565	0.005	176.090	176.078	-0.012	176.590	176.603	0.013
Dry Dock (m)		175.460	175.467	0.007	175.980	175.968	-0.012	176.480	176.486	0.006
St. Clair SP (m)		175.170	175.177	0.007	175.650	175.645	-0.005	176.140	176.150	0.010
Point Lambton (m)		174.880	174.882	0.002	175.300	175.303	0.003	175.780	175.783	0.003
Algonac (m)		174.830	174.838	0.008	175.260	175.254	-0.006	175.730	175.732	0.002
St. Clair Shores (m)		174.690	174.687	-0.003	175.100	175.097	-0.003	175.580	175.580	0.000

Table 4 - Comparison between measured and simulated levels after 2007 modified calibration

6. Comparison 1971 - 2007 levels

In these conditions, both 2007 (modified) and 1971 models have the same numerical representation of their bathymetry, and therefore their friction coefficients can be compared. Furthermore they were calibrated using the flow and level data available from their respective era, therefore their hydrodynamics can also be compared.

Both models were run with an inflow of 5680 m^3/s from Lake Huron, and St. Clair Lake level maintained at 175.29 m, which corresponded to the average flow and to the average lake level over the period 1962-1999 (post dredging years, ice-free months).

Table 5 shows that there is a drop of 3 cm in Lake Huron level when the St. Clair River carries the same flow between 1971 and 2007.

	Calibration with 1971 bathymetry	Calibration with 2007 bathymetry on 1971 location	
Flow from:	Calibration with flows from Conventional flow measurements 1968, 1973	Calibration with flows from EC existing relationships plus 125m³/s	
Run	C128	C141	
Q=5680 m³/s	1971 bathymetry	2007 bathy on 1971 location	difference
Lakeport	176.69	176.67	-0.03
Fort Gratiot	176.64	176.61	-0.03
Dunn Paper	176.52	176.49	-0.02
Point Edward	176.43	176.40	-0.03
Mouth Of Black	176.40	176.38	-0.02
Dry Dock	176.28	176.26	-0.02
St.Cl State Police	175.90	175.90	0.00
Point Lambton	175.52	175.52	0.00
Algonac	175.45	175.46	0.01
St. Clair Shores	175.29	175.29	0.00

Table 5 - Changes in levels along the river between 1971 and 2007

6.1 Comparison 1971 - 2007 bottom friction

The coefficients representing the roughness of the river are shown in Figure 15. It shows that in 2007 the roughness was slightly higher than in 1971. The average increase of the Manning roughness coefficient over the whole length of the river is 5%. One explanation could be that the increase would come from the removal of the finer material on the river bed. Figure 15 also shows a regular decrease in roughness from upstream to downstream, coming probably from the fine material being transported and deposited where velocities slow down closer to the estuary.

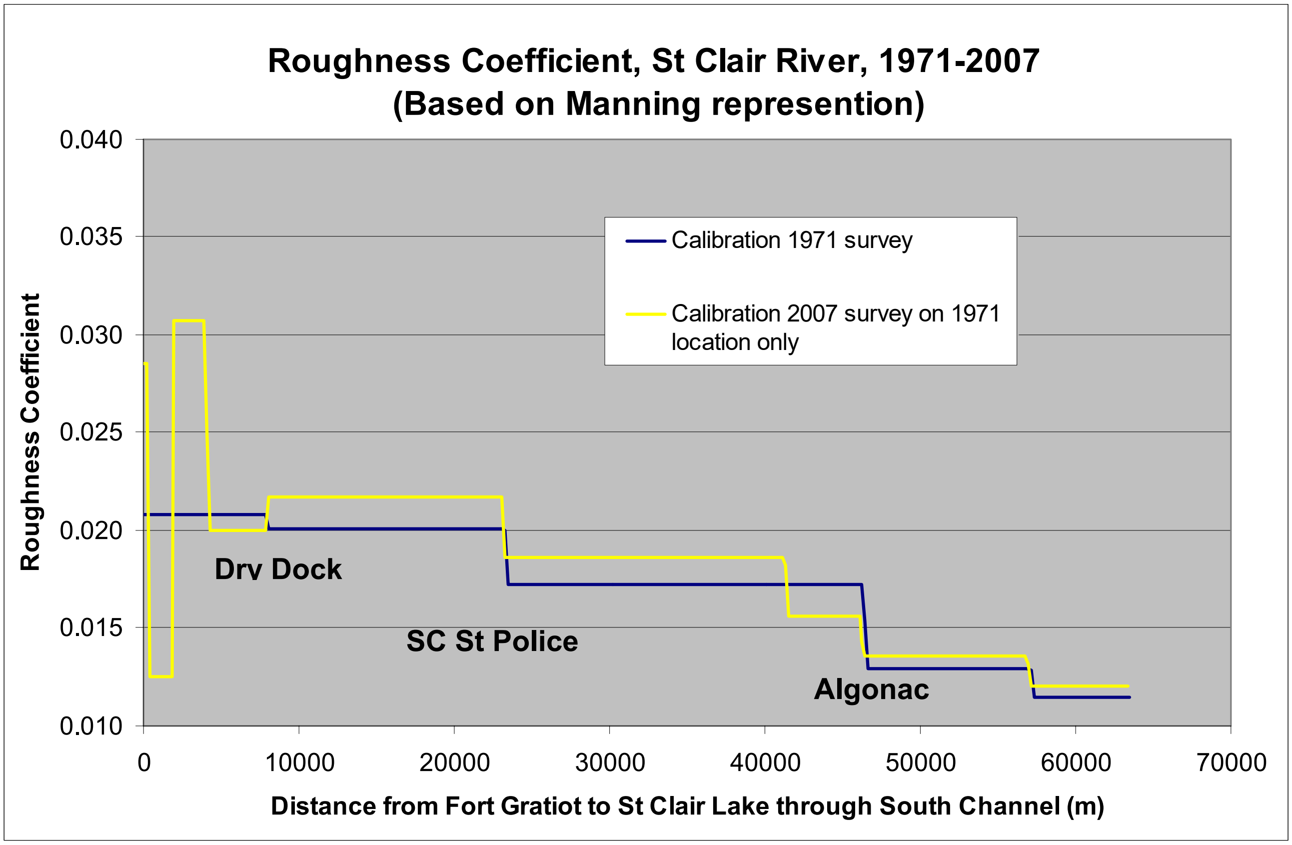

Figure 15 - Changes in roughness coefficient between 1971 and 2007

7. Further analysis on the 1971 - 2007 changes

7.1 Sensitivity of 1971 calibration

In order to asses the sensitivity of the 1971 calibration, three more models were prepared, each calibrated separately with 5000, 5750, and 6500 m^3/s using the 1971 bathymetry. A new set of roughness values was estimated for each flow in order to reproduce the average levels shown by the square dots on Figures 11 to 13. Then the 3 models were run with 5680 m^3/s. This analysis shows that the 3 cm drop would be plus or minus 7 cm. This was to be expected since Figures 11 to 13 show a spread of about ±5 cm in levels, for the same discharge, and the calibration was performed within 6 to 8 cm (Table 3).

7.2 Sensitivity of bottom roughness

The 3 cm drop in the level of Lake Huron has been calculated assuming changes in roughness and bathymetry. We remember (ref 1) that if we change only the bathymetry, between 1971 and 2007, then the model gives a 13 cm drop with the 2007 roughness. With the 1971 roughness, the drop in level is about the same: 12 cm.

7.3 Sensitivity on 2007 discharges used in calibration

If we use a 2007 model calibrated with the existing EC relationship, without the additional 125 m^3/s, then we find that levels in Lake Huron would have risen by 3 cm since 1971 instead of dropping by 3 cm. The net variation of 6 cm is close to what can be found on Figure 10, for 125 m^3/s.

7.4 Sensitivity on 2007 bathymetry representation

As mentioned earlier, the density of the bathymetric data influences the numerical representation of the bottom in the model.

A St. Clair river model was also prepared with the 2007 high density grid (6 and 10 m) — instead of the 150 m spaced cross–sections — during calibration. With an upstream flow of 5680 m^3/s, this model also set the level of Lake Huron at 176.67 m, identical to the level found with the 2007 multi bean reduced to 1971 location (Table 5). This indicates that the hydrodynamics of the river remain the same if the model is properly calibrated with the same set of bathymetric information.

But, it was found that the Manning friction coefficients for this 2007 model using high density bathymetric information were 12% higher than coefficients for the 2007 model using the low density 1971 locations.

8. Conclusion

The Elder algorithm simulating model turbulence gives a good representation of the large recirculation downstream from Blue Water Bridge.

In order to assess the change in River hydrodynamics between 1971 and 2007, several models were prepared. The accuracy of these models greatly depends on the quality of the input data.

- The 1971 model was calibrated with errors in levels estimated at ± 7 cm
- The 2007 model was calibrated with errors in levels estimated at ± 1 cm
- Model calibration with steady state data provide better results than calibration with actual flow measurements (1 to 2 cm uncertainty instead of 5 to 13 cm)
- The uncertainty in flow measurements would provide level uncertainty of the order of ± 6 cm

In these circumstances it was found that Lake Huron levels would drop by 3 cm between 1971 and 2007 if the same constant inflow of 5680 m^3/s was maintained and Lake St. Clair was maintained at 175.29 m.

The major uncertainty is the flow estimates on which the Telemac models were calibrated. Recent ADCP surveys seem to indicate a discrepancy between flow measurements and the existing stage-discharge relationships. We have assumed a 125 m^3/s difference. If the difference was 250 m^3/s, then Lake Huron levels would have dropped about 9 cm.

9. References

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