REGIME CHANGE (MAN MADE INTERVENTION) AND ONGOING EROSION IN THE ST. CLAIR RIVER AND IMPACTS ON LAKE MICHIGAN-HURON LAKE LEVELS

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NOTES ON ADDENDA

It is strongly recommended that Addendum A be read, prior to the Main Report. This Addendum explains that the 1948 hydrographic survey reference of NOAA in the Main Report is incorrect, and should be referenced as 1971 (upper St. Clair River) and 1970-71/1961 for the lower river and delta.

Addendum B provides additional detail on the possible causes for the observed river bed erosion. These causes fall into three primary groups: 1) changes to the upstream supply of sand and gravel through shore protection and harbor breakwater construction on the US and Canadian shores of Lake Huron leading up to the St. Clair outlet; 2) changes to the flow patterns at the outlet owing to the configuration of the outer navigation channel; and 3) removal of a protective gravel lag either through sand mining in the 1920's or through increased flow speeds related to point (2) above.

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Reporting History

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			Includes Addendum B		
			“Causes of River Bed Erosion”		
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Acknowledgements

Baird & Associates completed this investigation through funding from the GBA Foundation, a foundation of the Georgian Bay Association. The cooperation and assistance of the US Army Corps of Engineers, Environment Canada and the Great Lakes Environmental Research Laboratory (NOAA) is also gratefully acknowledged. We wish to thank Frank Quinn for his valuable input to our investigations and for his review and comments on the report.

NON-TECHNICAL SUMMARY

Baird & Associates was retained by the GBA Foundation to complete an investigation into the significant and ongoing drop in the levels of Lake Michigan-Huron (MH) relative to the levels of Lakes St. Clair (SC) and Erie (E).

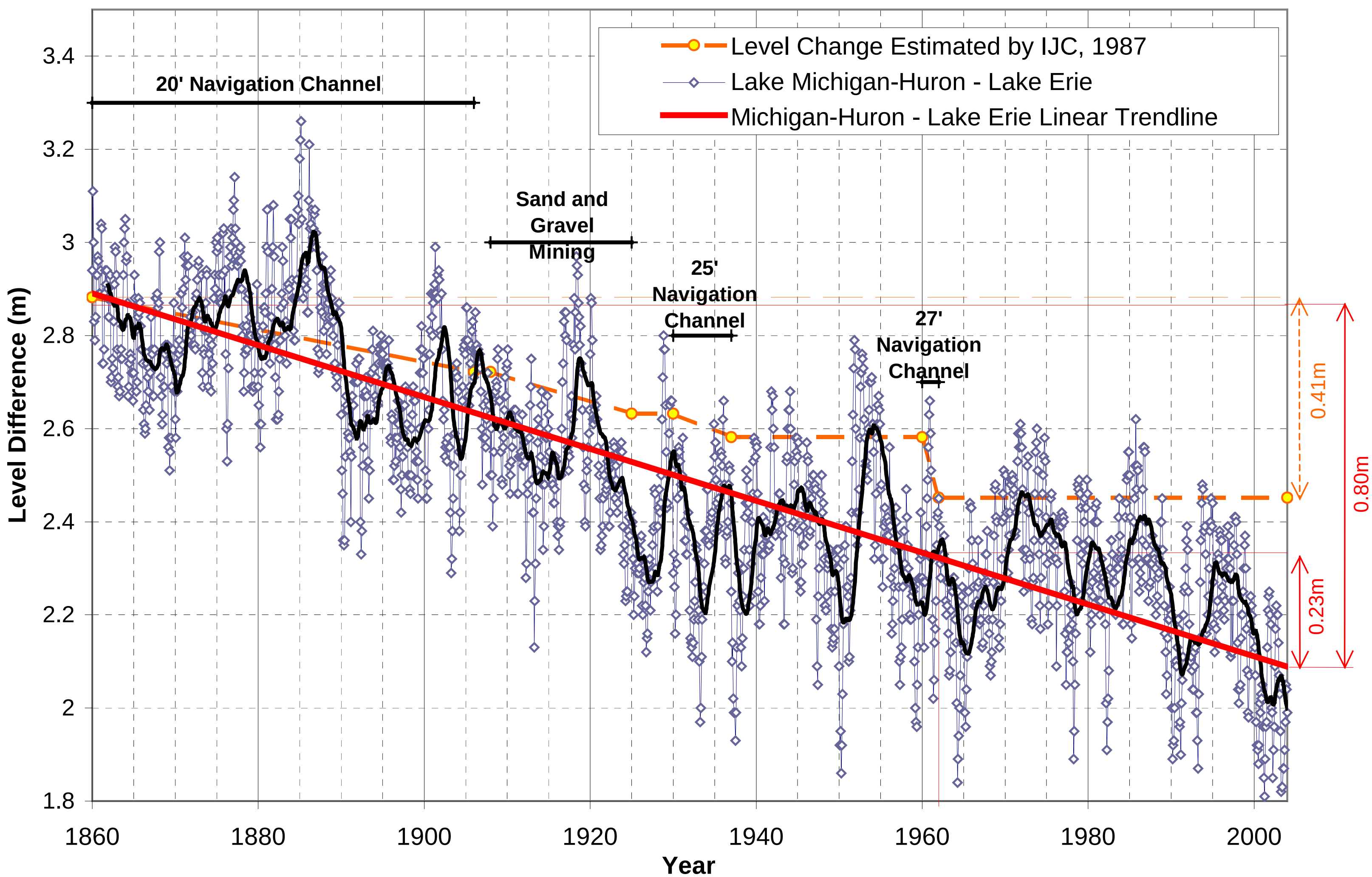
The drop in lake level difference between MH and E (and SC) has been well documented by the IJC and others up to and including the effects of the 8.2 m (27 ft.) dredging project completed between 1960 and 1962 (Derecki, 1985; IJC, 1987). However the water level data show that there has been an ongoing and significant drop since the 8.2 m (27 ft.) dredging project as shown in the following Figure. This decrease in MH water levels is in the range of 20 to 33 cm (8 to 13 in.), and may be closer to 33 cm (13 in.) because the high lake levels over the period from 1970 to 1998 have masked the full extent of the impact. Also, the IJC estimate of the drop in level difference between MH and E since 1860 is 36 to 46 cm (14 to 18 in.), compared to the actual observed drop of approximately 80 cm (2.6 ft). Without implementation of compensation measures, this drop represents an irreversible decline in the long-term average lake level of MH. When compared to the range of lake level fluctuations of +/- 1 m (3.3 ft) from a mean level on MH, this is very significant with potentially extensive socio-economic and environmental implications.

Three possible causes for the ongoing and significant drop in the MH level (relative to SC and E) were investigated through a review of the available evidence and through numerical modeling. The possible causes included: glacial rebound; a shift in the relative net basin supplies (NBS) making the E basin wetter than and MH basin; and erosion of the St. Clair River bed. Based on the review, glacial rebound was found to be negligible compared to the total drop, the NBS shift was found to be unsubstantiated, and the primary cause of the drop in MH lake levels is due to river bed erosion, particularly across a relatively short section, between the Fort Gratiot and the Mouth of the Black River water level gauges, at the upstream end of the river. It also is possible that changes to the Lake Huron approach channel alignment and depths have influenced the drop in lake level difference.

Based on a comparison of 1948 and 2000 river depth data, significant erosion in the order of 2 to 6 m (6.6 to 19.7 ft) occurred at the outer bend of the river just downstream of the Bluewater Bridge. The numerical modeling showed that this erosion significantly increased the flow capacity of the river. The erosion appears to have been triggered by the construction of the 8.2 m (27 ft) navigation channel in 1962 or sometime after this event.

Possible causes of the onset of river bed erosion are: changes to the hydrodynamic flow conditions (and the natural response of the river bottom contours) in the river due to the 8.2 m (27 ft) dredging project; a reduction in sand supply to the St. Clair River (at the outlet of Lake Huron) resulting from shore protection along the Canadian and US shores leading up to the outlet; and/or changes in the position of the outer channel in Lake

Huron that may have changed the efficiency of flow into the St. Clair River. These hypotheses will be explored further in the final phase of our work on this project, to be completed in December 2004.



Actual Level Difference Change for MH-E vs. Level Change Estimated by IJC

TECHNICAL SUMMARY

This investigation was performed to evaluate the significant and ongoing drop in the level of Lake Michigan-Huron (MH) relative to the levels of Lakes St. Clair (SC) and Erie (E). Possible causes for this drop were assessed through a review of the available evidence and through numerical modeling.

Description of the Head Drop between Lakes Michigan-Huron and Erie

Figure A shows the difference in lake levels (head) between MH-SC, SC-E and MH-E based on monthly mean data. A one-year moving average is plotted over the monthly means and trend lines are also plotted. From this plot it is evident that the level of MH has dropped relative to both SC and E. In other words, the change is due to a drop in MH (versus a rise in the lower two lakes). So wherever we refer to a drop in the head between MH and SC this is synonymous with a permanent drop in the level of MH over and above the normal weather and seasonal variations in level. Since the difference between SC and E is constant over 100 years, the level difference between MH and SC can be expressed just as well by using the level difference between MH and E. The lake level record for E is much longer than that of SC, and subsequent comparisons and discussion will focus on the MH-E comparison as representative of the MH-SC level difference, or the MH level. Between 1860 and the 2003 the head between MH and E has decreased by approximately 0.8 m (2.6 ft) from 2.9 m to 2.1 m (9.5 ft to 6.9 ft) as shown in Figure B.

Explanation for Historic Changes in Head between MH and E

The drop in head between MH and E (and SC) has been well documented by the IJC and others up to and including the effects of the 8.2 m (27 ft) dredging project completed between 1960 and 1962 (Derecki, 1985; IJC, 1987). Figure B superimposes the IJC estimates of the influence of various interventions on the St. Clair River over the observed change in head. A middle estimate for the 11 to 21 cm (4.3 to 8.3 in) range of influence was assumed for the dredging operations to create the original 6.1 m (20 ft) channel. The specific interventions and the IJC estimates are listed in Table A. It is clear from Figure B that there has been an ongoing and significant drop since the IJC estimated influence of the 8.2 m (27 ft) dredging project. The trend line through the level difference during this period suggests a drop of approximately 20 cm (8 in). Ignoring the gap between the IJC estimate of the change in level difference (head)and the actual condition after the 1960-1962 dredging operations, the decrease in head that has been experienced since the influence of the 8.2 m (27ft) dredging could be as high as 33 cm (13 in). Further explanation of why the higher end estimate may be equally appropriate is provided below. Also, the IJC estimate of head drop since 1860 is 36 to 46 cm (14 to 18 in.), compared to the actual observed drop of approximately 80 cm (2.6 ft).

Considering that the level of MH fluctuates within a range of about 2 m (6.6 ft), a drop of 20 to 33 cm (8 to 13 in) in the last 40 years, or 80 cm (2.6 ft) over 140 years, which effectively represents a permanent loss to the "long-term mean level" (unless compensated for), is very significant with potentially extensive socio-economic and environmental implications.

Understanding the Relationship Between Head and Lake Level and Possible Influences on this Relationship

A comparison of the drop in head between MH and E and the actual lake level on MH shows that there is a distinct relationship between head and lake level (see Figure C). As the MH lake level increases due to an increase in the net supply of water to the MH basin, the head also increases.

An important implication of the relationship between lake level and head is that periods of high lake levels (i.e. such as the extended period of highs between 1970 and 1998) would tend to mask the true extent of the head drop, in this case between MH and SC/E. In other words, the head drop would have been even greater had average to low lake levels been experienced between 1970 and 1998.

Figure D shows a plot of the level difference (head) that existed (MH-E) for each monthly mean level between 1860 and 2003 on MH. Only the data for the months of May to November have been included to eliminate the effects of ice jams on the St. Clair River. Clearly, the relationship between head and lake level has changed through time and continues to change (the latter conclusion based on the differences in the trend lines between 1969-1986 and 1987-2003). A trend line is not shown for the 1961 to 1968 due to the limited data available in this time period and the clustering of data at the lower water levels. The graph shows the relative head has dropped over time and that the slope of the relationship has changed with time. This will be explained further in the discussion of erosion effects on this change below.

Causes of the Drop in Head Subsequent to the 8.2 m (27 ft) Dredging Influence

Three possible primary causes for the ongoing and significant drop in the MH level (relative to SC and E) were investigated consisting of:

- Glacial rebound influences;
- A shift in the relative net basin supplies to the E and MH basins;
- Erosion of the St. Clair River bed.

Each of these possible causes is discussed in the following paragraphs.

The Possible Influences of Glacial Rebound

There are two possible influences of glacial rebound on the observed head drop between MH and E. The first relates to the possibility that the observed head drop can be explained by changing relative differences in elevations between the gages used to estimate the lake levels on MH and E. The gages at Harbor Beach located 90 km (60 miles) north of the outlet of Lake Huron on the US side, and Cleveland on Lake Erie have been used in our analyses. The most recent estimates of glacial rebound (Coordinating Committee, 2001) indicate that these two gages are in an area of small and similar rebound (both showing less than 3 cm or 1.2 in/century). Therefore, the impact of differential change in elevations of the two gauges due to glacial rebound can be ruled out as a primary cause for the observed drop over the last 40 years.

The second possible influence of glacial rebound relates to the effect of the tilting land and lake bed levels on the distribution of water over the surface of Lakes Michigan-Huron. Rising levels along the east shores of Georgian Bay and falling levels at the south end of Lake Michigan will cause a transfer of water from the rising to the falling side. Rather than contributing to falling water levels on Lake Huron, the tilting of the lake could be expected to cause an increase in water levels at the outlet of lake Huron as water is moved toward the southern end of the lake.

The Possible Influence of a Shift in the Net Basin Supplies between MH and E

Early in our investigation of the drop in head between MH and E, it appeared that a shift between the net supply of water to MH and E basins could partly explain the drop. In other words, it appeared that the lower water levels on MH are simply the result of less net basin supply (NBS) to the MH basin relative to the E basin. This preliminary conclusion was based on a comparison of the NBS determined through the residuals method for MH and E as shown in Figure E. This figure shows the ratio of E to MH NBS for annual values and 10-year moving averages for both the residuals and the components method. The comparison of NBS derived from the residuals method indicates that the NBS for E increased from an average of about 20% of the MH NBS for the period 1948 to 1980, to consistently above 20% in the last 20 years. Furthermore, when the NBS from the residuals method was run through the Great Lakes Routing model for us by Frank Quinn, it could explain much of the drop in head over the last 40 years.

The flaw in the argument that the MH basin has simply had lower NBS compared to E is elucidated through the comparison of the ratio of NBS for E and MH using the components method. The E/MH NBS ratio derived from annual mean and 10-year running average for the components method is also shown in Figure E. The E/MH NBS ratio determined with the components method continued to hover around or just less than 20% through the last 20 years. It would appear that the NBS derived from the residuals and components approaches started to diverge in the late 1970's.

A possible explanation for the divergence between the NBS determined from the residuals and components methods relates to the fact that it is inherent in the assumption of the development of the residuals method that the St. Clair River channel has remained stable since the 8.2 m (27 ft) dredging project. Specifically, the residuals approach relies on stage-discharge and stage-fall-discharge relationships that have remained unchanged through the last 40 years. As will be shown in the next section, it is likely that there has been significant erosion of the St. Clair River bed through this period. As the channel deepens more water can be conveyed for the same lake level. As the current stage-discharge relationships for the St. Clair River do not account for this change in flow capacity, the result is that the NBS to MH is artificially reduced with the residuals approach. In other words, the only way for the residuals approach to explain lower levels on MH is through reduced NBS to MH or higher NBS to E. The components approach does not require the stage-discharge relationships to determine the NBS for each basin, and therefore is unbiased with respect to changes in the connecting channels and flow computations.

It may be concluded that it is highly questionable that a significant and real shift in relative NBS between MH and E has occurred. Therefore, this possible cause cannot explain the large drop in head between MH and E.

The Possible Influence of Erosion of the St. Clair River Channel

The first step in the assessment of the possible influence of erosion was to determine if the channel has eroded in the last 40 years. The two most recent comprehensive surveys of the water depths on the St. Clair River were completed in 1948 and 2000. A detailed analysis of the change between river bed levels in 1948 and 2000, after significant effort to bring the data sets into the same horizontal and vertical datum, was completed for the entire length of the river. This comparison showed widespread erosion throughout the river channel in the order of 0.5 to 3 m (1.6 to 9.8 ft), particularly through the upper two thirds of the river. There were some areas of higher erosion and other areas of localized sedimentation. Considering that the average depth of the upper two thirds of the St. Clair River is approximately 10 m (33 ft) and that the original erosion or incision of the outlet occurred over a period of almost three thousand years (i.e. between 5,100 and 2,100 years before present – see Larsen, 1994), the recent erosion of 0.5 to 3 m (1.6 to 9.8 ft) is unusual and dramatic. Larsen (1994) suggested the erosion of the outlet, and the influence on reducing the MH lake level, ceased 2,100 years before present. Baedke and Thompson (2000) suggest that the MH lake levels stabilized within their current range 3,500 years before present. In any case, the rate of erosion over the last 50 years is unprecedented, even on a geologic time scale.

The next step was to determine what the erosion over the last 50 years has meant in terms of flows through the river. Many measurements of flow speed have been made in the river over time to determine the river flow at different cross-sections. These measurements have been used by the US Army Corps of Engineers (USACE) to calibrate and verify the 2-dimensional numerical model (referred to as RMA2) of the St. Clair

River (Holtschlag and Koschik, 2002). This model was obtained from the USACE to complete numerical model simulations to estimate the impact of erosion on the head difference between MH and E. The advantage of the numerical model is that specific hypothetical cases can be simulated to provide a direct comparison. For example, the head (between MH and SC) required to convey the same flow can be determined for two or three different channel conditions.

One of the primary findings of the numerical modeling with RMA2 was that the main controlling section for the river is located between the water level gauges at Fort Gratiot (and nearby Dunn Paper) and Point Edward. This key controlling section may extend out to the outer end of the Lake Huron approach channel and downstream as far as the Mouth of the Black River gage. Figure F shows the measured bathymetry change (from 1948 to 2000), the measured water surface elevation and the thalweg (deepest depth in the cross-section) depth profile from 1948 and 2000. The large drop in lake/river bed elevation from the shallow area (sand bars) near the opening to the St. Clair River and the rise at the downstream end of the deep hole between the Dunn Paper and the Point Edward gauges act much like weirs to control flow through this section. The cut through the bar by the 8.2 m (27 ft) dredging project (and earlier projects) and the subsequent erosion downstream of the bar have significantly increased the efficiency of the flow through this section of the river. The numerical model simulations shed further light on this observation.

Models runs were completed for three main river bed conditions: (1) with the 1948 bathymetry (with the 7.6 m (25 ft) channel); (2) 1948 bathymetry with the 8.2 m (27ft) channel including over dredging up to 9.1 m in some locations; and (3) with the 2000 bathymetry. The difference between conditions (2) and (3) is the influence of erosion beyond the channel limits. Flows in the river were simulated for each of these model bathymetry conditions using the mean flow rate of 5,200 m^3/s.

Figure G shows the numerical model output for water surface elevation for the three model runs. The results show that for the same input flow condition, the water level on MH has decreased from 176.59 to 176.36 m IGLD between 1948 and 2000, a drop of 23 cm (9.1 in). A comparison of the 1948 data, with the 1948 data with the 8.3 m (27 ft) navigation channel shows a decrease in MH water levels of 4 cm (1.6 in). This represents the change in water level that can be attributed to the dredging of the 8.3 m (27 ft) channel. The decrease in water level due to erosion of the riverbed is the difference (0.23-0.04 m) or 19 cm (7.9 in). In other words, the flow capacity of the channel has been significantly increased by erosion.

Without additional bathymetry data between 1948 and 2000, it is not possible to develop a full time series simulation with the 2D model to determine the integrated influence of river bed erosion on the drop in head between MH and E (or SC) over the last 40 years. In addition, the computational time required to apply RMA2 over this period may make the simulation impractical. Nevertheless, it may be possible to complete this simulation with some estimate of bed change represented in a stepwise manner through time, and using a more computationally efficient model (either a 1D model or a 2D/3D model with a more sophisticated mathematical scheme). The USACE have cross-sectional data for at least the gauge stations at several times through the last 40 years that could be used in such a simulation. This data has been requested from the USACE.

The additional evidence pointing to the central role of erosion in explaining the head drop between MH and SC (or E) relates to the changing relationship between lake level and head as described in the previous section (and shown in Figure D). Changes in the slope of the relationship between head and lake level can be explained through changes in river cross-section. A downward shift of the relationship (i.e. where the slope is maintained) is explained through lowering or downcutting of the river bed. Therefore, the changes since the 1960's in the relationship between head and MH lake level can primarily be explained through increased flow capacity caused by river bed or lake bed erosion.

The final question we asked related to when this river bed erosion was triggered, and how it was triggered. In other words, we have two river wide snapshots of the river bed in 1948 and 2000; was the rate of erosion continuous through this period, did it begin part way through this period and was there river bed erosion prior to 1948. Aside from applying a numerical model to simulate long periods of time as discussed above, the only way to address this question is to extract the lake level influence (i.e. the impact of fluctuating NBS) from the head time series, leaving only the influence of dredging projects and natural erosion. Unfortunately, the components approach to estimating NBS only starts in 1948 so it could not be used as a basis to remove NBS fluctuation influences through the full lake level record dating back to 1860. In order to extract the temporal fluctuations of NBS, the Lake Erie water level was used to represent the NBS for MH based on the assumption that the outflow characteristics through the Niagara River have not been altered through time. It is recognized that there have been regime changes (man made intervention) to the Niagara River that will have affected flow, however the resulting change in E water levels is small compared with the changes that have occurred on MH. The approach and justification for the assumptions associated with the approach are described in more detail in the main report.

The normalized head estimate is presented in Figure H. It should be noted that the line presented is a 10-year moving average. The reader should be aware that a moving average tends to skew the exact date when events occur, and it is for this reason that the 1960-62 dredging of the 8.2 m (27 ft) channel appears to occur in 1958. The head drop between 1948 and 2000 is 23 cm (9.1 in). This is the same value that was predicted by the numerical model as described previously. The drop in head between 1885 and 2000 is 0.7 m (2.3 ft). Without the rolling mean the drop between 1885 and the present is slightly greater than 0.8 m (2.6 ft). The graph shows an unexplained increase in the head during the 1960's. It is possible that this apparent reduction in flow capacity may be related to changes in the lake bed morphology as will be discussed in the report. A key finding of the normalization analysis is that the river bed erosion would appear to be a relatively recent phenomenon, that started sometime after the 8.2 m (27 ft) dredging project that was completed in 1962 as shown in Figure H. One possible explanation would be that the 8.2 m (27 ft) dredging project caused a change in river flow conditions that triggered the natural erosion process. A related explanation is the change in the alignment of the deepest channel from the lake into the river and the related changes to the geomorphology of the lake bed through this area. Another possible explanation is that the shoreline protection efforts along the Canadian and US shores of Lake Huron (much of which was constructed in response to the high lake levels in the 1950's and 1970's), together with harbour construction near the river mouth, have decreased the supply of sand and gravel to the river. This may have triggered a long-term imbalance or deficit in total supply, and as a result, erosion. These various hypotheses for the cause of the recent and ongoing erosion trend (and resulting head drop) will be investigated in the final phase of our work to be completed in December 2004.

It may be concluded that the increased flow capacity due to erosion over the last 40 years is likely the main cause of the drop in head between MH and SC (and E).

Summary

The trend of level difference drop between 1960 and 2000 indicates a drop of 20 cm (8 in) over this period. The drop in level difference to the end of 2003 is closer to 33 cm (13 in) and this is a more representative estimate because the high lake levels over the period from 1970 to 1998 masked the full extent of the impact. The reduction in level difference is continuing. Between 1860 and present the drop has been approximately 80 cm (2.6 ft). This drop represents an irreversible decline in the long-term average lake levels without compensation measures. When compared to the range of lake level fluctuations of +/-1 m (3.3 ft) from a mean level on MH, this is a very significant decline and considerably larger that the glacial rebound influence of 20 cm (8 in)/century representative of the central eastern shore of Georgian Bay.

A comparison of the 1948 and 2000 bathymetry indicates that there is a general pattern of erosion throughout the river, and the erosion appears to be greater at the upstream end of the St. Clair River. This pattern of increasing river bed degradation (or erosion) moving in an upstream direction is consistent with the classic response of a river where the sediment supply has been reduced or cutoff, such as in the case of a dam. The most significant erosion, in the order of 2 to 6 m (6.6 to 19.7 ft) has occurred at the outer bend of the river between the Dunn Paper and Point Edward. The numerical modeling showed that this erosion significantly increased the flow capacity of the river. The erosion appears to have been triggered sometime after the 8.2 m (27 ft) dredging completed in 1962. It is certain that the historic and natural sand supply to the upper end of the river has been interrupted and reduced through various actions including: dredging and sand mining and the implementation of shore protection and harbour structures along both the US and Canadian shores (trapping sand and preventing erosion that would otherwise supply the shore with sand and gravel). Most of these actions have occurred over the last 50 years where the erosion of the river bed has been detected.
The sediment supply deficit hypothesis fails to explain two key observations from our investigations: a) the pattern of very high localized erosion and accretion in the upper reach of the St. Clair River (i.e. in addition to the general trend of erosion); and b) the fact that after the triggering of a significant head drop with the 1960 dredging project,

there was a reversal (or relaxation) of the trend in the latter half of the 1960's as shown if Figure H. These observations lead us to consider that the change in the position of the outer channel in Lake Huron, and related geomorphic changes to the lake bed, may have changed the efficiency of flow to the St. Clair River, contributing to the recent period of erosion of the river bed, particularly above the Mouth of the Black River.

The extent of erosion of the river bed over the last 30 to 50 years is unprecedented, even on a geologic time scale. The river bed was believed to have stabilized 2,100 to 3,200 years ago. The evidence suggests that the resulting drop in head between MH and SC/E is probably ongoing.

It is not surprising that this phenomenon has only recently come to light. The 2000 bathymetry data has only been made available in the last couple of years, allowing comparison to the 1948 bathymetry. Also, the lake levels have generally been high since the 1970’s, masking the drop in head. The low levels of the last three years have only recently revealed the true extent of the underlying head drop. The new normalized approach to view the head drop caused by dredging and erosion alone, provides a method for tracking changes in the future, independent of lake level conditions.

Both the impact of reduced sediment supply and a shift in the position of the outer approach channel as causes of the change in river cross-section and flow capacity will be explored further in the final phase of our work on this project, to be completed in December 2004.

Table A Estimates of Head Change (IJC, 1987)

Regime Change (man made intervention)	Date	Estimated Effect on Lake Huron Water Level (m)
6.1 m Navigation Channel Dredging	1855 to 1906	-0.11 to -0.21
Removal of Shoal from St. Clair Flats	1906	-0.01
Sinking of Steamers Fontana and Martin	1900	+0.03
Sand and Gravel Mining	1908 to1925	-0.09
Dredging 7.6 m (25 ft.) Navigation Channel	1930 to 1937	-0.05
Dredging 8.2 m (27 ft.) Navigation Channel	1960 to 1962	-0.13
NET EFFECT	1855 to 1962	-0.36 to –0.46

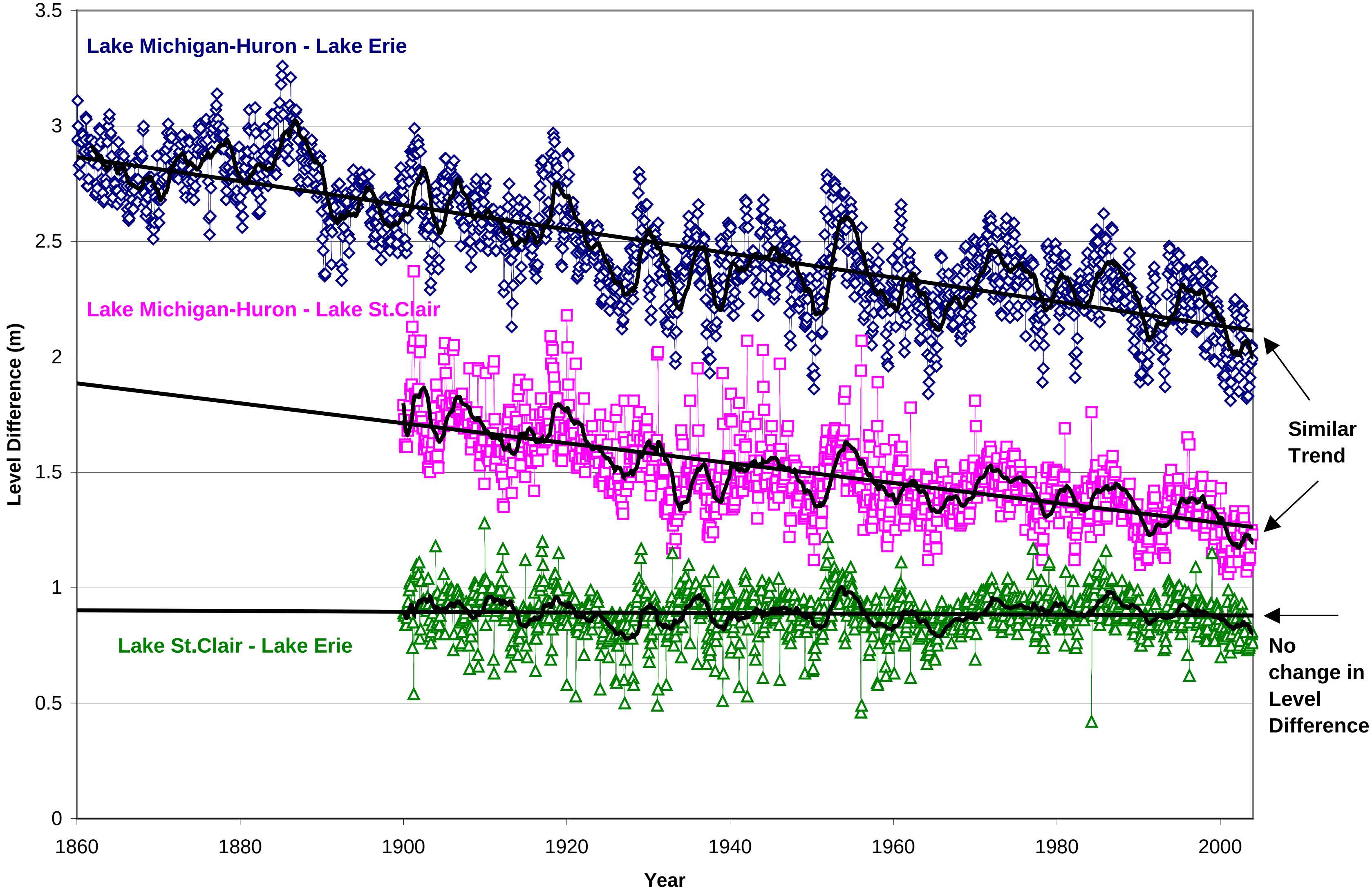


Figure A Historic Level Difference Change

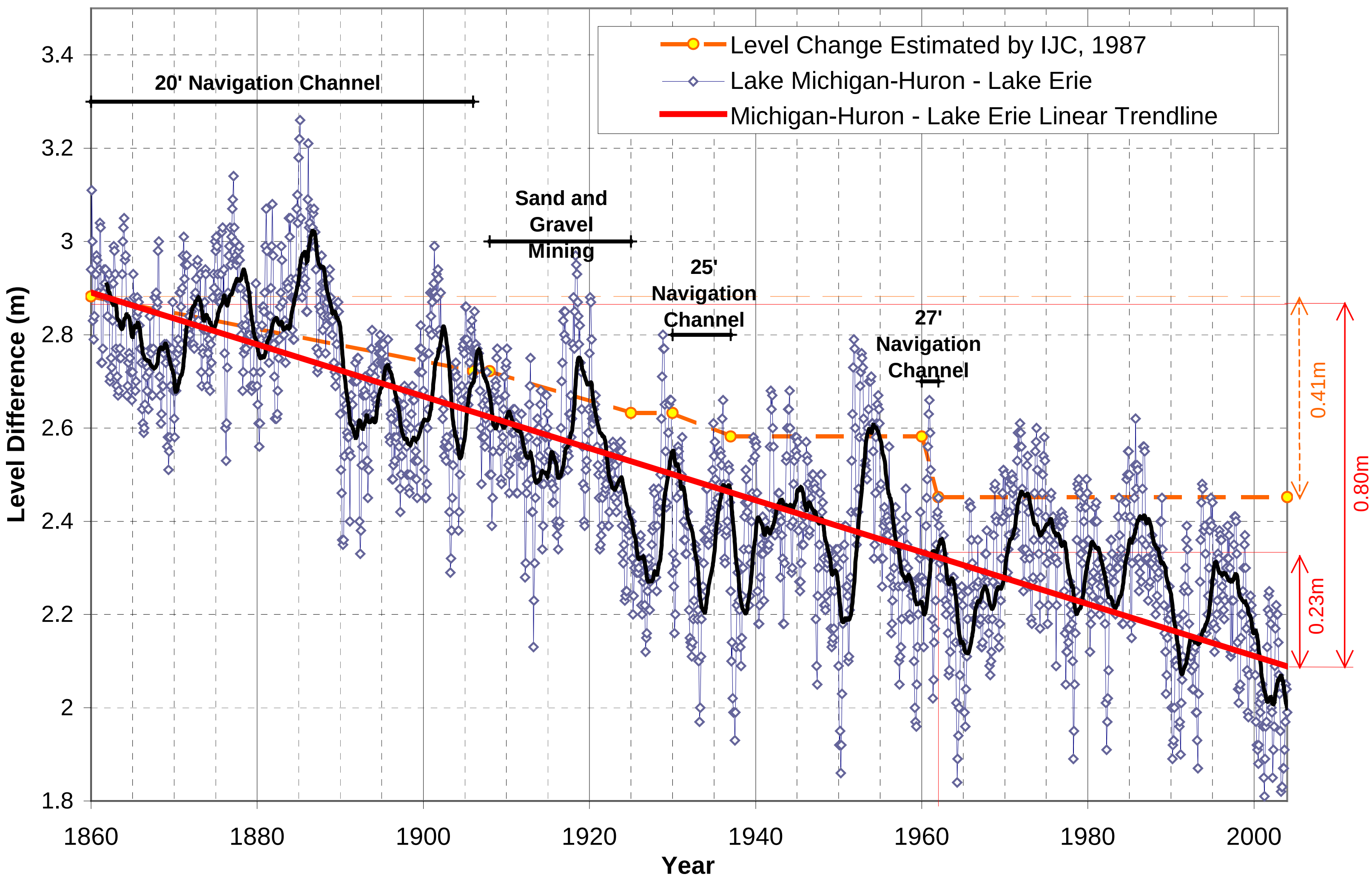


Figure B Actual Level Difference Change for MH-E vs Level Change Estimated by IJC

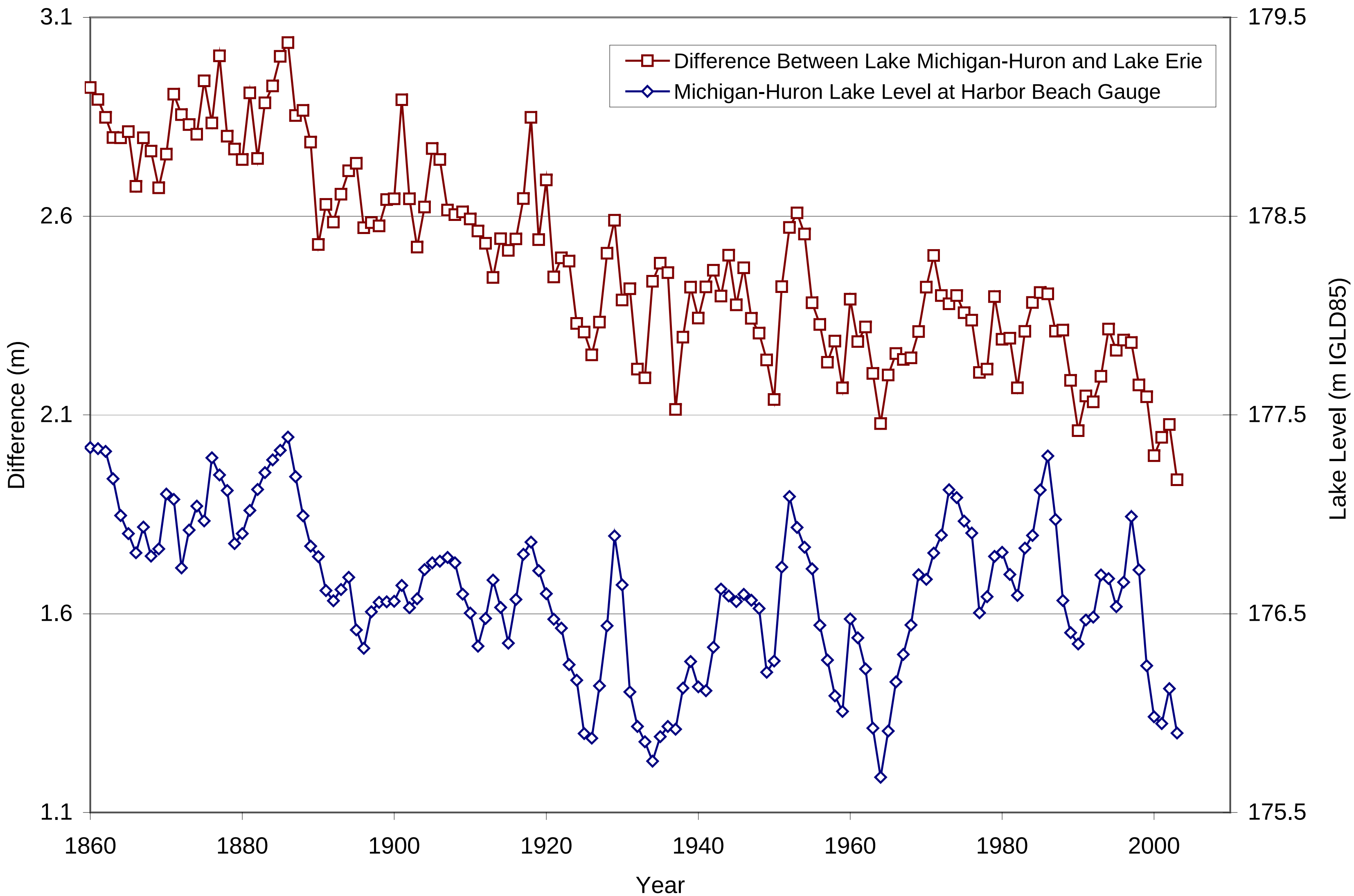


Figure C Comparison of Level Difference (MH-E) and MH Lake Levels

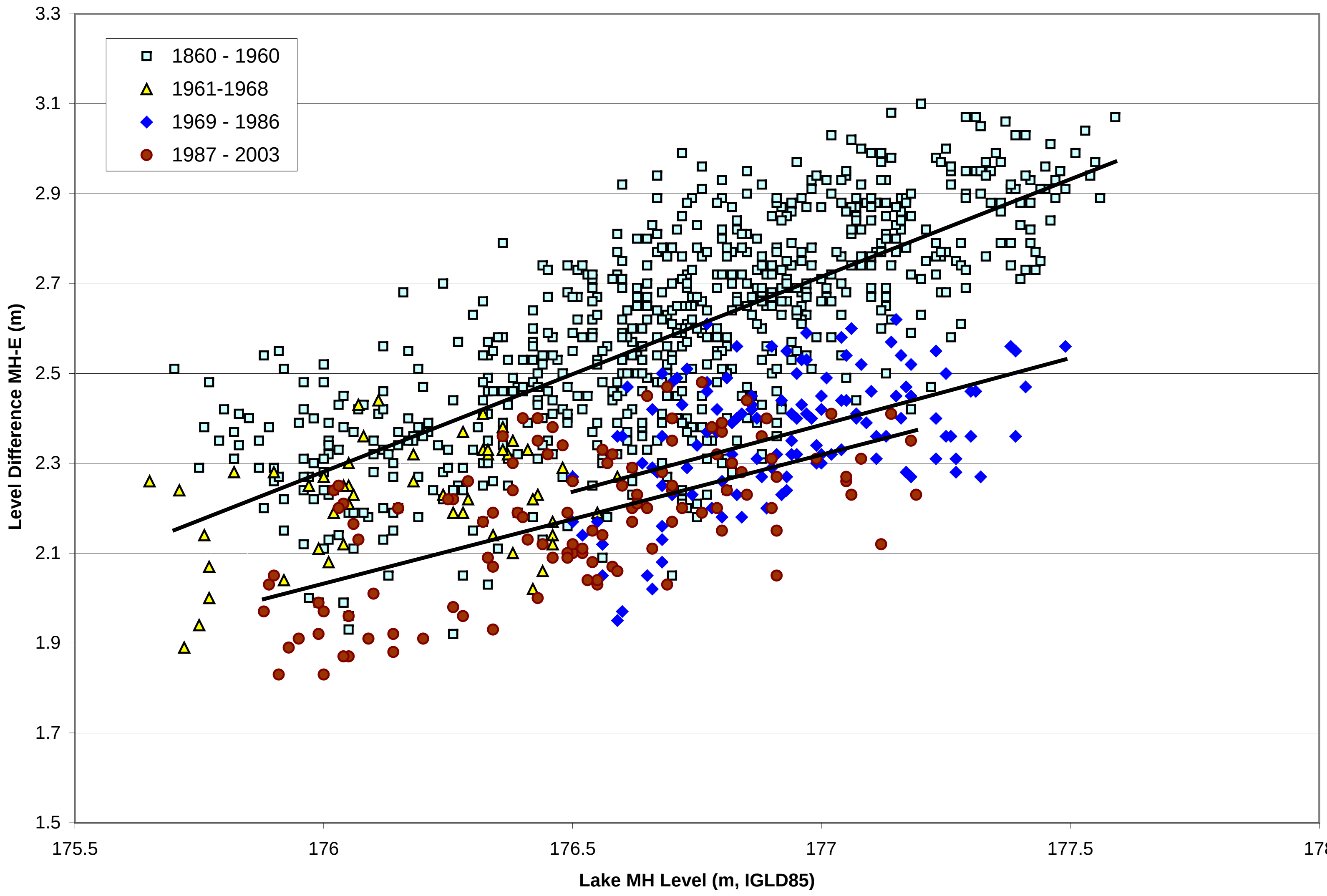


Figure D Correlation between Lake Level and Level Difference

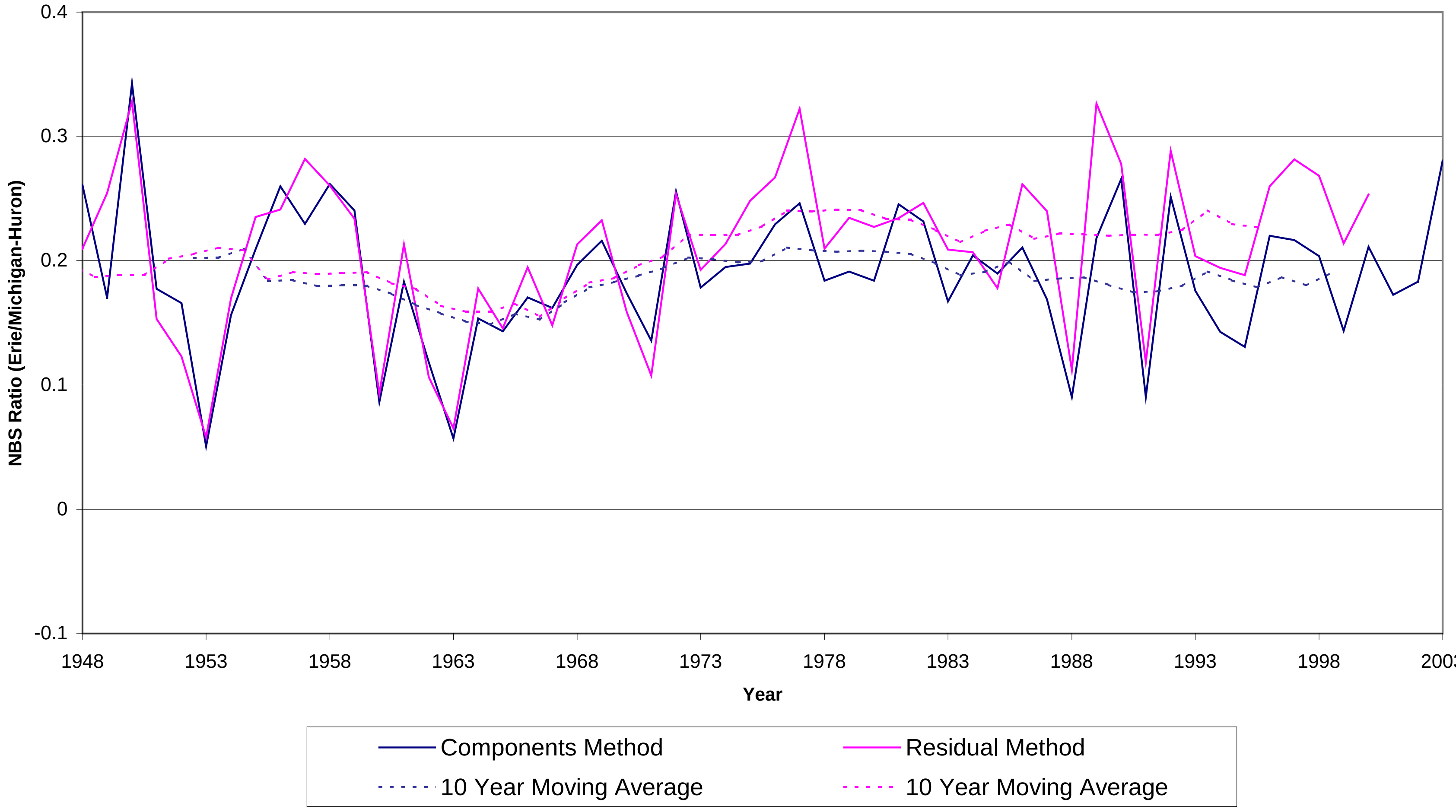


Figure E Comparison of E/MH Ratio of NBS for Residual and Components Method

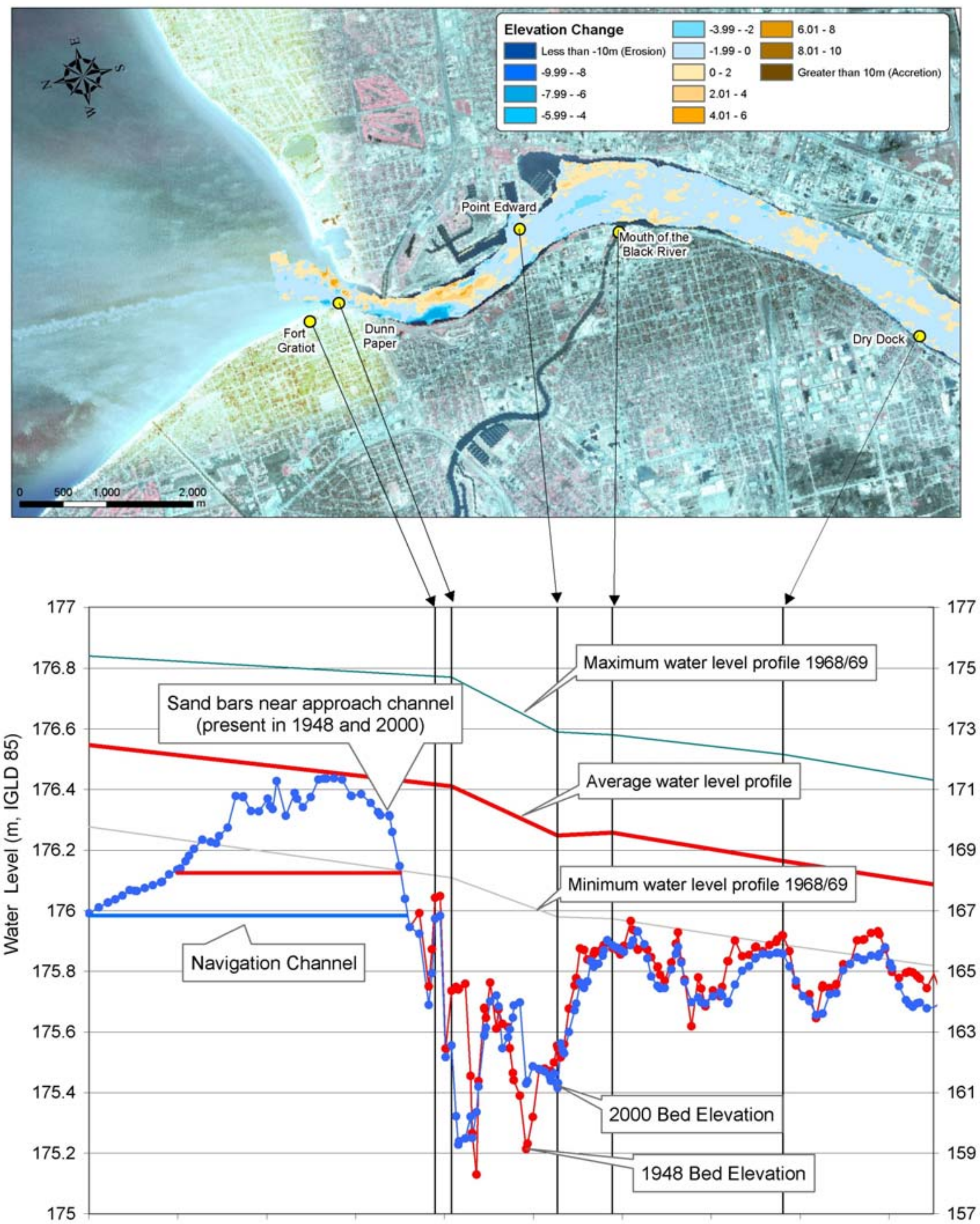


Figure F River Bed Change (1948-2000) and Water Surface Profiles in the St. Clair River

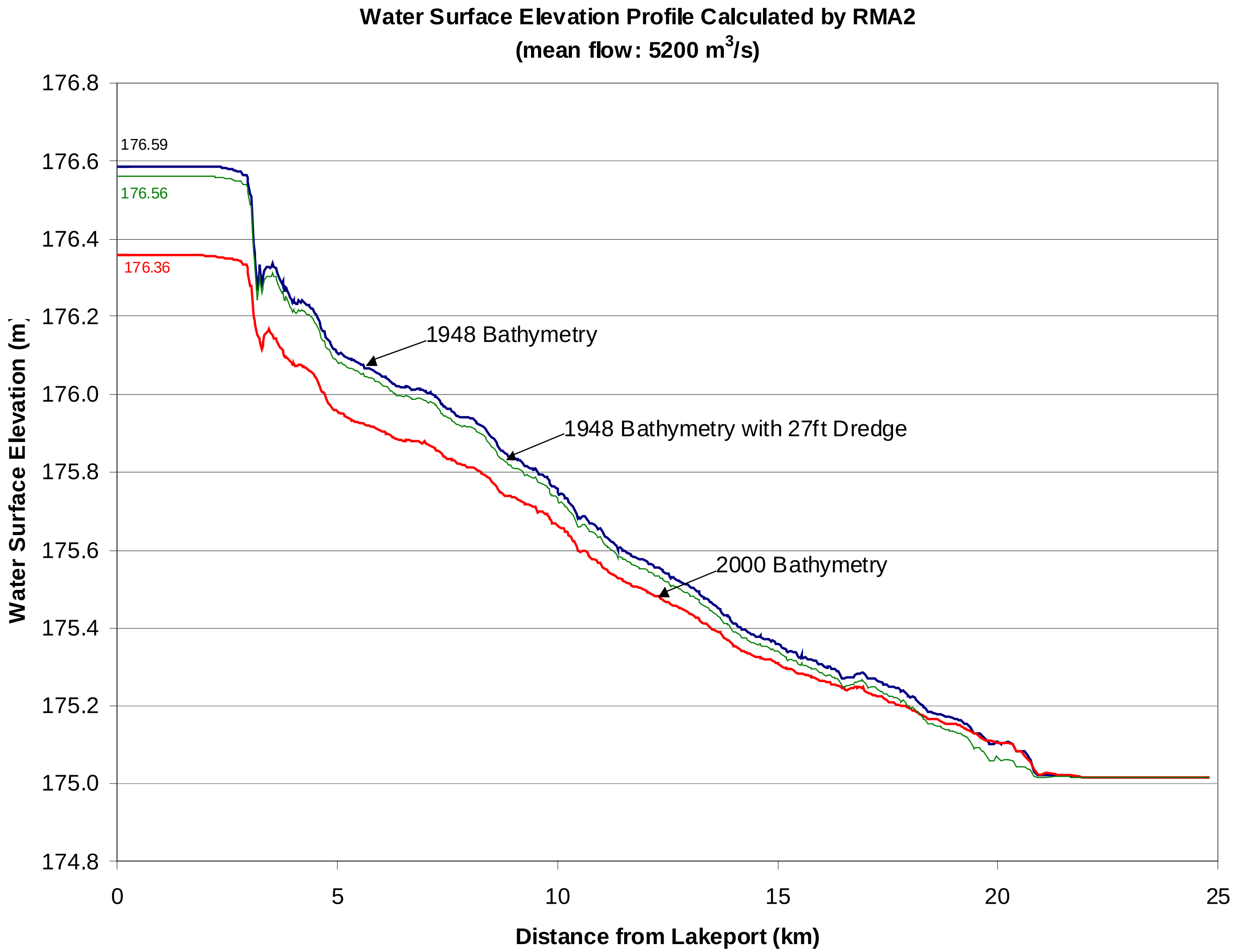


Figure G Water Surface Profile from the Numerical Model Simulations

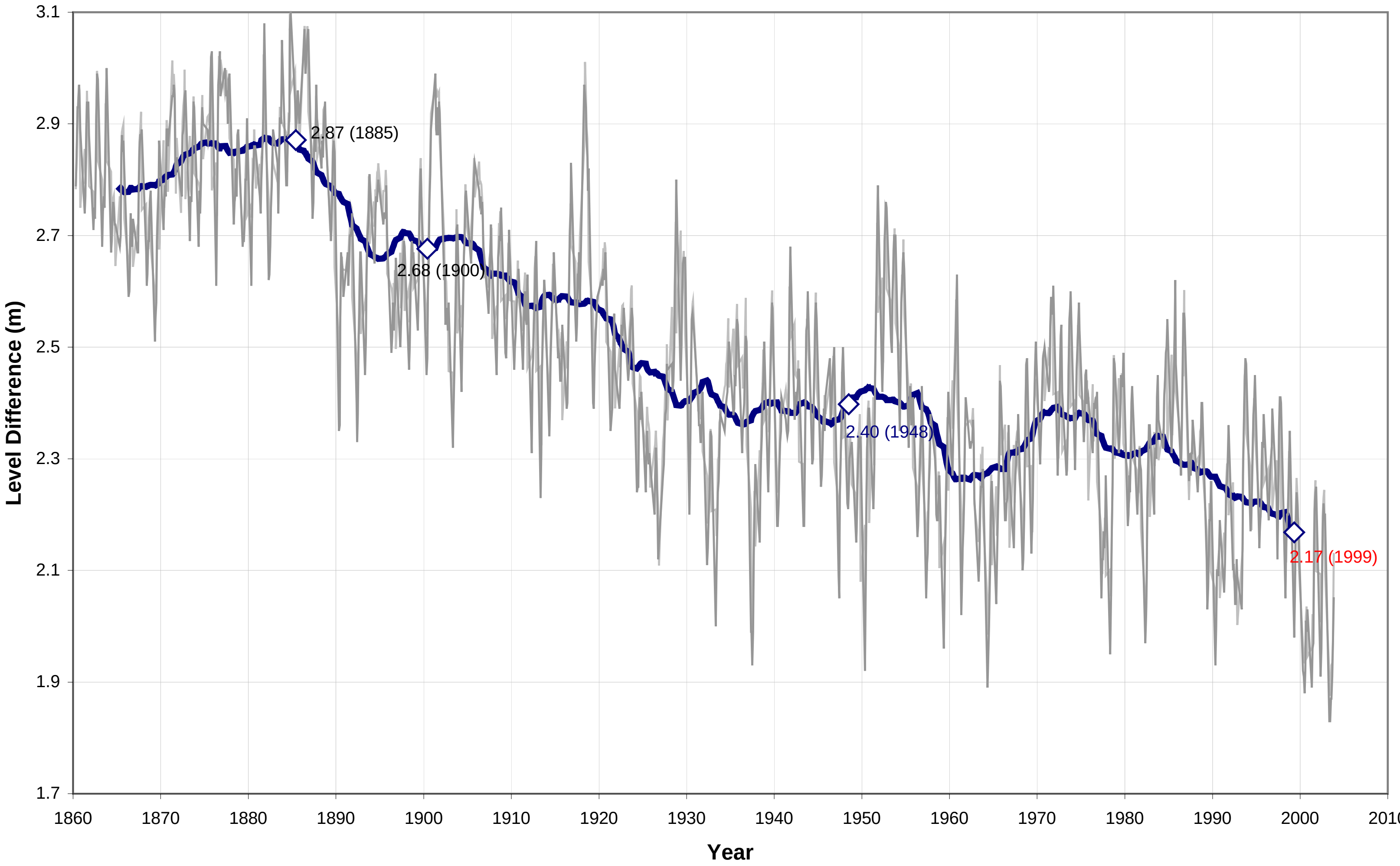


Figure H Change in Level Difference between Lakes Michigan-Huron and Erie due to Erosion and Man-Made Intervention (seasonal and weather induced changes removed through normalization)

TABLE OF CONTENTS

1 INTRODUCTION

Baird & Associates were retained by the GBA Foundation to complete an investigation into the recorded drop in the difference between lake levels on Lake Huron and Lake St. Clair, and possible relationships to historical changes in the St. Clair River. Our methodology and results are summarized in the following sections of the report:

2. Lake Levels and Head Drop
3. Possible Causes of Reduction in Head
4. Regime Change (man-made intervention) and Erosion
5. Numerical Modelling
6. Normalization Analysis of Water Levels
7. River Bed Erodibility and Causes of Erosion
8. Summary and Conclusions

2 LAKE LEVELS AND HEAD BETWEEN LAKES MICHIGAN-HURON AND ERIE

2.1 Decreasing Water Levels on Lake Michigan-Huron

Water level data were analysed to evaluate the change in head between Lakes Michigan-Huron (MH), St. Clair (SC) and Erie (E). Data are collected at water level gauges on the Great Lakes as shown in Figure 2.1 and on the St. Clair River as shown in Figure 2.2.

Average annual water levels at Harbor Beach on Lake Huron and St. Clair Shores on Lake St. Clair are shown in Figure 2.3. The head between the two lakes is also shown. Although it is difficult to see a trend in the lake levels due to the irregularity of the data, there is clearly a continuous decrease in the head between the two lakes during the period of the data record (1900 to 2002).

The level difference (head) and lake levels at Harbor Beach on Lake Michigan-Huron and Cleveland on Lake Erie are shown in Figure 2.4. Data for Lake Erie dates from 1860 providing a longer record than the data for Lake St. Clair. There is a clear trend of decreasing head between Lake Michigan-Huron and Lake Erie during the last century, while water levels on Lake Erie have remained relatively constant. The trend is similar to the observed decrease in head between Lakes Michigan-Huron and Lake St. Clair, and suggests that the longer data record for Lake Erie may be used in the analysis of head change.

The water level differences between Lakes Michigan-Huron and Erie; between Lakes Michigan-Huron and St. Clair; and between Lakes St. Clair and Erie based on monthly mean data are shown in Figure 2.5. A one-year moving average is plotted over the monthly means and trend lines are also plotted. There is no obvious change in the head between Lakes St. Clair and Erie. It can be concluded that the lake level on Lake Michigan-Huron is declining and this is the cause for the observed decrease in head between Lakes Michigan-Huron and St. Clair. Since the difference between Saint Clair and Erie is constant over 100 years, the level difference between Michigan-Huron and Saint Clair can be expressed just as well by using the level difference between Michigan-Huron and Erie. Because the lake level record for Lake Erie is much longer than that of Lake St. Clair, subsequent comparisons and discussion will focus on Lake Michigan-Huron/Lake Erie comparisons as representative of Lake Michigan-Huron/St. Clair head, or the Michigan-Huron lake level. Based on Figure 2.5, the head between Lakes Huron-Michigan and Lake Erie decreased by approximately 0.8 m (from 2.9 m to 2.1 m) between 1860 and 2003.

2.2 Hydrologic Cycles and Impact of Water level on Head

Long term cyclical fluctuations in water levels on the Great Lakes are an important consideration when analyzing historical trends (see Figure 2.6). Great Lakes water levels fluctuate with hydrologic cycles (change in total water supply caused by increases and decreases in precipitation, evaporation and runoff). These cyclical variations are well documented (Thompson and Baedke, 1997; Larsen, 1994; and Chagnon 2004). On the basis of previous paleo-climatologic studies of historic beach ridge data, the lake level fluctuation cycles consist of at least the following:

- **120 to 200 year cycle:** Thompson and Baedke (1997) collected data from beach ridges that show an increase and decrease in foreshore and dune crest elevation from 200 to 4,700 cal BP. With the vertical isostasy removed from the data and using Fourier smoothings to filter out the high frequency components of the data, the long-term change of lake-level fluctuations are readily apparent. The 120 to 200 year quasi-periodic fluctuation (~160 year) was clearly observed in the smoothed data;

- **33-year cycle:** The beach ridges used by Thompson and Baedke (1997) only preserve high stands of lake level. The data indicate that a beach ridge is formed approximately every 33 years (33 ± 6.6 years) in response to a fluctuation of about 0.5 to 0.6 m. This is confirmed in the actual measured water level records for Lake Erie once smoothed using a 15 year moving average from annual mean lake levels. The period of this hydrologic cycle is in the range of 29 to 37 years and about 33 years in average from the 15 year moving averaged mean lake level;

- **4 to 8 years cycle:** A hydrologic cycle with a period of 4 to 8 years is clearly observed. The magnitude of the hydrological cycle is about 0.4 m. The cycle is probably explained by short-term climate change;

- **1-year fluctuation:** It is well known that lake level varies with season. This results from the seasonal changes of precipitation and temperature (evaporation). The lake level is high in summer and low in winter.

The highest amplitude cycle, and therefore the most important cycle to consider, is the 160-year cycle. Figure 2.6 shows that recent data, from 1940 to present is in the rising phase of the 160-year cycle. A comparison of the drop in level difference between Lake Michigan-Huron and Lake Erie, and the actual lake level on Lake Michigan-Huron shows that there is a distinct relationship between head and lake level (see Figure 2.7). As the Michigan-Huron lake level increases due to an increase in the net supply of water to the basin, the level difference also increases. Similarly, when water levels decrease due to a decrease in net basin supply, the head also decreases.

An important implication of the relationship between lake level and head is that periods of high lake levels (i.e. such as the extended period of highs between 1970 and 1998) would tend to mask the true extent of the head drop, in this case between Lakes Michigan-Huron and Erie. In other words, the head drop would have been even greater had average to low lake levels been experienced between 1970 and 1998. Figure 2.6 shows that in the near future (up to 2015), water levels can be expected to rise by another approximately 0.2 m. However after 2015, we will be in the falling phase of the 120 year cycle and there is a predicted 1 m decrease in water levels over a 60 to 80 year period. The head drop will be more apparent during periods of low water level.

Figure 2.8 shows a plot of the head that existed (Lakes Michigan-Huron minus Erie) for each monthly mean level between 1860 and 2003 on Michigan-Huron. Only the data for the months of May to November have been included to eliminate the effects of ice jams on the St. Clair River. Clearly, the relationship between head and lake level has changed through time and continues to change (the latter conclusion based on the differences in the trend lines between 1969-1986 and 1987-2003). A trend line is not shown for the 1961 to 1968 due to the limited data available in this time period and the clustering of data at the lower water levels. The graph shows the relative head has dropped over time and that the slope of the relationship has changed with time.

2.3 Flow Data

Flow measurement data for the St. Clair River were obtained from the USACE. Daily flow rates calculated by Environmental Canada using stage-discharge relationships were also reviewed. The stage-discharge relationships were developed on the basis of flow measurement and stage records in the river. The stage discharge relationships are not updated on a regular basis and may not therefore reflect ongoing changes to the river (i.e. due to erosion or sedimentation). In addition, flow measurements are only taken at specific stations, and changes to the river at other locations may not be identified and considered. Therefore, calculated flow rates have not been used in this analysis. Historical water level data have been used instead to identify change in the flow capacity of the river.

Figure 2.1 Relevant Water Level Gauges on Great Lakes and St. Clair River

Figure 2.2 Water Level Gauges on St. Clair River

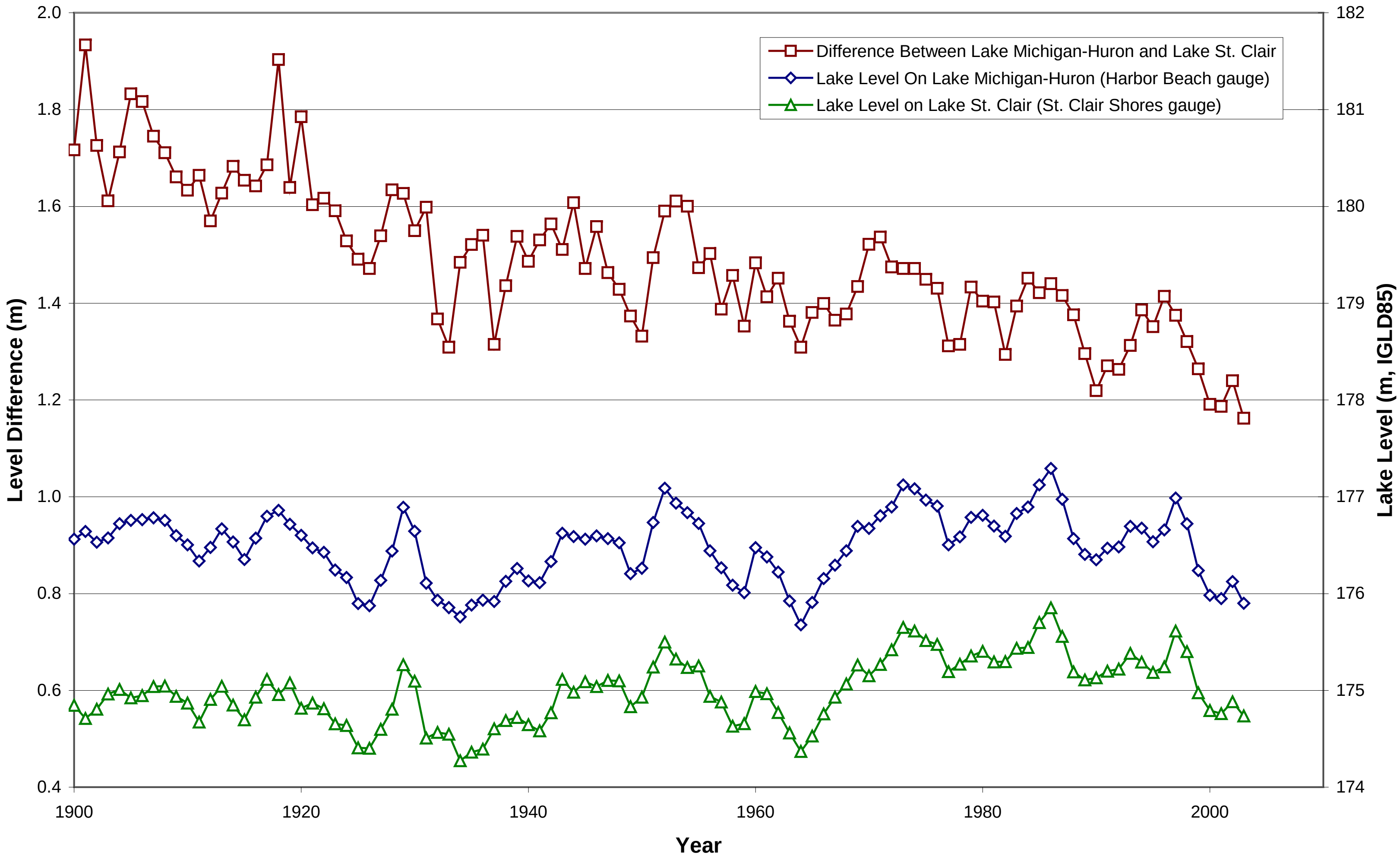


Figure 2.3 Comparison of Lakes Levels and Head for Lakes Michigan-Huron and St. Clair

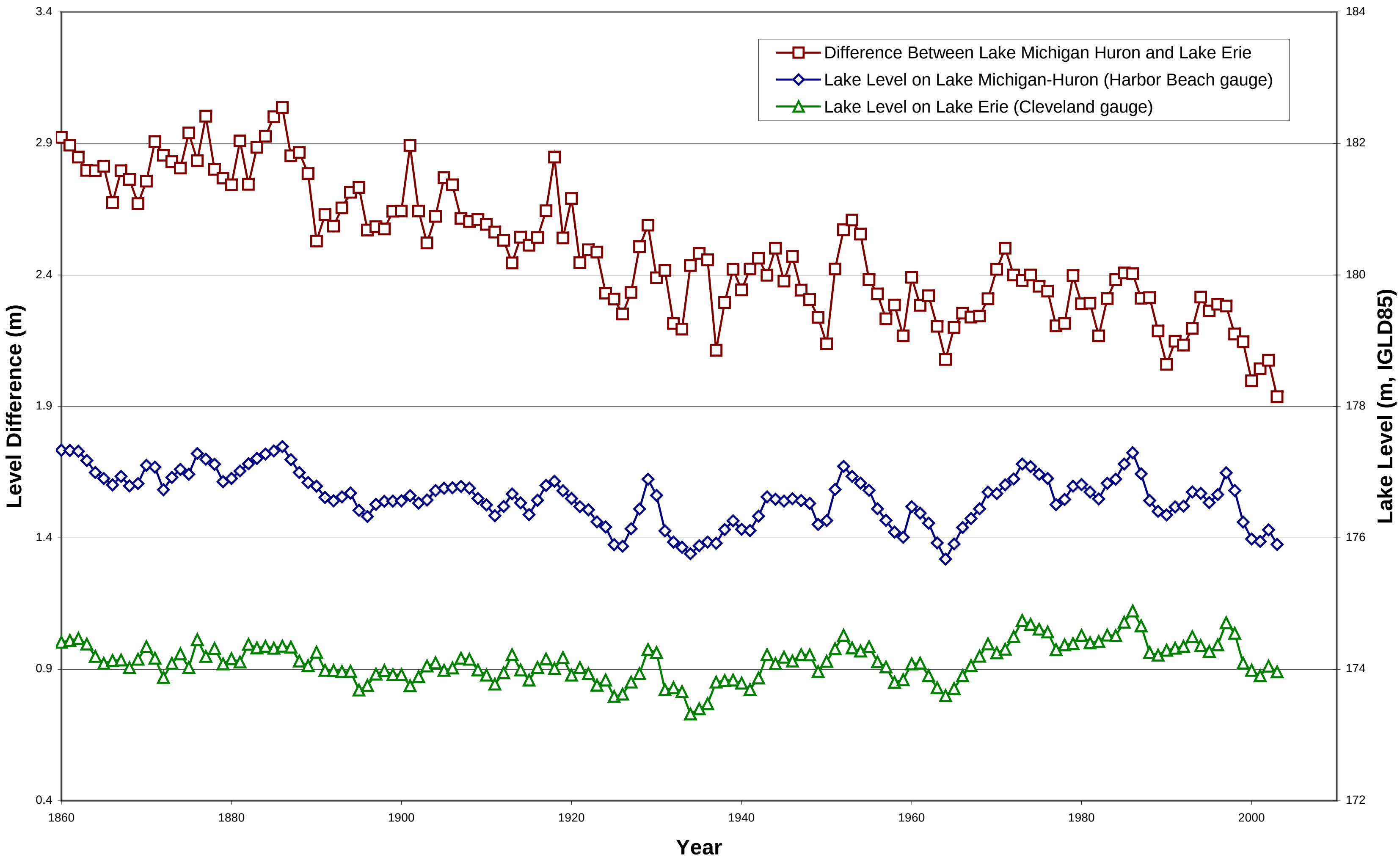


Figure 2.4 Comparison of Lakes Levels and Head for Lakes Huron-Michigan and Erie

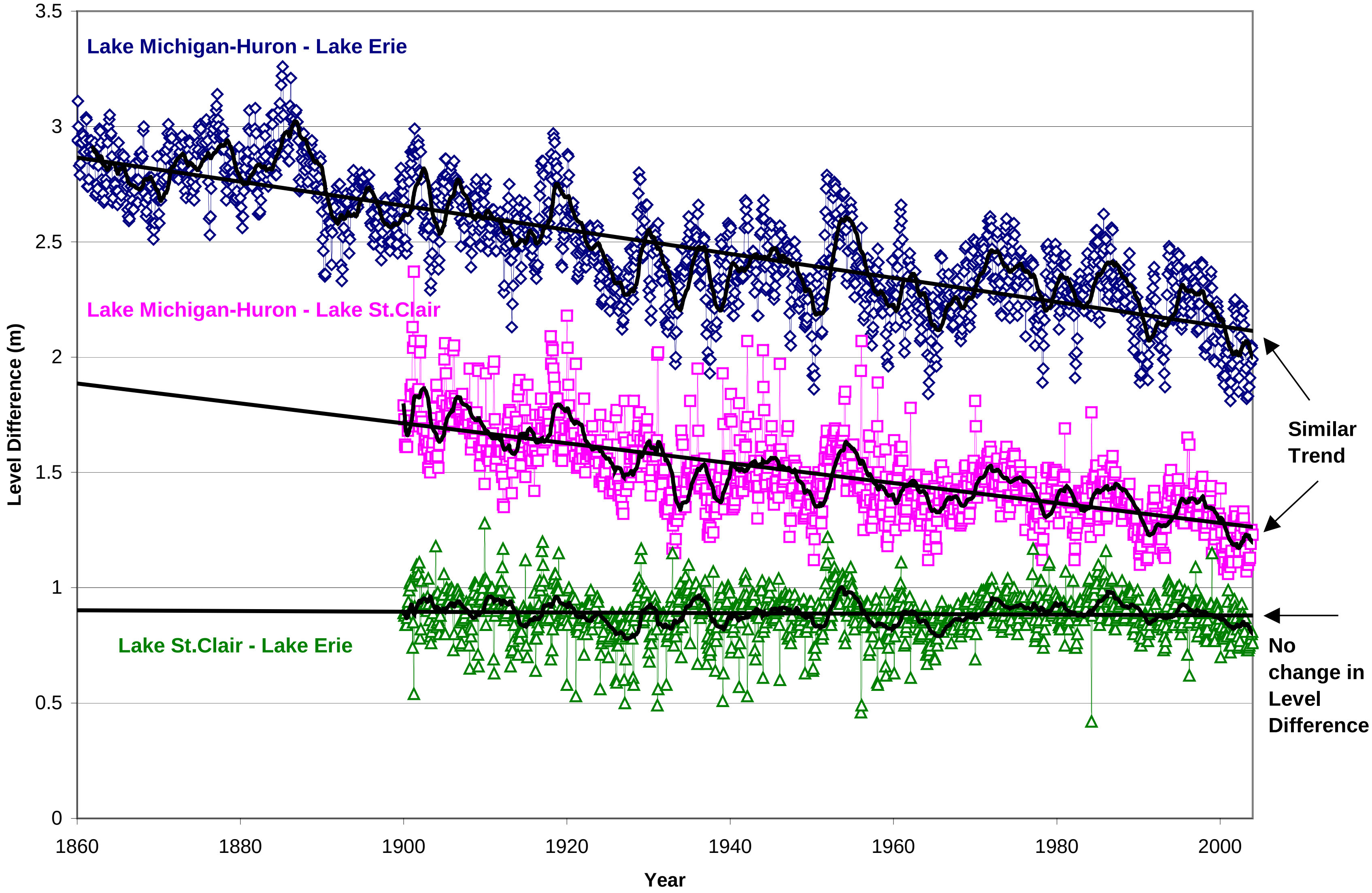


Figure 2.5 Comparison of Level Difference between Lakes Huron-Michigan, St. Clair and Erie

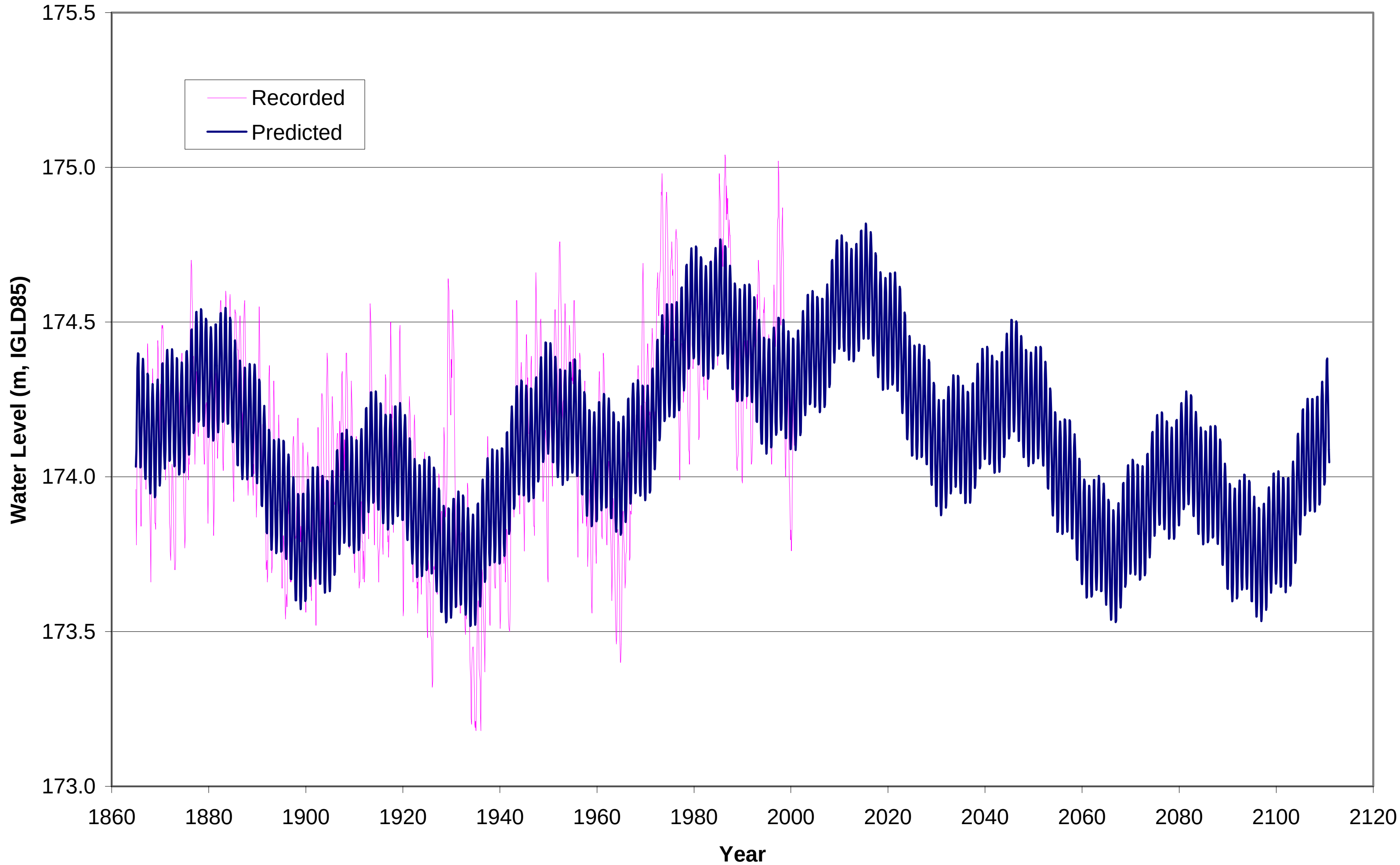


Figure 2.6 Lake Erie Annual Mean Water Levels Showing 160 and 33 Year Cycles

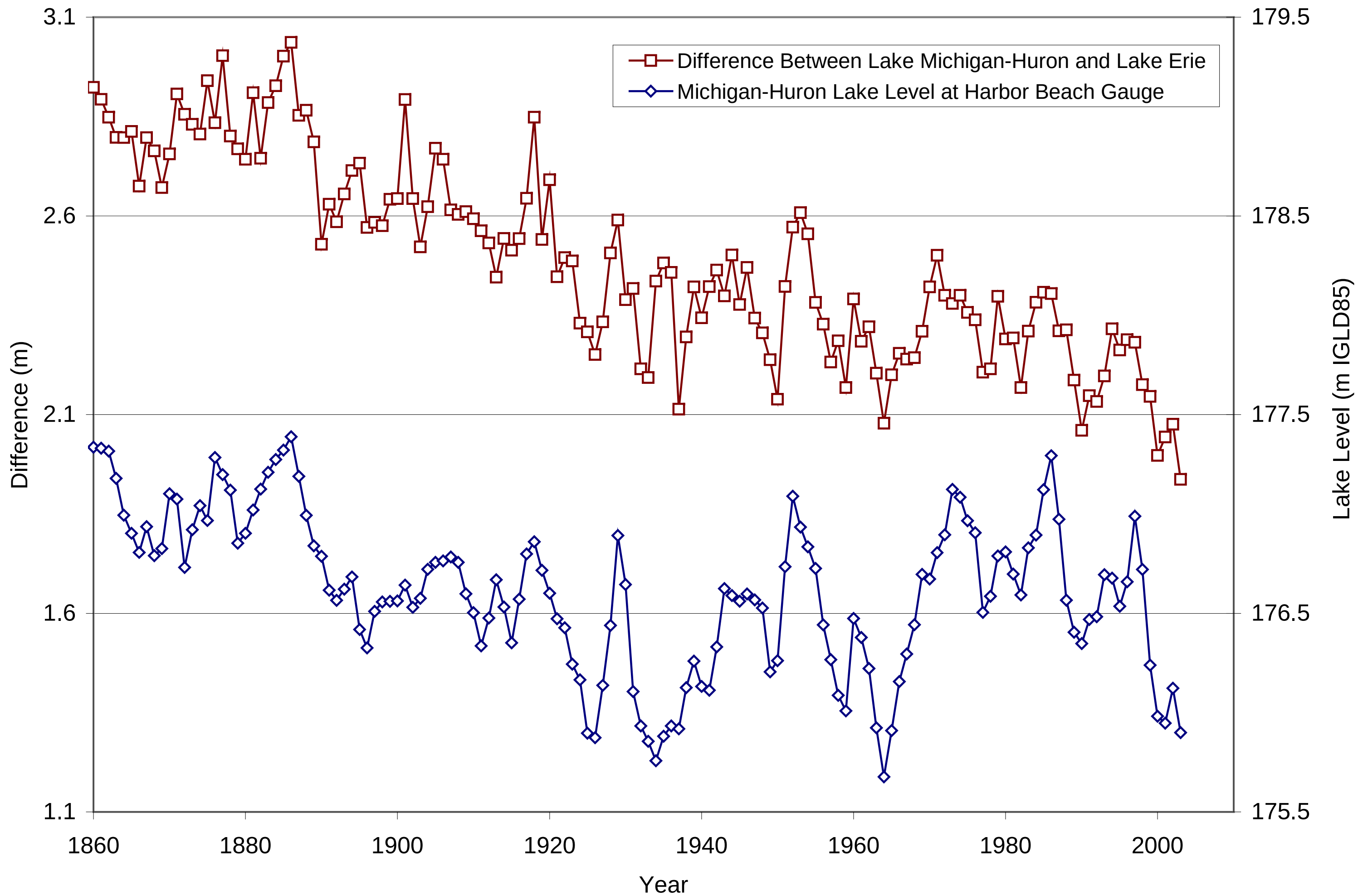


Figure 2.7 Comparison of Level Difference (MH-E) and MH Lake Levels

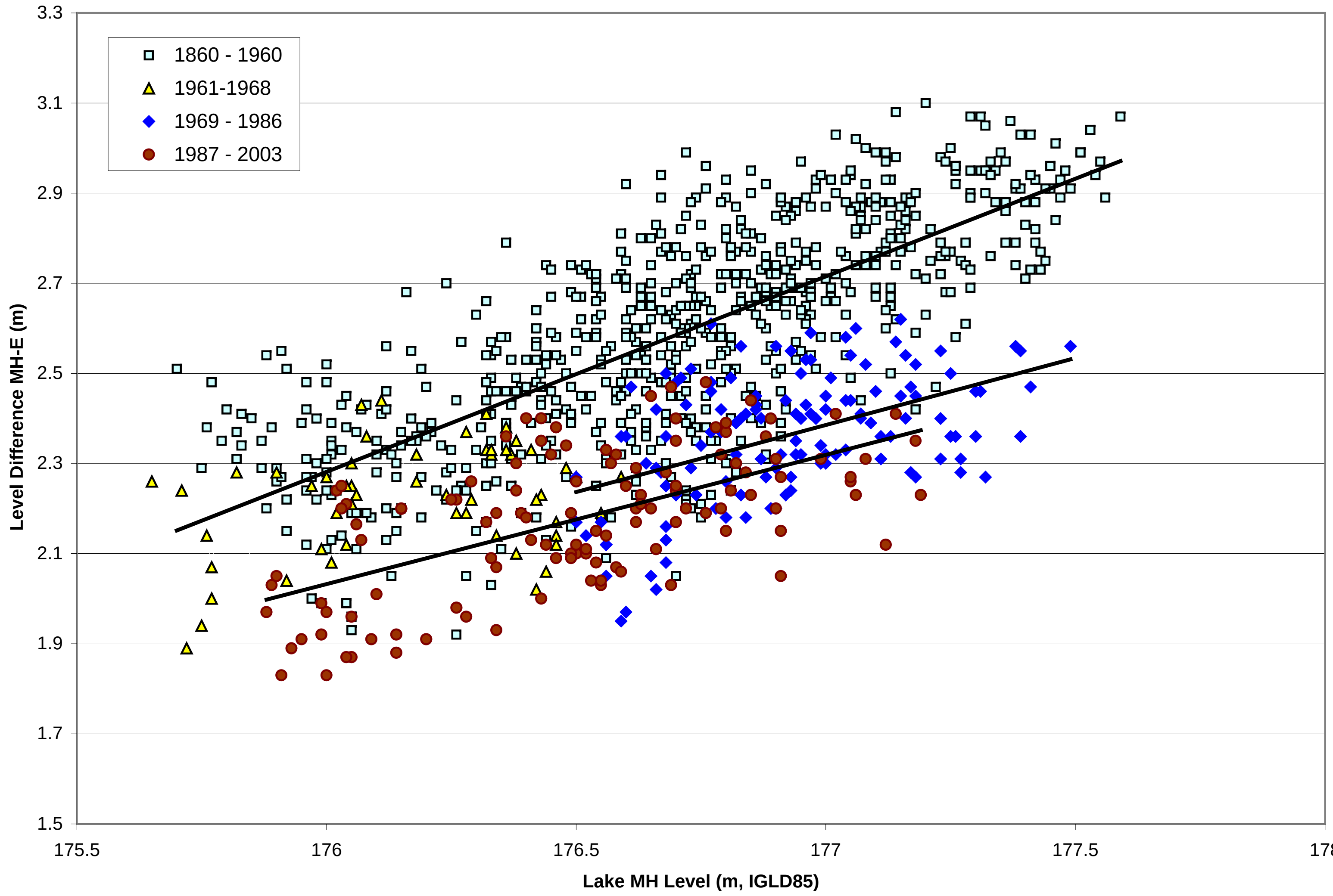


Figure 2.8 Correlation between Lake Level and Level Difference

3 POSSIBLE CAUSES OF REDUCTION IN HEAD

Having established that there has been a long-term trend toward lower water levels on Lake Huron-Michigan, and that this is associated with a change in head between the lakes, this section investigates the possible causes of the reduction in head. It is important to keep in mind that the reduction in head appears to be generally continuous in recent years and not in discrete steps. This may point to the root cause also being more continuous than discrete in nature.

There are several factors that could cause the change in head between the lakes. Changes to the St. Clair river cross-section such as deepening of the channel through dredging and/or erosion might make the river more efficient. Although higher flow rates would result initially, this would be followed by a drop in water levels on Lake Huron and an increase in water levels on Lake St. Clair. The reduced head between the two lakes would then result in reduced flow and the system would return to an equilibrium. A change in the relative net basin supply to the lakes could change the lake levels. Glacial rebound could also affect flow through the connecting channels of the Great Lakes. These factors are discussed in the following sections.

3.1 Changes to Flow Capacity in the St. Clair River

A decrease in head between Lakes Huron-Michigan and St. Clair could potentially be caused by increased capacity through the St. Clair River. Possible causes for changes in flow capacity (either increase or decrease) in the St. Clair River may be grouped into two general categories: change in flow cross-section; and change in roughness. In the short term, ice jamming can also affect flow. These are presented and briefly discussed below.

3.1.1 Changes to River Cross-Section

Changes to the river cross-section can result from human intervention (i.e. dredging or aggregate mining) and from natural erosion. Changes resulting from human activities are referred to as having caused regime change. Regime change and erosion may have had a significant influence on flow capacity, particularly if they occurred at a critical location where the flow is restricted or along a substantial length of the river.

Historical dredging of the St. Clair River will have influenced the cross-sectional area available to convey water. Brunk (1968) indicates that the first major dredging began in 1855. Other key events include sand and gravel mining between 1908 and 1925, dredging of the navigation channel to 7.6 m (25 ft.) in the 1930s and dredging of the navigation channel to 8.2 m (27 ft.) in the 1960s. These discrete changes in river channel depth would have resulted in a temporary increase in flow as described in Quinn (1985), and a long-term reduction in head as the lake level compensated to maintain flows through the more efficient channel. Estimated changes in head for historical dredging are discussed further in Section 4.1.

Land reclamation efforts along the banks of the river have likely decreased the overall channel width in local areas. This may have resulted in a minor increase in flow resistance.

Less sand and gravel may now be delivered to the St. Clair River owing to interruption/impacts of shore protection and harbour structures along the upstream shores of Lake Huron. This could have two impacts: 1) increase in depth of the channel as more sand is lost than is supplied to the channel over time; and 2) reduction in protective lag cover over underlying irreversibly erodible glacial sediments, thus further increasing channel depth.

An estimated 2.7 million cubic metres of sand, gravel and cobble aggregate was mined from the St. Clair River bed between 1908 and 1925 (see Freeman, 1925 and Quinn, 1985). Gravel/cobble "lag" deposits often occur along Great Lakes shorelines and river channels that are eroding into glacial sediment deposits. It has been shown that in many locations this lag, once developed to sufficient thickness, acts to protect the underlying glacial sediment from further erosion. However, when this natural armour is removed by dredging, the glacial sediment will be prone to irreversible erosion for many years resulting in ongoing deepening of the channel.

Propeller scour from large ships can cause a significant increase in water depth in shipping channels. This increase in depths would be generally continuous with some discrete changes related to introduction of deeper draft vessels with changes in channel project depths.

3.1.2 Changes in Flow Resistance

A key factor influencing flow resistance in channels is the presence of submerged and emergent aquatic vegetation. It is likely that there has been a reduction in aquatic vegetation as a result of dredging and land reclamation efforts. On the other hand, in some areas on the Great Lakes invasive species of vegetation have thrived and dramatically increased flow resistance. Efforts to obtain historical and present mapping of vegetative cover for comparison were unsuccessful.

Removal of gravel and cobbles from the river bed (as discussed above) would have also resulted in a reduction of channel bed roughness. However, this would have been a discrete change even if implemented over a period of years.

3.1.3 Ice Jamming

Ice has been shown to have a dramatic influence on the flow through the St. Clair River (see Freeman, 1925 and Quinn, 1985). In very cold heavy ice winters ice jams and thick ice cover can significantly reduce flows. Regional warming trends have more than likely resulted in a gradual reduction of ice cover (thickness and duration) over the last 150 years. This would potentially decrease flow resistance and increase flow rates. However the effect would be short term, i.e. contained within the months of the ice jam, and would not be apparent in long term trends.

3.1.4 Summary of Regime Change (Man-made Intervention) Impacts

Based on the above, the most significant changes to the St. Clair River that would have affected flow, likely involve changes to the river cross-section. These changes have resulted from dredging for the 7.8 m (25 ft.) and 8.3 m (27 ft.) navigation channels, aggregate mining and riverbed erosion. Natural processes may have caused riverbed erosion, a reduction in sand and gravel supplied to the river from Lake Huron, exposure of the underlying erodible cohesive riverbed due to aggregate mining, and/or propeller scour.

In the long term, the flow rate in the St. Clair River must be balanced for the net basin supply. Otherwise the lakes would dry up or flood. If the net basin supply is constant, erosion or dredging in the river initially increases the flow due to lower resistance. Water levels on Lake Huron-Michigan drop because the outflow is greater than the net basin supply. Because the flow rate in the river is a function of water depth and head loss, the lower head decreases the river flow resulting in a new equilibrium. Measured regime change (man-made intervention), the predicted impact on lake levels and the observed change in head are discussed further in Sections 4 and 5.

3.2 Relative Changes in Net Basin Supply

3.2.1 Methods of Calculating Net Basin Supply

The water supply to a lake is referred to as Net Basin Supply (NBS). NBS data were reviewed to determine if changes in NBS might account for changes in the head between Lakes Huron-Michigan and Erie (and St. Clair). In particular, relative changes in the NBS to the two lakes could potentially affect the head.

NBS is one type of hydrologic data used by government agencies in the U.S. and Canada for simulation, forecasting and water resource studies on the Great Lakes-St. Lawrence and their basins. Two different approaches for determining NBS are used by the agencies.

The NOAA Great Lakes Environmental Research Laboratory (GLERL) uses the Components Method. NBS is calculated as the sum of over-lake precipitation and basin runoff minus evaporation from the lake's surface:

$$NBS=P+R-E \quad (1)$$

where P is over-lake precipitation, R is basin runoff and E is lake evaporation.

The U.S. Army Corps of Engineers (USACE) and Environment Canada (EC) use the Residual Method, which is based on the change in storage, accounting for inflow/outflow and any diversions into or out of the lakes:

$$NBS=\Delta S-I+O-D \quad (2)$$

where ΔS is change in lake storage computed from lake level change, I and O are inter-basin inflow and outflow through natural channel respectively and D is inter-basin diversions into the lake.

The NBS data calculated by GLERL using the Components Method are released independently from the NBS data calculated by the USACE and EC (Residual Method). USACE and EC coordinate the values they calculate.

Water balance errors can result in significant differences between NBS estimates computed from equations 1 and 2 (Croley and Hunter, 1994). Croley compared NBS estimates computed using the two methods and found significant differences. Lee (1992) showed that NBS calculated using the Residual Method are consistently lower than NBS calculated using the Components Method.

Errors in the Residual Method result from inaccuracies in estimating the storage, inflows, outflows, diversions, and errors in ignoring thermal volumetric changes, consumptive use and groundwater. Calculation of storage change is based on comparison of beginning and end of month water levels based on a two-day average. The largest errors occur during the stormy fall and winter months. Lake outflows on Lakes Huron-Michigan and St. Clair are determined from stage-discharge relationships and are accurate within 5%. These relationships do not consistently take into consideration regime changes. Quinn and Guerra (1986) showed that small outflow errors can result in large NBS errors - a 5% error in the Detroit River flow can result in a 34% error in the residual NBS. Omissions such as ignoring thermal expansion of the water result in even more significant errors in residuals.

There are also errors inherent in the Component Method of estimating NBS including errors in estimating precipitation, runoff and evaporation. Land based meteorologic stations are used for estimating over-lake precipitation and this can give erroneous data. Evaporation rates are based on modeling results, which also introduce errors.

Differences between the Residual and Component methods also result from their treatment of the Ogoki, Long Lac and Chicago diversions.

3.2.2 NBS Data

The ratio of NBS (Lake Erie/Lake Huron-Michigan) is shown in Figure 3.1 for the period 1948 to 2000. Both the GLERL (Components Method) and USACE/EC (Residual Method) data are shown. The NBS data developed using the Residual Method show an increasing trend in the NBS ratio, suggesting a relative increase in the NBS to Lake Erie or a decrease in the NBS to Lake Michigan-Huron. This could potentially suggest that the decrease in the head between the lakes is linked to a change in the NBS. However, the NBS data developed using the Components Method do not show the same trend.

The Residual NBS data are calculated directly from the stage-discharge relationships which do not consistently take into consideration ongoing changes to the river regime due to erosion. Based on discussions with Environment Canada, the stage-discharge relationships are recalibrated approximately every 30 years and after significant changes to the river regime, i.e. due to large dredging projects. Figure 3.1 shows that the Residual and Components NBS are in good agreement until the mid 1970's. The stage-discharge relationships were likely recalibrated after the 8.2 m (27 ft.) dredging project (1960-1962). If ongoing changes to flow occurred as a result of erosion, these would not have been accounted for in the stage-discharge relationships. One would therefore expect to see a gradual divergence of the Components and Residual NBS, similar to that shown in Figure 3.1. The flow rates used to calculate Residual NBS data therefore include inherent errors, which bias the Residual-based NBS estimates. It may be concluded that it is unlikely that a significant and real shift in relative NBS between Lake Michigan-Huron and Lake Erie has occurred. Therefore, this possible cause cannot explain the large drop in head between Lake Michigan-Huron and Erie.

3.3 Tectonic Uplift

During the last glacial era, the earth's crust north of the Great Lakes was compressed by up to 3 km of ice. When the ice melted some 10,000 years ago, the crust began to rebound. As a result of post-glacial rebound (PGR) areas north of the Great Lakes are rising and the land south of the Great Lakes is subsiding. The southern tip of Lake Huron, St. Clair River, Lake St. Clair and much of Lake Erie are located within a stable area (zero rate of elevation change due to post-glacial rebound) as shown in Figure 3.2.

The differential movement of the crust can have an impact on lake levels and flow though connecting channels. On an individual lake, the movement of a shoreline relative to the lake's outlet determines the rate of change in water depths along that shoreline. Estimates of water level change on the Great Lakes, with respect to the outlet are shown in Figure 3.3. A positive vertical velocity indicates that the shoreline is rising with respect to the outlet. Parry Sound on Georgian Bay is therefore rising at a rate of 24 cm per century relative to Lake Huron's outlet at the St. Clair River. Differential crustal movement is therefore a major issue for water levels on Georgian Bay. Depths are decreasing along this shoreline at a rate of 17 to 27 cm per century.

To determine if the lakes' relative surface is actually falling over time (due to increased flow through the outlet), one would have to determine if the volume of water displaced as the upper basin rises with time, exceeds the volume that would flow into the southern end of Lake Michigan (which is subsiding). If it does, the excess water will increase the water level at the lake's outlet and result in a higher outflow. The lakes' relative surface would then drop over time. This is shown in Figure 3.3 (pers. communication: C. Southam, Environment Canada). In any event, rising levels along the east shores of Georgian Bay and falling levels at the south end of Lake Michigan will cause a transfer of water from the rising to the falling side. Rather than contributing to falling water levels on Lake Huron, the tilting of the lake could be expected to cause some increase in water levels at the outlet of lake Huron as water is moved toward the southern end of the lake.

When analyzing historical lake levels and head between lakes, differential rebound must be taken into consideration. In particular, the use of lake-wide average water levels may bias data used to calculate historical change in head. Gauge data from tectonically neutral locations were used in water level analyses as described in Section 2.

C. Southam at Environment Canada provided an assessment of the difference between Lakes Huron-Michigan lake-wide average water level data and gauge data for Harbor Beach, located at the inlet to the St. Clair River (see Figure 2.1). A six-gauge network is used to determine Lake Huron-Michigan lake-wide average water levels. The gauges used are shown in Figure 3.4. Averaging the relative crustal movement at each of the gauges, the lake-wide average is decreasing at a rate of 3.5 cm per century relative to the outlet. The data bias that can be expected to result from using lake-wide average data, instead of gauge data at the outlet is relatively small (3.5 cm per century), compared to the change in head described in Section 2. Nevertheless, as mentioned previously, gauge data from tectonically neutral locations were used in this study.

3.4 Summary

The most probable cause of the decrease in head between Lake Michigan-Huron and Lake St. Clair is an increase to the river cross-section at the critical flow section of the river, resulting in an increase in flow capacity. Because the decrease in head has been continuous since the early 1970's, rather than in discrete steps (as will be confirmed in Section 6), the drop in head since that time is likely due to ongoing erosion of the riverbed. Possible causes of the erosion have been discussed.

The NBS data developed using the Residual and Components Methods show inconsistent trends. Although the Residual NBS data show a rising trend for the ratio of Lake Erie /Lake Michigan-Huron NBS, suggesting a change in the relative NBS, the Components Method NBS data do not show the same trend. The NBS data developed using the

Residuals Method use flow data calculated from the stage-discharge equations, which do not reflect ongoing changes to the river cross-section, and particularly the influence of erosion increasing flow capacity. This will bias the Residual NBS data. It may be concluded that it is unlikely that a significant and real shift in relative NBS between Lakes Michigan-Huron and Erie has occurred. Therefore, this possible cause cannot explain the large drop in head between Lakes Michigan-Huron and Erie.

There are two possible influences of glacial rebound on the observed head drop between Lakes Michigan-Huron and Erie. The first relates to the possibility that the observed head drop can be explained by changing relative differences in elevations between the gauges used to estimate the lake levels on the lakes. The gauges used in our analyses are located in areas of small and similar rebound (both showing less than 3 cm or 1.2 in/century). Therefore, the impact of differential change in elevations of the two gauges due to glacial rebound can be ruled out as a primary cause for the observed drop over the last 40 years. A second possible influence of glacial rebound relates to the effect of the tilting land and lake bed levels on the distribution of water over the surface of Lakes Michigan-Huron. Rising levels along the east shores of Georgian Bay and falling levels at the south end of Lake Michigan will cause a transfer of water from the rising to the falling side. Rather than contributing to falling water levels on Lake Huron, the tilting of the lake could be expected to cause an increase in water levels at the outlet of lake Huron as water is moved toward the southern end of the lake.

As the most probable cause of the decrease in head between Lake Michigan-Huron and Lake St. Clair has been identified as an increase to the river cross-section at the critical flow section of the river, this is investigated in Sections 4,5 and 6. Section 4 includes an assessment of historical bathymetry change in the St. Clair River. In Section 5, the impact of these changes is investigated through numerical modeling and compared with measured change in the head. A new approach of discerning the influence of dredging and river bed erosion on head drop is presented in Section 6. The erodibility of the riverbed is discussed in Section 7.

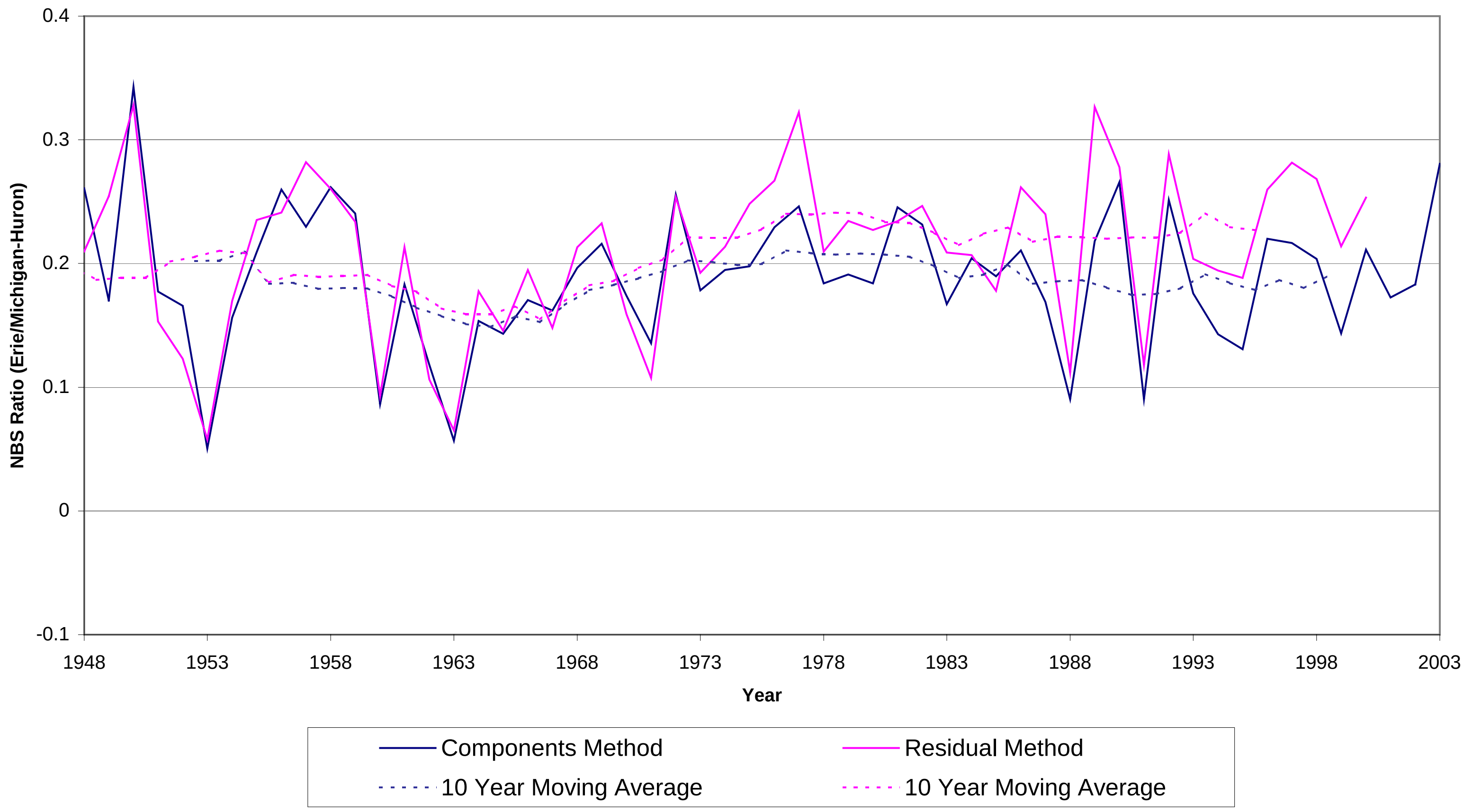


Figure 3.1 NBS Ratio (Lake Erie/Lake Huron-Michigan) using Components and Residual Methods

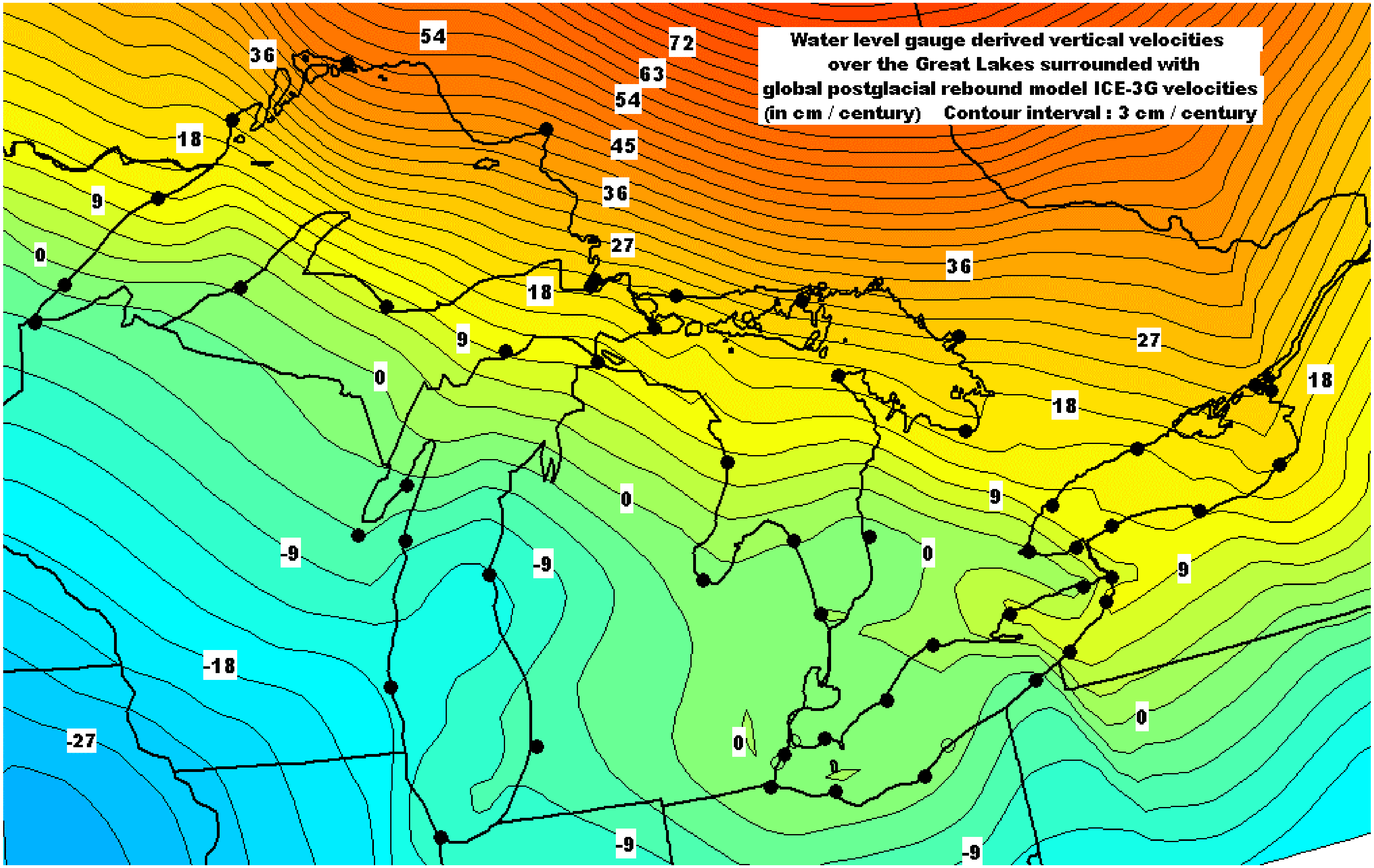


Figure 3.2 Crustal movement from post-glacial rebound (Coordinating Committee, 2001)

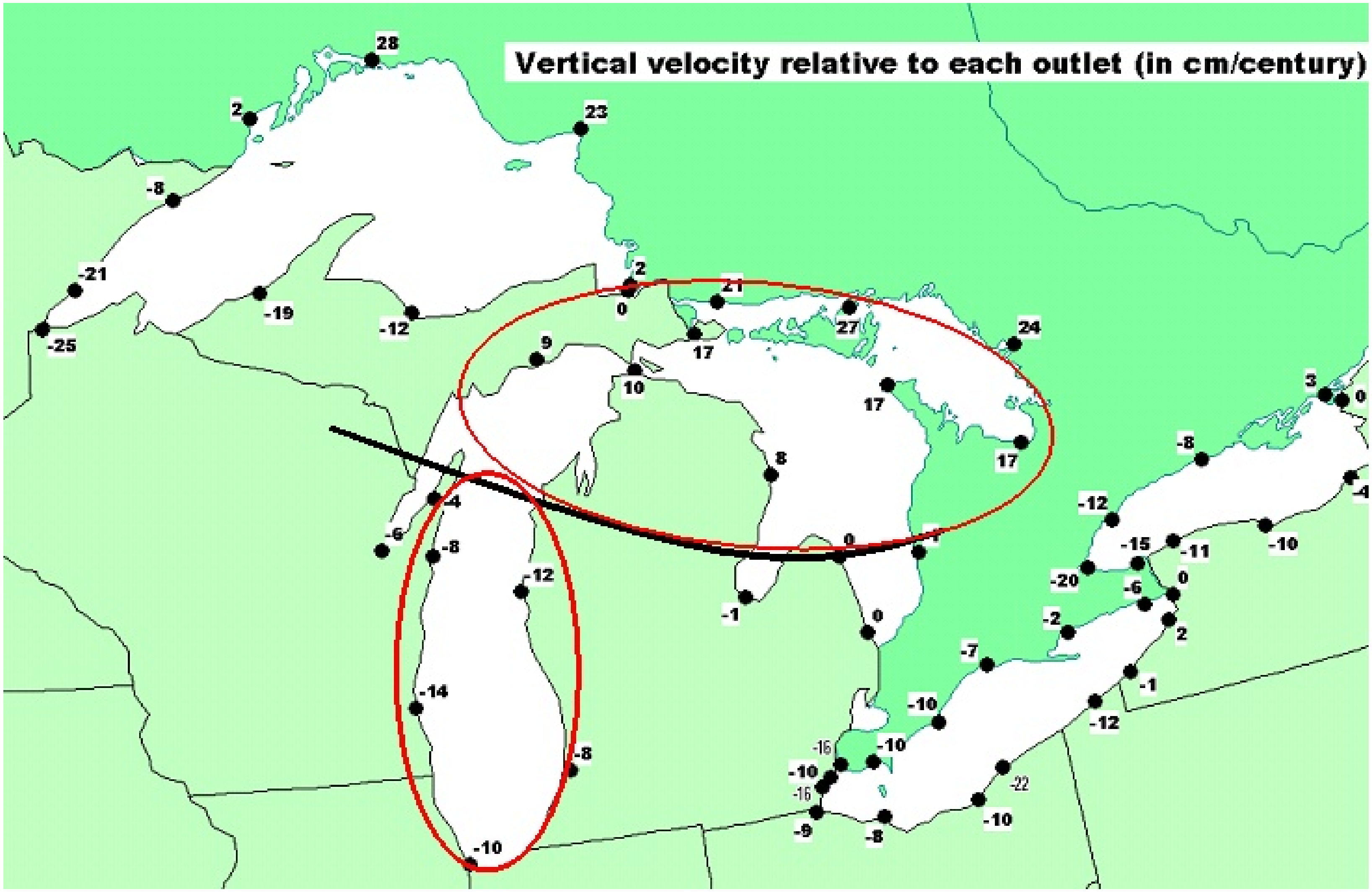


Figure 3.3 Effect of Relative Crustal Movement on Water Movement in Lakes Huron-Michigan (provided by C. Southam, Environment Canada)

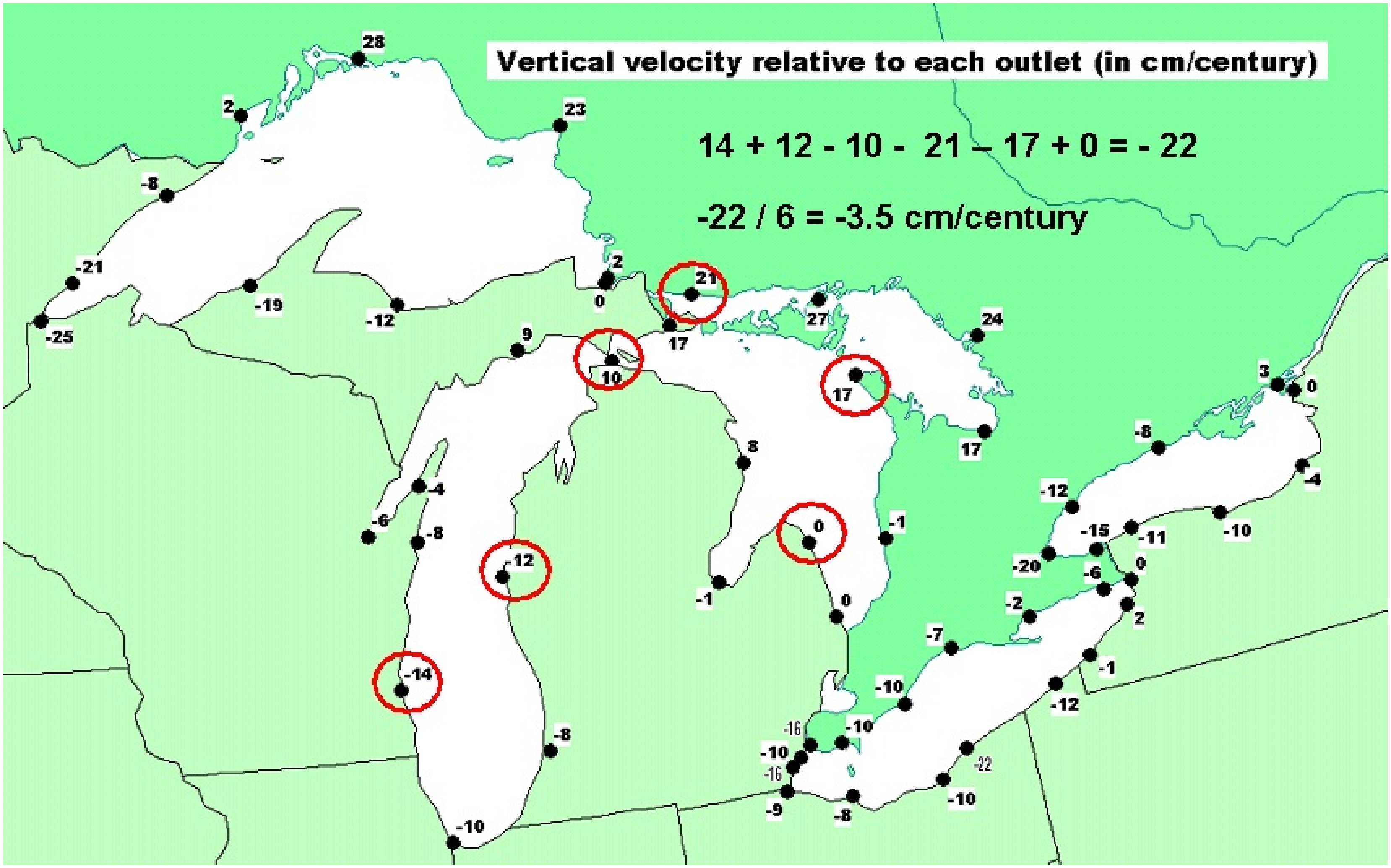


Figure 3.4 Relative Crustal Movement with Respect to Lakewide Average at the Water Level Gauge Network (provided by C. Southam, Env. Canada)

4 REGIME CHANGE (MAN-MADE INTERVENTION) AND EROSION

4.1 Historic Changes due to Dredging and Aggregate Mining (1855 to 1962)

The issue of changes to the St. Clair River and the impacts on the water levels of Lakes Michigan-Huron and St. Clair have been discussed and investigated by others including: Quinn (1985), Derecki (1985), Brunk (1968), IJC (1973) and Freeman (1925) among others. These regime changes are described below and the estimated effects on Lake Huron water levels are summarized in Table 4.1.

Dredging for navigation and mining of the river bed for aggregate date back to the 1800's. Dredging of the St. Clair Flats began in the 1850's. Between 1906 and 1907, 1.2 million cubic metres were dredged from the St. Clair Flats (Coordinating Committee, 1998). From 1900 to 1930, a minimum depth of 6.1 m (20 ft) was maintained in the river for navigation. Effects of this early dredging on flows are difficult to quantify since bathymetry data are not readily available prior to 1900 and water level records were of poor quality (Coordinating Committee, 1988).

In 1900, two steamers (Fontana and Martin) sank in the narrows at the head of the St. Clair River. Although the superstructure of the vessels was removed, the hulls remain in the river near the west shore. The wrecks have decreased the cross-sectional area of the river at its narrowest point, causing a reduction in flow that has affected water levels on Lake Huron (Coordinating Committee, 1988).

It is estimated that between 1908 and 1925, approximately 2,700,000 m^3 of sand and gravel were removed from the river bed by commercial interests. Most of the material was removed from the river bed north of Dry Dock, much of it from the narrowest sections of the river. Sand and gravel mining from the river bed north of Marysville was prohibited in the U.S. in 1925 and shortly after in Canada.

Between 1920 and 1922 further dredging was undertaken to improve navigation. Large quantities of sand and gravel were removed from the North Channel in the St. Clair Flats.

Two major dredging projects were undertaken in the 1930's and 1960's to deepen the navigation channel. Dredging of the 7.6 m (25 ft.) channel was carried out between June 1933 and October 1936. Coordinating Committee (1988) reports that no compensation for the impacts of the dredging on flow rates and Lake Huron water levels was provided, except to dump spoil material in the deeper sections of the river.

Dredging of the 8.2 m (27 ft) channel was undertaken between 1960 and 1962. The project included deepening of the channel and excavation of a new cut-off channel through the St. Clair Flats. Spoil was used to create a new island in the Flats. Although compensation works were authorized, they were never constructed (Coordinating Committee, 1988).

Based on dredging records provided in Coordinating Committee (1998), it is estimated that between 1841 and 1992 approximately 22 million cubic metres of material were dredged from the riverbed including the approaches in Lake Huron and the St. Clair Flats. Figures 4.1 and 4.2 show the locations where significant dredging occurred and the volumes dredged.

Figure 4.3 superimposes the IJC estimates of the influence of various interventions on the St. Clair River (from Table 4.1) over the observed change in level difference (head). The estimates for the earlier interventions are more difficult to quantify due to limited data. A middle estimate for the 0.11 to 0.21m range of influence was assumed for the dredging operations to create the original 6.1 m (20ft) channel. It is clear from Figure 4.3 that there has been an ongoing and significant drop in the head since the IJC estimated influence of the 8.2 m (27 ft) dredging project. The trend line through the head drop during this period suggests a drop of approximately 20 cm. Ignoring the gap between the IJC estimate of the head drop and the actual condition after the 1960-1962 dredging operations, the head drop that has been experienced since the influence of the 8.2 m (27ft) dredging could be as high as 33 cm (13 in) considering the effects of water level cycles as discussed previously. Since 1860, the observed drop is about 80 cm compared to the IJC estimate of 36 to 46 cm.

Considering that the level of Lake Michigan-Huron fluctuates within a range of about 2 m, a drop of 33 cm in 40 years (or 80 cm over 140 years), which effectively represents a permanent loss to the "long-term mean level" (unless compensated for), is very significant with potentially extensive socio-economic and environmental implications.

Table 4.1 Estimated Effect of Regime Changes in the St. Clair River on Lake Huron Water Levels 1855 to 1962 (based on IJC, 1987)

Regime Change (Man-made Intervention)	Date	Estimated Effect on Lake Huron Water Level (m)
6.1 m Navigation Channel Dredging	1855 to 1906	-0.11 to -0.21
Removal of Shoal from St. Clair Flats	1906	-0.01
Sinking of Steamers Fontana and Martin	1900	+0.03
Sand and Gravel Mining	1908 to1925	-0.09
Dredging 7.6 m (25 ft.) Navigation Channel	1930 to 1937	-0.05
Dredging 8.2 m (27 ft.) Navigation Channel	1960 to 1962	-0.13
NET EFFECT	1855 to 1962	-0.36 to –0.46

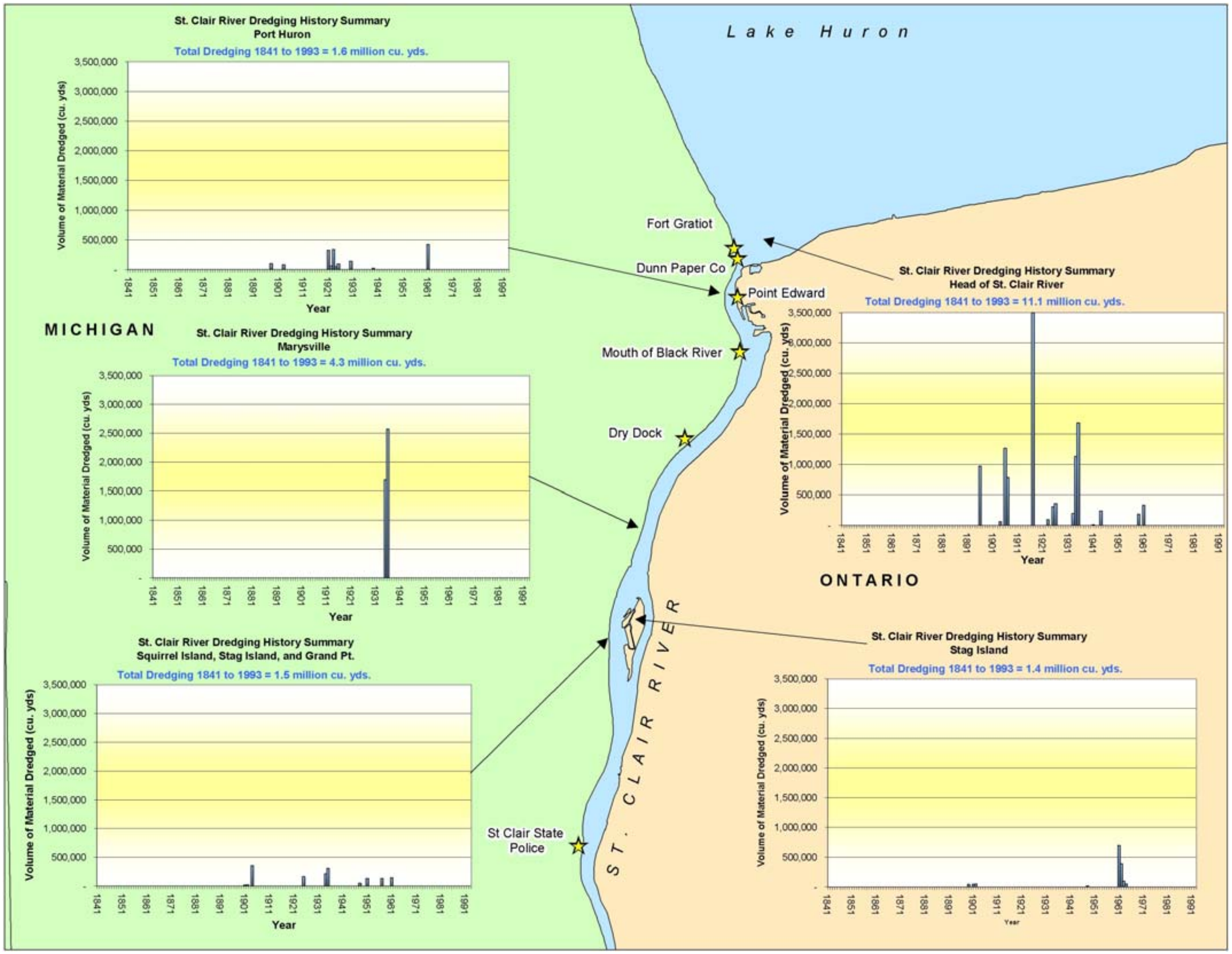


Figure 4.1 Historical Dredging in St. Clair River (North Section)

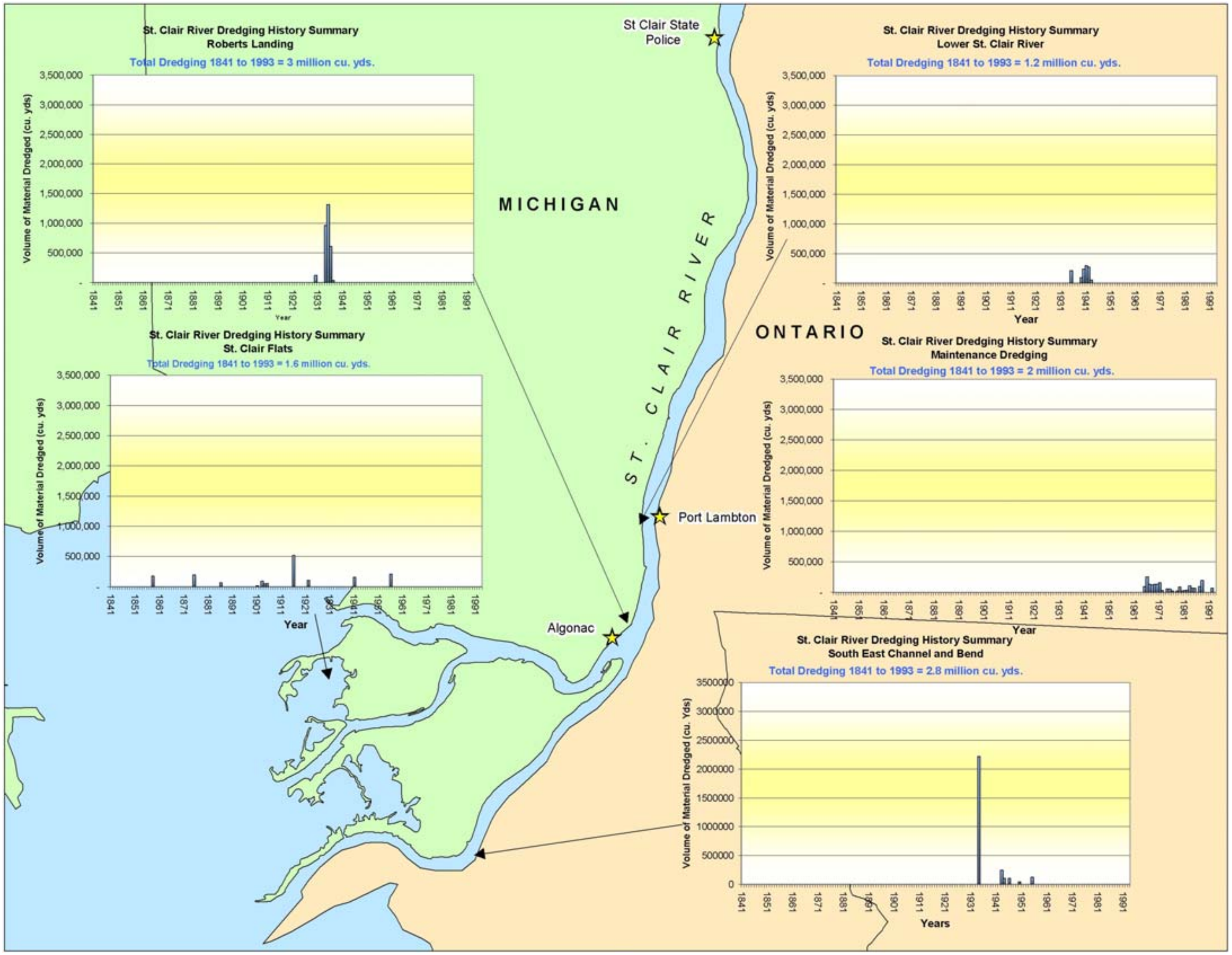


Figure 4.2 Historical Dredging in St. Clair River (South Section)

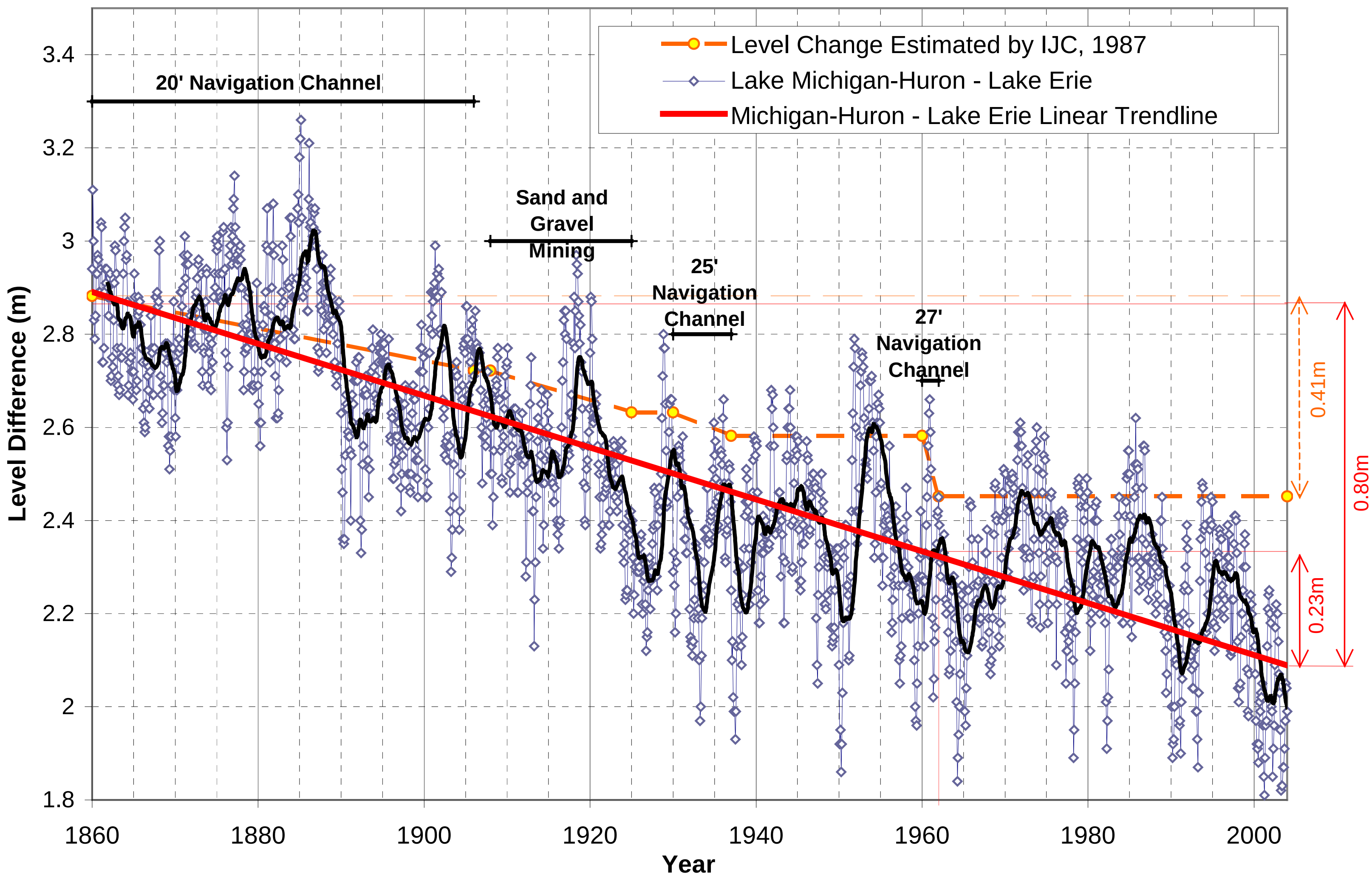


Figure 4.3 Actual Level Difference Change for MH-E vs. Level Change Estimated by IJC

4.2 GIS Analysis of Bathymetry Data (1948 to 2000)

4.2.1 Vertical Datums

The historical bathymetry data are referenced to different vertical datums as noted below. For comparison purposes, all bathymetry data were converted to a common datum. The datum used was the sloping surface of the river corresponding to a Lower Water Datum (LWD) for Lake Huron (176.0 m) and for Lake St. Clair (174.4 m) above IGLD 1985. IGLD85 is a dynamic datum, which refers to the mean sea level at the tide station of Rimouski, Quebec, Canada. All relevant datums used in this study are listed in Table 4.2. The relationships between these datums are developed on the basis of:

- An IGLD85 background document (The Coordinating Committee on Great Lakes Basis Hydraulic and Hydrologic Data, 1995). The document indicates that IGLD85 and North American Vertical Datum 1988 (NAVD88) are the same. The only difference between IGLD85 and NAVD88 is that the IGLD85 bench mark elevations are published as dynamic heights and the NAVD88 elevations are published as Helmert Orthometric heights;

- NOAA published benchmark sheets (NOAA, 2003.4) of Sandy Hook, New Jersey (#8516990) and The Battery, New York (#8518750). The two stations are located close together at the mouth of Hudson River, New York. It has been assumed that the Battery Station is the one referenced as Mean Tide at New York (MTNY) as mentioned in the 1929 historical field sheets. The station has long-term tide records and is located at the mouth of Hudson River;

- NOAA published mean sea level trends at Sandy Hook, New Jersey (#8516990) and the Battery, New York (#8518750) were used to estimate historical sea level change at the gages. As described in the document, the published mean tide level for datum reference has been adjusted every 19 years. The historic sea level trend is used to determine the elevation offset from the historic datum to the modern datum IGLD85 corresponding to the time of the historic surveys.

Table 4.2 All Datum Lists Used in This Study

Datum Name	Bench mark above IGLD85 (m)	Remarks
NAVD88	0.000	North American Vertical Datum 1988 Adjustment
IGLD85	0.000	International Great Lakes Datum 1985 Adjustment
IGLD55	-0.191	International Great Lake Datum 1955 Adjustment, only applicable to St. Clair Shores on Lake St. Clair
Mean Tide, Sandy Hook, NJ	-0.084	Mean Tide at Sandy Hook gage, N.J. (NOAA Station #8531680) for the current tidal epoch 1983-2001
Mean Tide, NY	-0.094	Mean tide level at The Battery, N.Y. (NOAA Station #8516990) for the current tidal epoch 1983-2001
Mean Tide, NY (1929)	-0.210	Mean tide level at The Battery, N.Y. (NOAA Station #8516990) for the current tidal epoch 1983-2001 (-0.094) plus mean sea level change (-0.210) inform 1929
NGVD29	-0.329	National Geodetic Vertical Datum 29

4.2.2 Historical Data

A review of historical bathymetry data depicts the morphological change in the river. Early data can be less accurate and there are often difficulties associated with converting the data to a known datum. Historical bathymetry data were collected from USACE, NOAA, and the National Archives and reviewed. The historical bathymetric data reviewed are described below.

- **1867 National Archives:** Survey of N. and N.W. Lakes, St. Clair River surveyed by Lt. James Mercur. Scale 1:16,000. Soundings in feet. No datum provided. Bathymetry from approaches to St. Clair River to south of Stag Island. This chart includes descriptions of bottom material as well as depths. The section of the chart showing the northern reach of the river is shown in Figure 4.4. Sizeable sand shoals are visible at the inlet to the St. Clair River.

- **1929 National Archives:** A 1929 chart for the St. Clair River, from Lake Huron to Sarnia was supplied by the USACE Detroit District. The chart is titled, Survey of the Northern and Northwestern Lakes Sheet No. 12, St. Clair River made under the direction of Corps of Engineers, U.S. Army, scale 1:5,000. Soundings are in feet reduced to the sloping surface of the river corresponding to 578.5 feet on Lake Huron and 573.5 feet on the St. Clair Flats Canal. These elevations being the height above Mean Tide at New York. The chart was georegistered using ArcGIS 9.0. Bathymetric soundings were collected using heads-up digitizing at specific profile locations in the coverage area. The section of the chart showing the northern reach of the river is shown in Figure 4.5.

- **1948 NOAA digital soundings:** Bathymetry data from 1948 were acquired from multiple hydrographic surveys from the Geophysical Data System for Hydrographic Survey Data (GEODAS), maintained by the National Ocean Service, NOAA. Coverage includes the entire river. The datum was reduced to Lake St. Clair, Low Water Datum 571.7 ft International Great Lakes Datum (IGLD) 1955. For all datasets, the GEODAS software has adjusted the horizontal datum to NAD83.

- **2000 NOAA digital soundings:** Data were collected between April and September 2000. A preliminary copy of this dataset was provided to Baird by the USACE Detroit District office. Coverage includes the entire river with 129,534 soundings. Baird performed some basic quality control reviews of the data and deleted over 400 anomalous (spike value) points. The vertical units were feet, with resolution to the nearest foot. According to the notes in the spreadsheet, the vertical datum is "IGLD 1985, referenced to LWD step-down planes." LWD stepdown planes were provided by the USACE. The data are currently still unpublished. The horizontal datum is NAD83.

Additionally, cross-section data collected for calculating hydraulic discharge rates were requested from the USACE and are described below. This information was not available at the time this report was prepared, however it would be useful to review when available.

- **Dry Dock**: Dry Dock is located 4 km south of the Mouth of the Black River. It was established as a discharge monitoring station in 1901 and surveyed frequently in the early 1900's. It was also surveyed in 1947 and 1973.

- **Bay Point**: Bay Point is located north of the Black River, near the foot of Rawlins Street in Port Huron. It was established as a discharge monitoring station in 1959 and surveyed in 1960, 1962, 1963, 1964, 1966, 1968,1977 and 1985.

4.2.3 Bathymetry Comparison

The 1948 and 2000 bathymetry data were used to evaluate change in depth over this time period. These two data sets represent the only complete surveys of the river that were identified. A spatial grid with one metre resolution was created using ArcView for bathymetry comparison. The grid covers the entire St. Clair River. The water depths at the grid points were calculated using spatial interpolation with the raw data points from both the 1948 and 2000 bathymetry data. The grids were used to calculate the change in depth from 1948 to 2000. Figures 4.6a, 4.6b and 4.6c show the change in depth for the north, central and southern stretches of the river. The negative values represent the erosion of the river bed (blue) while the positive values represent deposition on the river bed (yellow).

The comparison shows widespread erosion throughout the river channel in the order of 0.5 to 3 m, particularly through the upper two thirds of the river. There were some areas of higher erosion and other areas of localized sedimentation. Considering that the average depth of the upper two thirds of the St. Clair River is approximately 10 m and that the original erosion or incision of the outlet occurred over a period of almost three thousand years (i.e. between 5,100 and 2,100 years before present – see Larsen, 1994), the recent erosion of 0.5 to 3 m) is unusual and dramatic. Larsen (1994) suggested the erosion of the outlet, and the influence on reducing the Huron-Michigan lake level, ceased 2,100 years before present. Baedke and Thompson (2000) suggest that the Huron-Michigan lake levels stabilized within their current range 3,500 years before present. In any case, the rate of erosion over the last 50 years is unprecedented, even at a geologic time scale.

Areas of highest change (in excess of 7 m) occur in the region south of the Bluewater Bridge. It is interesting to note that there has been erosion along the west side of the river and accretion on the eastern side. The accretion extends into the lake and appears to be sedimentation of the original approach channel, which was shifted westward. The other area of significant change occurs in the South Channel of the St. Clair Flats where the navigation channel was dredged in the early 1960's.

A close examination of Figure 4.6a also shows accretion in the vicinity of the old Lake Huron approach channel to the St. Clair River. This is coupled with the influence of dredging and possibly related erosion, showing up as erosion along the current alignment of the approach channel to the west of the old channel alignment. This importance of these observations will be explained later in Section 6.

4.3 Cross-section Comparisons

The critical section of the river for flow is the northern section of the river where flow velocities are highest. This is discussed further in Section 5. In order to review the bed change in detail at the critical section of the river, bed elevations along six transverse cross-sections were extracted from bathymetry data from 1867, 1929, 1948 and 2000. The locations of the cross-sections are shown in Figure 4.7. The comparisons of the bed elevations along these cross-sections are shown in Figures 4.8 to 4.13.

Profiles 1 and 2 are located at the inlet to the St. Clair River. It is interesting to note that there is a deep channel on the east side of the river inlet. The channel is up to 22 m deep, much deeper than the navigation requirement of 8.2 m. The channel is evident in the surveys dating back to 1867. There has been some deposition in the channel since 1948, particularly at Profile 2.

The deep channel or gully is not present in Profiles 3 and 4 and depth changes between surveys are less marked.

Profile 5 is in the area of highest erosion. The profile shows a shifting of the channel location over time. In 1867 the channel was located on the west side of the river. This would be expected as the river curves and the outer bend is on the west side. In 1929 the channel is on the east side and there appears to be significant deposition west of the channel. The surveys suggest that a channel was dredged on the east side of the river and the dredge spoils were deposited on the riverbed beside the channel, however this has not been confirmed. In 1948 the channel appears to be migrating back to the west side of the river and significant erosion occurred between 1948 and 2000.

Profile 6 also shows ongoing erosion. Again, the channel is significantly deeper than the required navigation channel depth of 8.2 m.

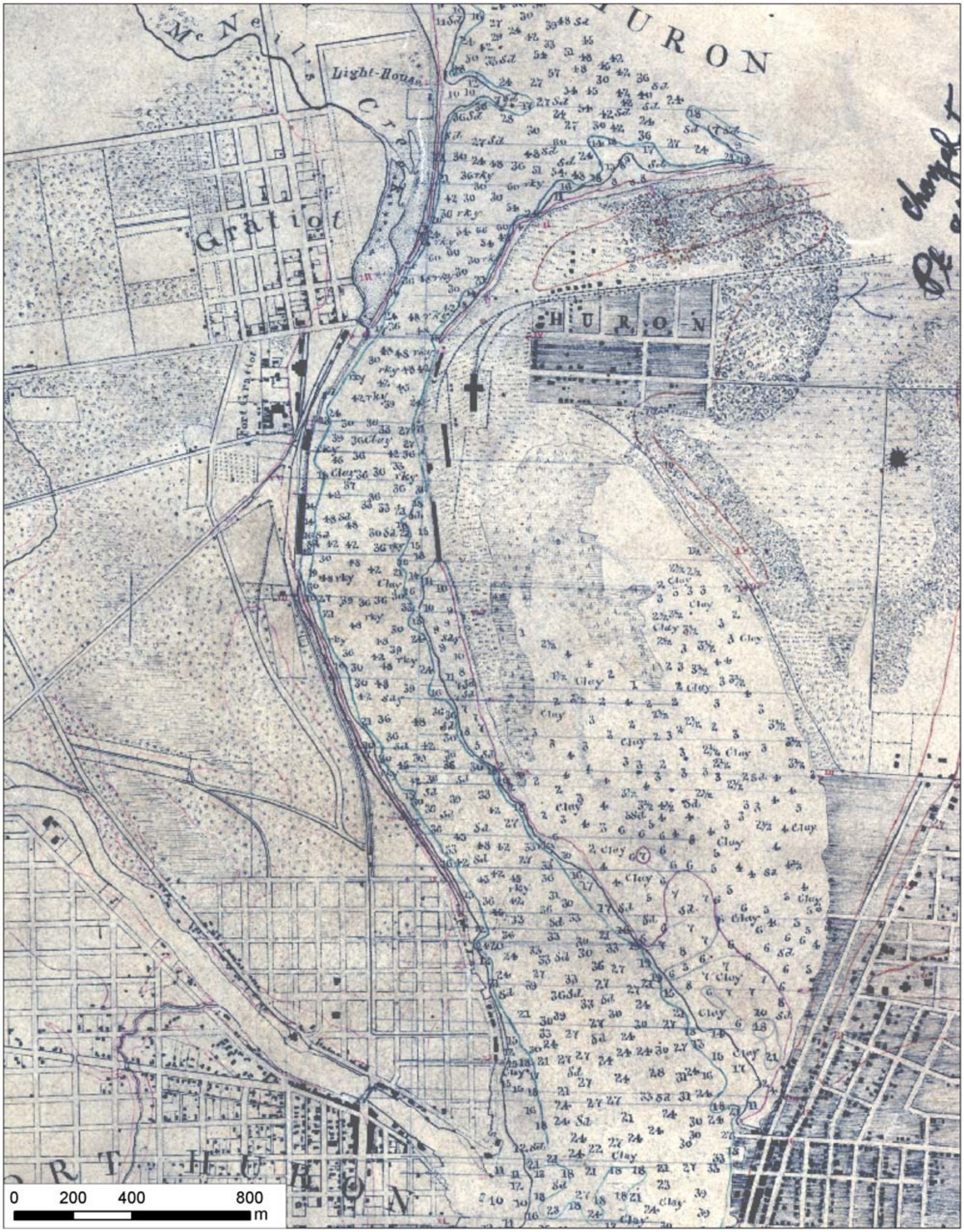


Figure 4.4: North St. Clair River and Approaches from 1867 Chart

Figure 4.5: North St. Clair River and Approaches from 1929 Chart

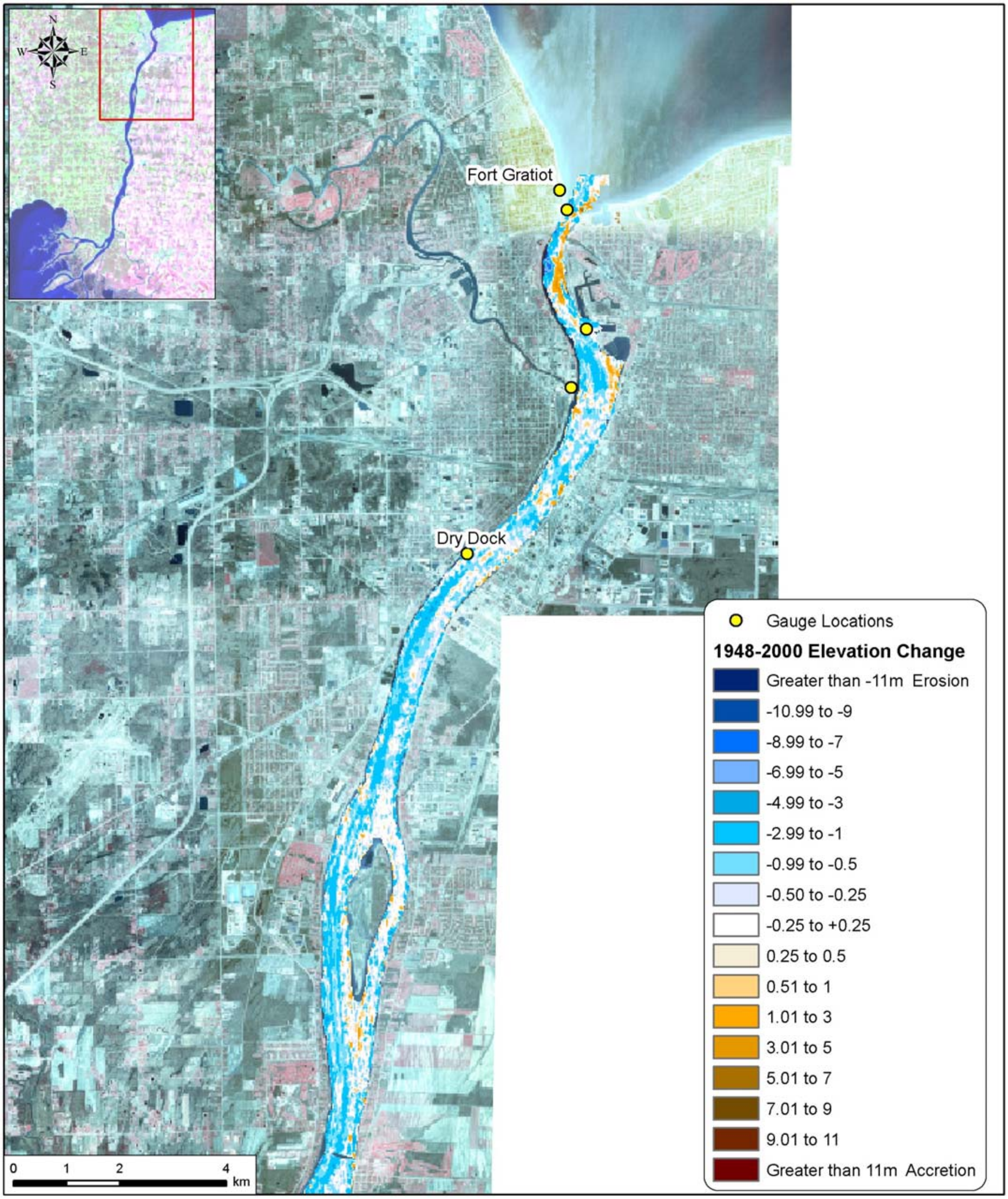


Figure 4.6a Bathymetry Change 1948 to 2000 (North Reach St. Clair River)

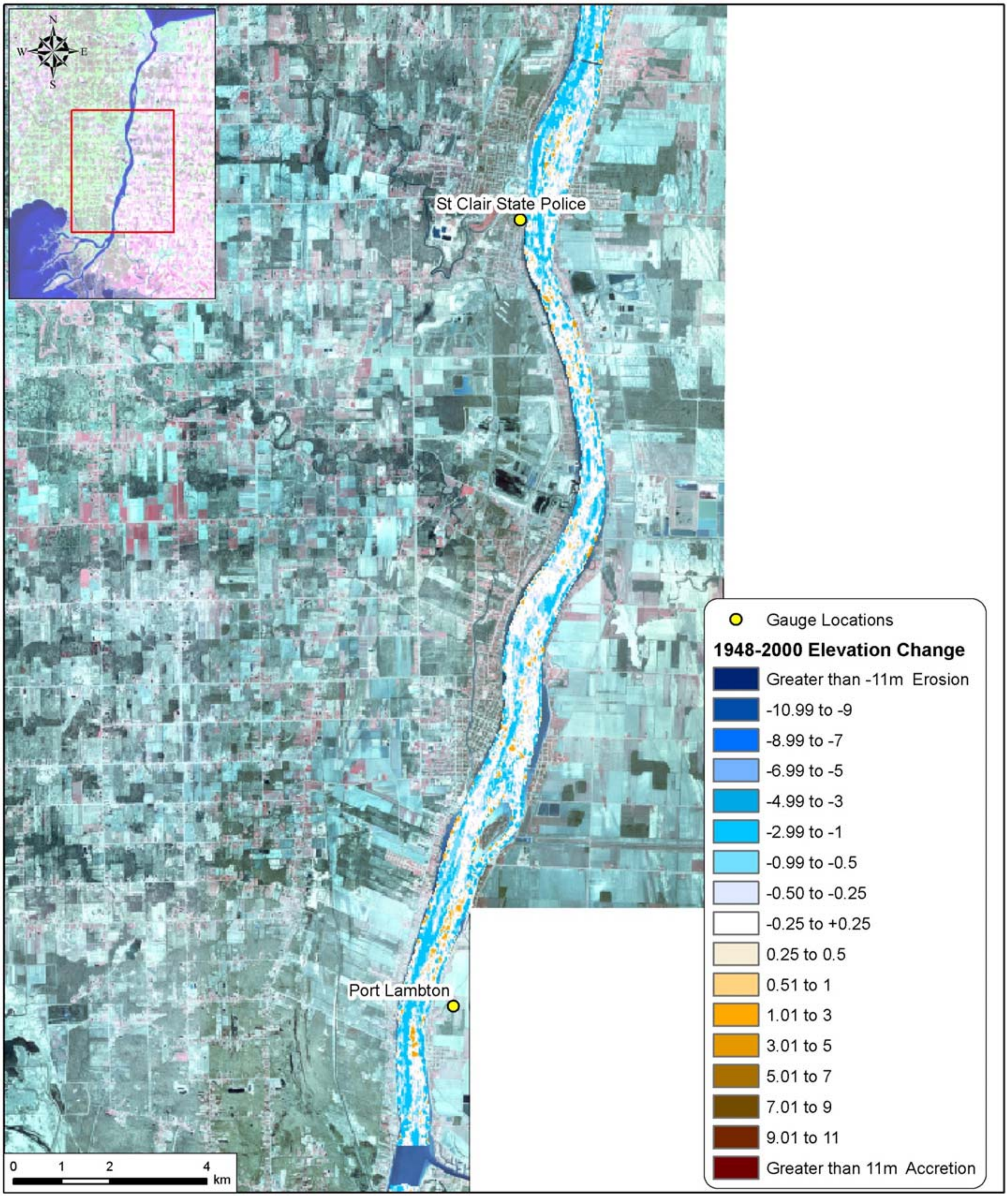


Figure 4.6b Bathymetry Change 1948 to 2000 (Mid Reach St. Clair River)

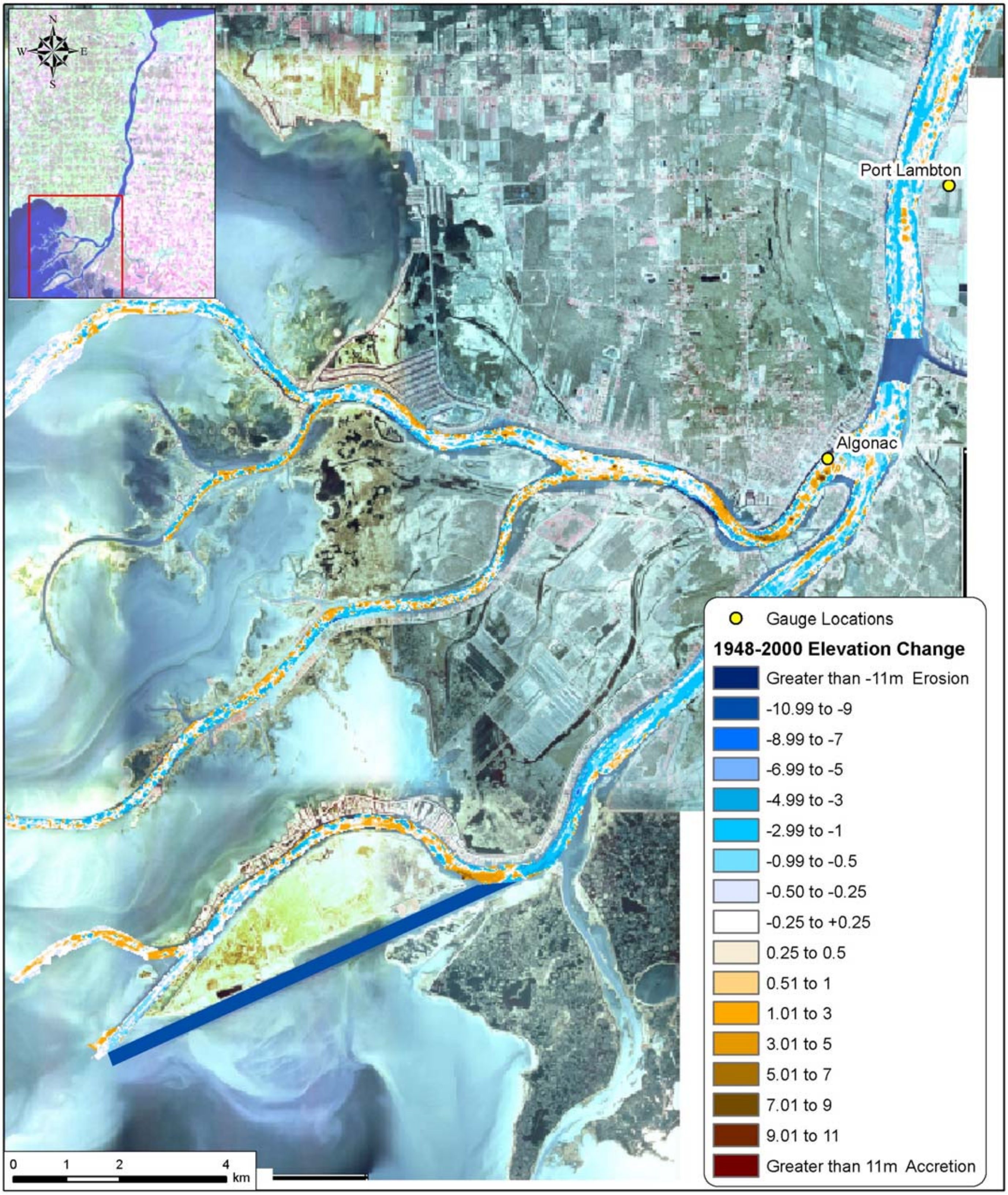


Figure 4.6c Bathymetry Change 1948 to 2000 (Delta St. Clair River)

Figure 4.7 Locations of Cross-Sections for Bathymetry Comparison (1867, 1929, 1948, 2000)

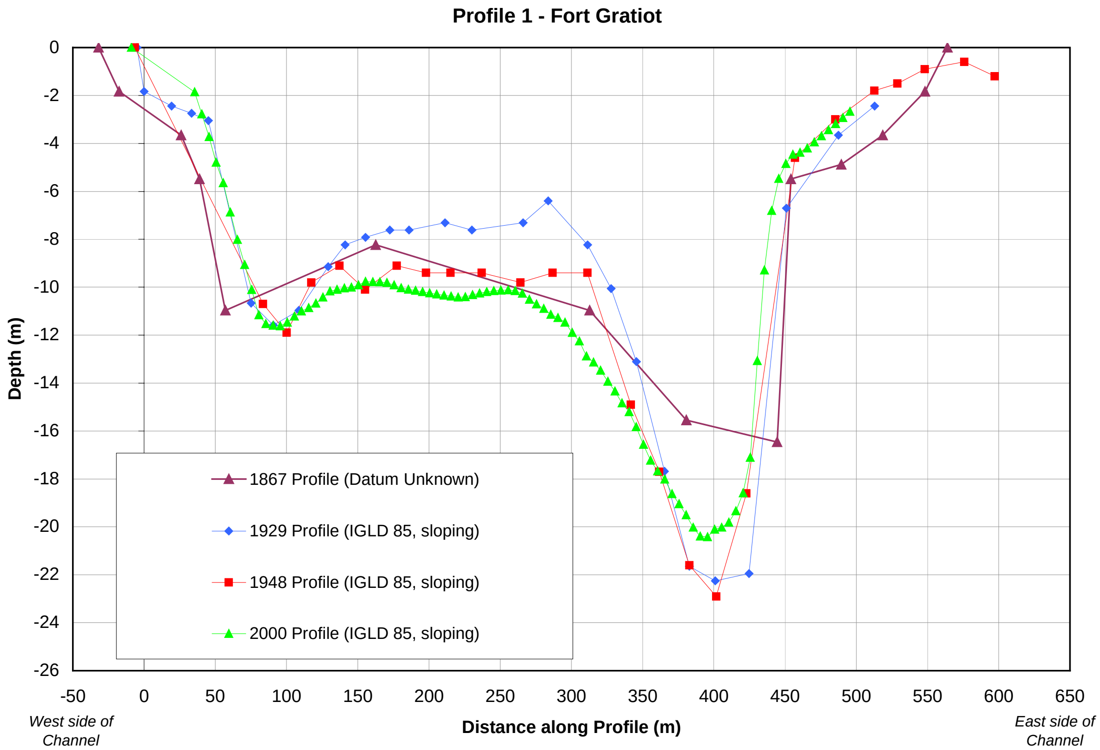


Figure 4.8 Historic Bathymetry Comparison Profile 1

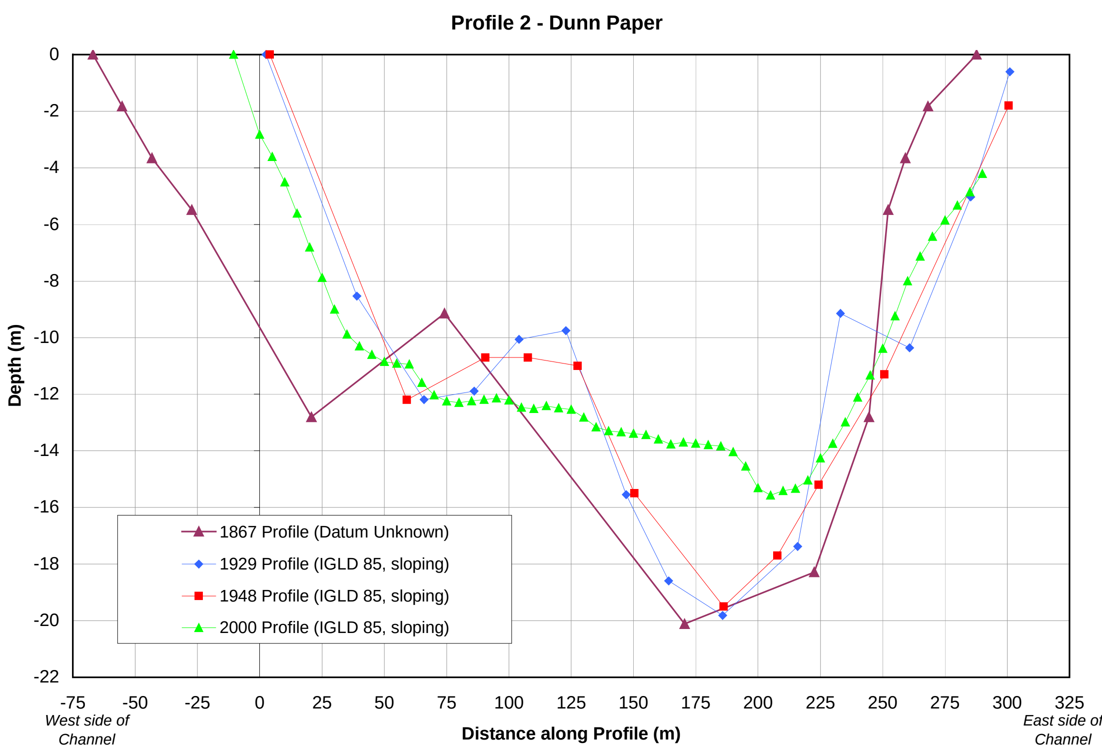


Figure 4.9 Historic Bathymetry Comparison Profile 2

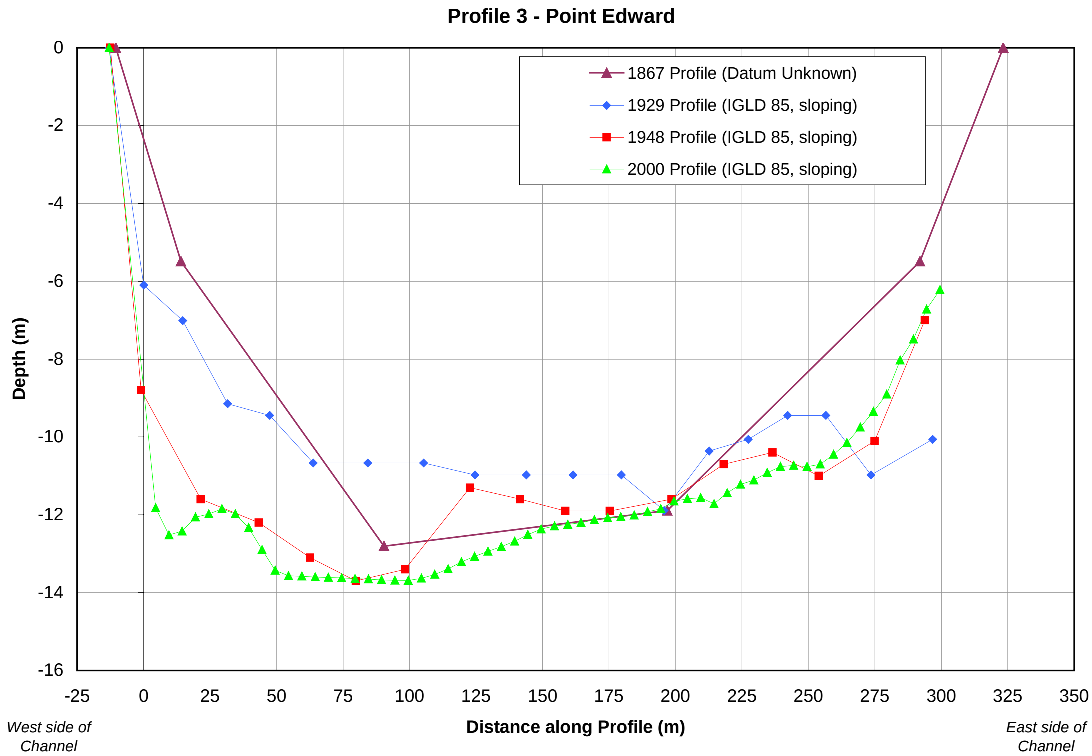


Figure 4.10 Historic Bathymetry Comparison Profile 3

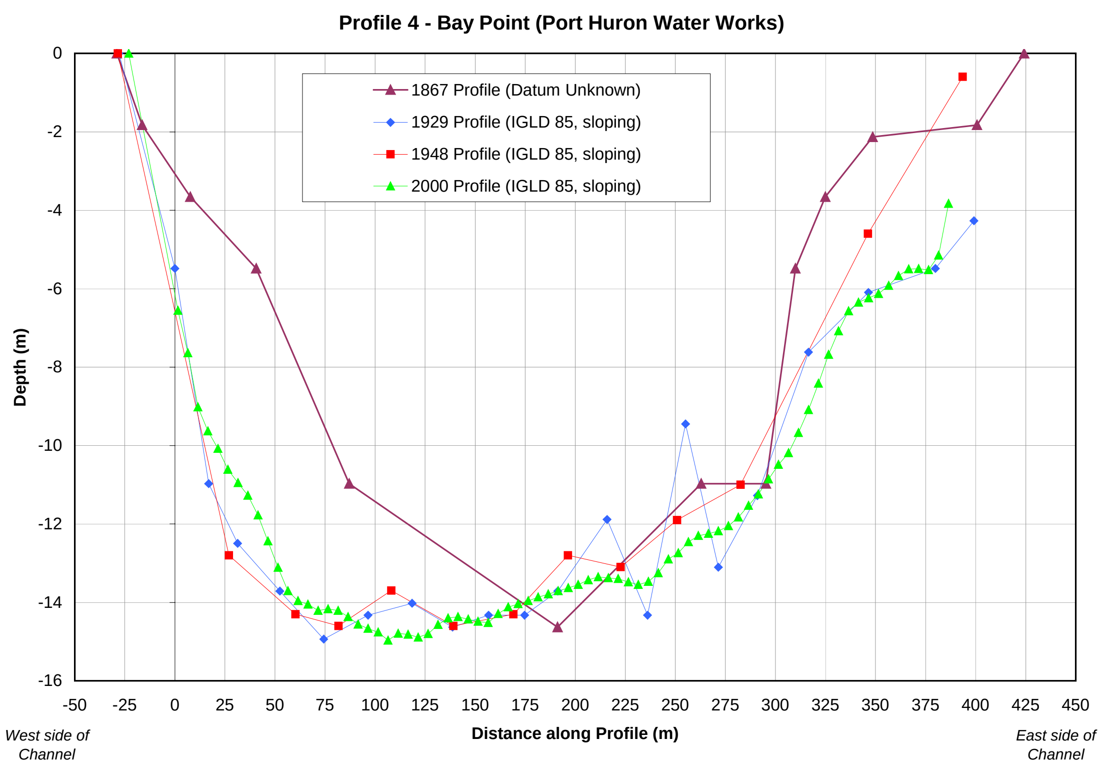


Figure 4.11 Historic Bathymetry Comparison Profile 4

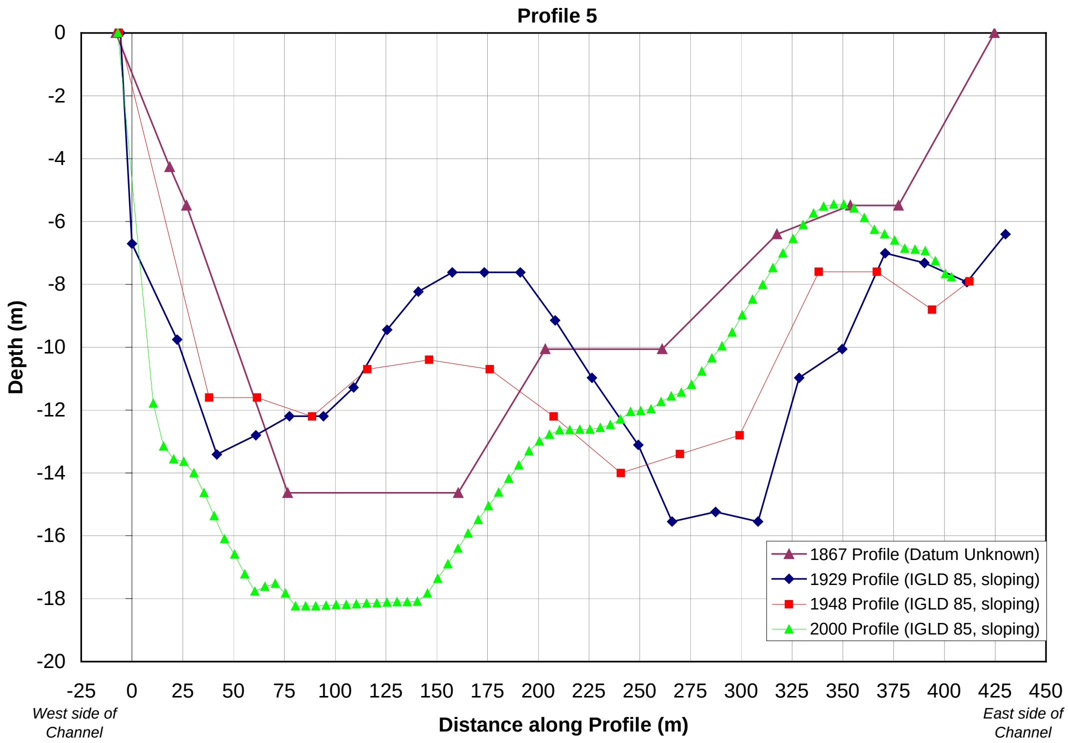


Figure 4.12 Historic Bathymetry Comparison Profile 5

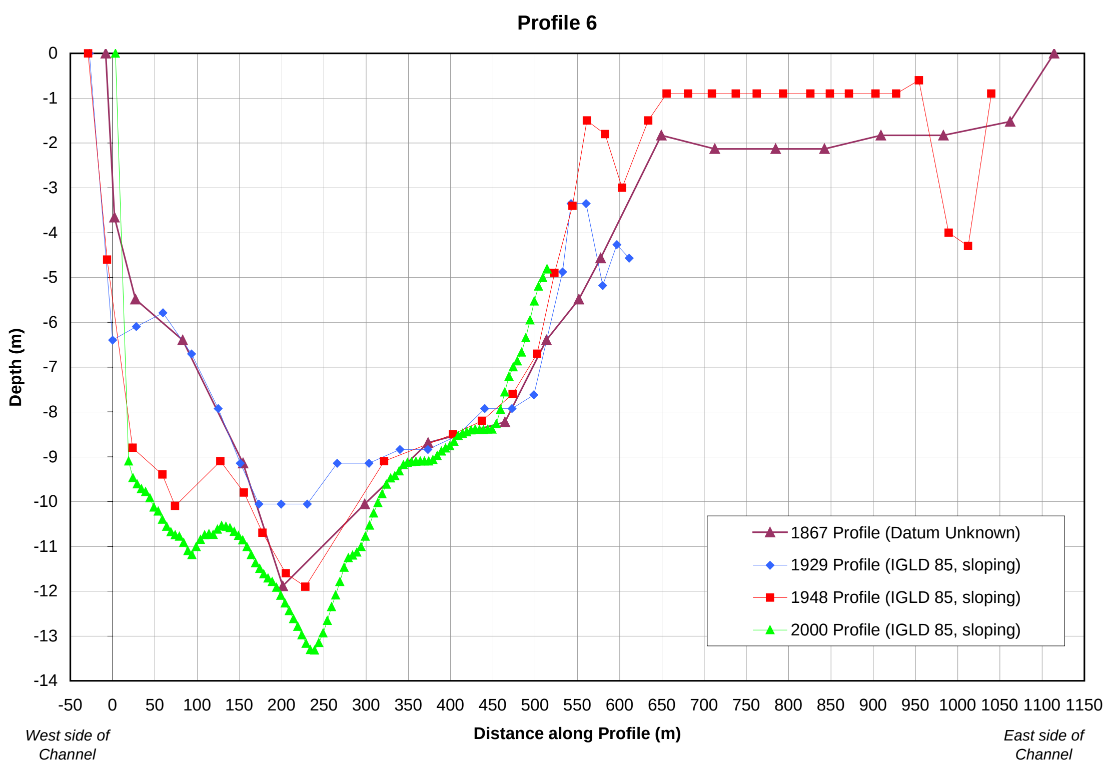


Figure 4.13 Historic Bathymetry Comparison Profile 6

5 NUMERICAL MODELLING

The St. Clair River flows for approximately 63 km from Lake Huron to Lake St. Clair. The fall in water level from Lake Huron to Lake St. Clair is roughly 1.5 m. The river can be divided into three distinct reaches. The upper reach extending from the inlet at Lake Huron to approximately 5 km south of the Blue Water Bridge is the narrowest and deepest stretch of the river. At its narrowest location, the river is approximately 240 m wide, depths range from 9 to 21 m and average velocities of up to 1.8 m/s occur during high flows (1.5 m/s during medium flows). The middle reach extends downstream approximately 44 km with an average width of approximately 800 m and depths ranging from 8 to 15 m. Average velocities range from 0.7 to 1.0 m/s for medium flows. The lower reach of the river extends roughly 14 km to Lake St. Clair and includes the river delta (St. Clair Flats). The Coordinating Committee (1988) reports average flows of 5,200 m^3/s between 1900 and 1986 with monthly mean discharges ranging from 3,000 m^3/s to 6,700 m^3/s.

A two-dimensional hydrodynamic model was used to simulate the flow in the St. Clair River including parts of Lake Huron and Lake St. Clair. The model was developed using the U.S. Army Corps of Engineers (USACE) RMA2 model. The objective of the modeling was to reproduce the historical hydrodynamic conditions in the river using reliable water level records, and to assess the impacts of bathymetry changes on the flow rate of the river and ultimately the head between Lakes Huron and St. Clair. Adjustment of USACE RMA2 model domain, model verification, and modeling results are described in this section.

5.1 USACE RMA2 Model

The model used in this study was the USACE RMA2 model for the St. Clair and Detroit Rivers. It is a public domain model maintained by USACE Waterway Experiment Station (WES). RMA2 is a two-dimensional finite element model for hydrodynamic simulation (Holtschlag and Koschik, 2002). It computes depth-averaged horizontal velocity components and water levels for subcritical and free-surface flow. The model was developed as part of the Source Water Assessment Program (SWAP) of the Michigan Department of Environmental Quality (MDEQ), to reproduce the flows in the St. Clair River, Lake St. Clair, and the Detroit River.

The area of coverage extends from the NOAA gauge station at Fort Gratiot on Lake Huron to the CHS gauge at Bar Point on Lake Erie. The boundary conditions are controlled by the inflows specified at the upstream boundary and the water level at Bar Point. Manning's equation is used to calculate bottom friction and is a key parameter for modeling calibration. The model had been well calibrated against the gauge stages along the rivers by adjusting the Manning's coefficient. Eddy viscosity parameters are used to control numerical stability and describe energy losses associated with viscosity and turbulence.

5.2 Adjustment of Model Domain

The model grid (or mesh) used in this study is based on the RMA2 model developed by the USACE. The original node arrangement and its associated physical features such as Manning's coefficients were maintained. The model was run with existing (2000) and historical bathymetries to evaluate the impact of bathymetry change on flow. The model grid was adjusted to reflect the historic bathymetry.

The flow in the St. Clair River is driven by the loss of potential energy that is described by the head between Lake Huron and Lake St. Clair. The head is controlled by the lake level in Lake Huron. Therefore, the river flow varies (or is driven by) the lake level on Lake Huron.

The USACE model is driven by flow discharge at the Fort Gratiot gauge. Discharge data for Fort Gratiot are calculated from the developed stage-flow function, using water levels at Fort Gratiot as input. As discussed previously, there are inherent errors in the discharge calculations, which may not account for erosion in sections of the river where flow is not monitored. In addition, water level at the upstream boundary in the USACE model, i.e. at the Fort Gratiot gauge, does not represent the mean lake level at Lake Huron because of the head loss between the Fort Gratiot gauge and Lake Huron.

It was therefore necessary to extend the model domain into Lake Huron so that Lake Huron water levels could be used to drive the model. Extending the model also allowed us to include and consider the impact of changes to the approach channel on flow capacity and head. The upstream boundary was extended to the Lakeport gauge on Lake Huron. Since the focus of this study is the St. Clair River, the Detroit River and part of Lake St. Clair were removed from the USACE model for this application. The mesh of the adjusted model is shown in Figure 5.1. The Manning's coefficients for Lake Huron were established based on those used for Lake St. Clair, which has similar physical features.

5.3 Model Verification

Though the parameters used for this modeling are the same as USACE's model which was well calibrated against the stage records at a number of gauges along the river, model verification was still required to confirm that the model results represent the flows in the river. Two model runs were carried out for this verification.

Measured flow data from Sept. 23, 1999 were simulated using 2000 bathymetry and the recorded water level at Lakeport gauge to control the model. The 1999 data represent the date nearest to 2000 for which flow data were available. The purpose of this run was to verify the accuracy of the flow rate modeled by using water level boundary condition. The flow rate calculated at that day was about 4741 m^3/s which is very close to the flow measurement range of 4743 to 4949 m^3/s at that time.

To verify the profile of the water surface elevation along the river, the simulation for mean flow was carried out using stage data from August 1968. This is the only period for which water level data were collected at all gauges along the river. The model was run with two sets of bathymetry data; 1948 and 2000. The comparison of the modelled water surface elevation for 1948 and 2000 bathymetry, with monthly mean stage records is shown in Figure 5.2. The modelled water surface elevations agree well with the stage measurement. Though the modelled water surface elevation at the Point Edward gauge is higher than the measured value, the modeled elevation is still in the range of stage variation for that month (see the error bar in Figure 5.2). Discrepancies in the model results may be due to changes in the bathymetry between 1948 and 2000 (the bathymetry in 1968 would be somewhere in between), and/or the 2D model may not precisely reproducing the three-dimensional flow in the meandering river segment (see Figure 5.3).

In summary, the model verification runs demonstrated that that the extended model reproduces reasonable flow and water level profiles for the river using Lake Huron water level as the boundary condition. The model can therefore be used to reproduce the flows for a range of historic scenarios.

5.4 Model Results

The objective of the model runs was to evaluate the change in head for three historical periods using three different bathymetry grids: 1948 bathymetry, 1948 bathymetry with 8.2 m (27 ft.) navigation channel, and 2000 bathymetry. The 1948 bathymetry with the 8.2 m (27 ft.) navigation channel was modelled to differentiate the effects of erosion and dredging. The overdredged depths of the 27 ft. channel were used in the model bathymetry. All data were converted to a common datum as described in Section 4.2 (IGLD85).

The model was run for the average flow condition (5,200 m^3/s). Figure 5.4 shows the flow velocities for the 2000 bathymetry. The model output showing water surface profile, bed elevation and velocity is provided in Figure 5.5. The predicted water surface elevations for 1948, 1948 with navigation channel and 2000 are shown in Figure 5.6. The water level on Lake St. Clair was fixed at mean lake level (1900 to 2003). The model predicted a decrease in water level on Lake Huron of 0.04 m (176.59-176.55 m) as a result of dredging the 8.2 m navigation channel and the drop in water level on Lake Huron due to erosion was 0.19 m (176.55-176.36 m), or a total predicted change of 0.23 m (9 in) due to dredging and erosion.

5.5 Key Cross Sections

One of the primary findings of the numerical modeling with RMA2 is that the main controlling section for the river is located between the water level gauges at Fort Gratiot (and nearby Dunn Paper) and Point Edward. The modeling shows that the slope of the water surface is much steeper at the upstream section of the river than the downstream as shown in Figure 5.6. The flow speed in the upstream section is also much higher, up to 2.0 m/s (3.9 knots), which is high for river flow (see Figure 5.5). This implies that this upper section of the river is the critical area for river flow. Changes to the riverbed in this area would cause the most significant changes to river flow. The modeling results also show a reverse slope in the water surface profile between the Fort Gratiot and Point Edward gauges (see Figure 5.6). Bed changes downstream of this reverse slope are unlikely to have a significant impact on the river flow.

Figure 5.7 shows the comparison of bed elevation between 1948 and 2000 along the thalweg line of the river (deepest profile) for 1948. The figure also shows a dashed line representing the 27-feet deep navigation channel. These are likely areas where the most significant dredging occurred and potential impacts on flow capacity would have been significant.

Figure 5.8 shows the measured bathymetry change (from 1948 to 2000), the measured water surface elevation for several representative months and the thalweg profile. The large drop in lake/river bed elevation from the shallow area near the opening to the St. Clair River and the deep hole between the Dunn Paper and the Point Edward gauges act as weirs to control flow through this section. The cut through the bar by the 27 ft (8.2 m) dredging project (and earlier projects) and the subsequent erosion downstream of the bar have significantly increased the efficiency of the flow through this section of the river.

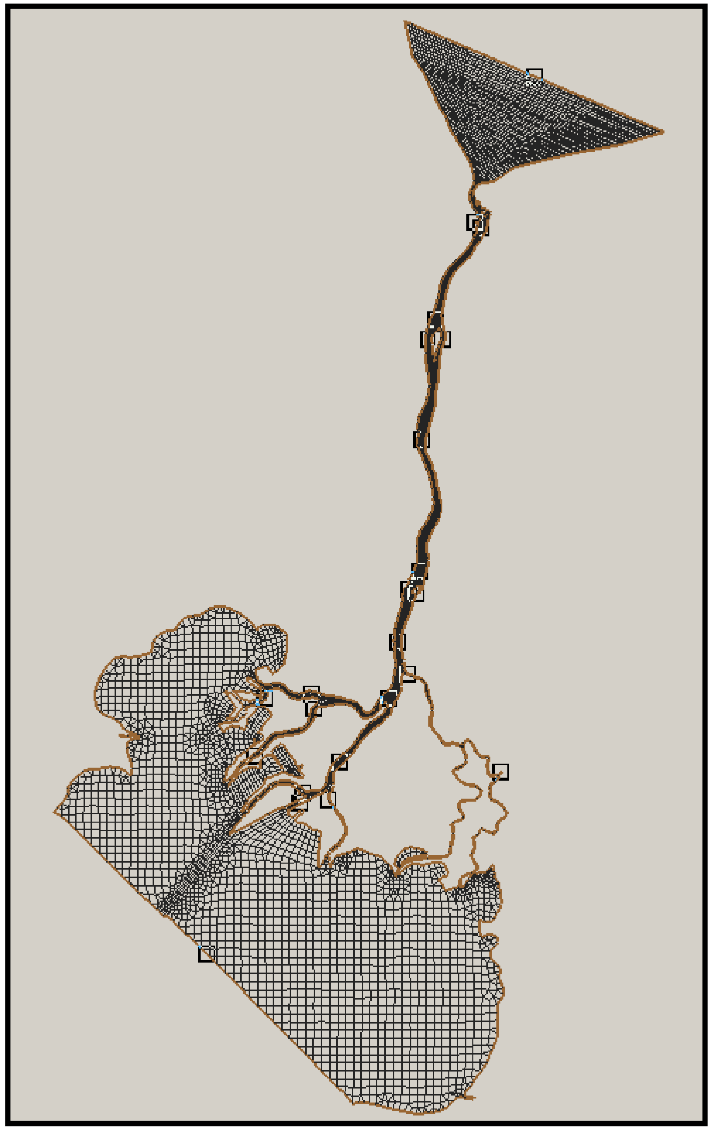


Figure 5.1 RMA2 Mesh

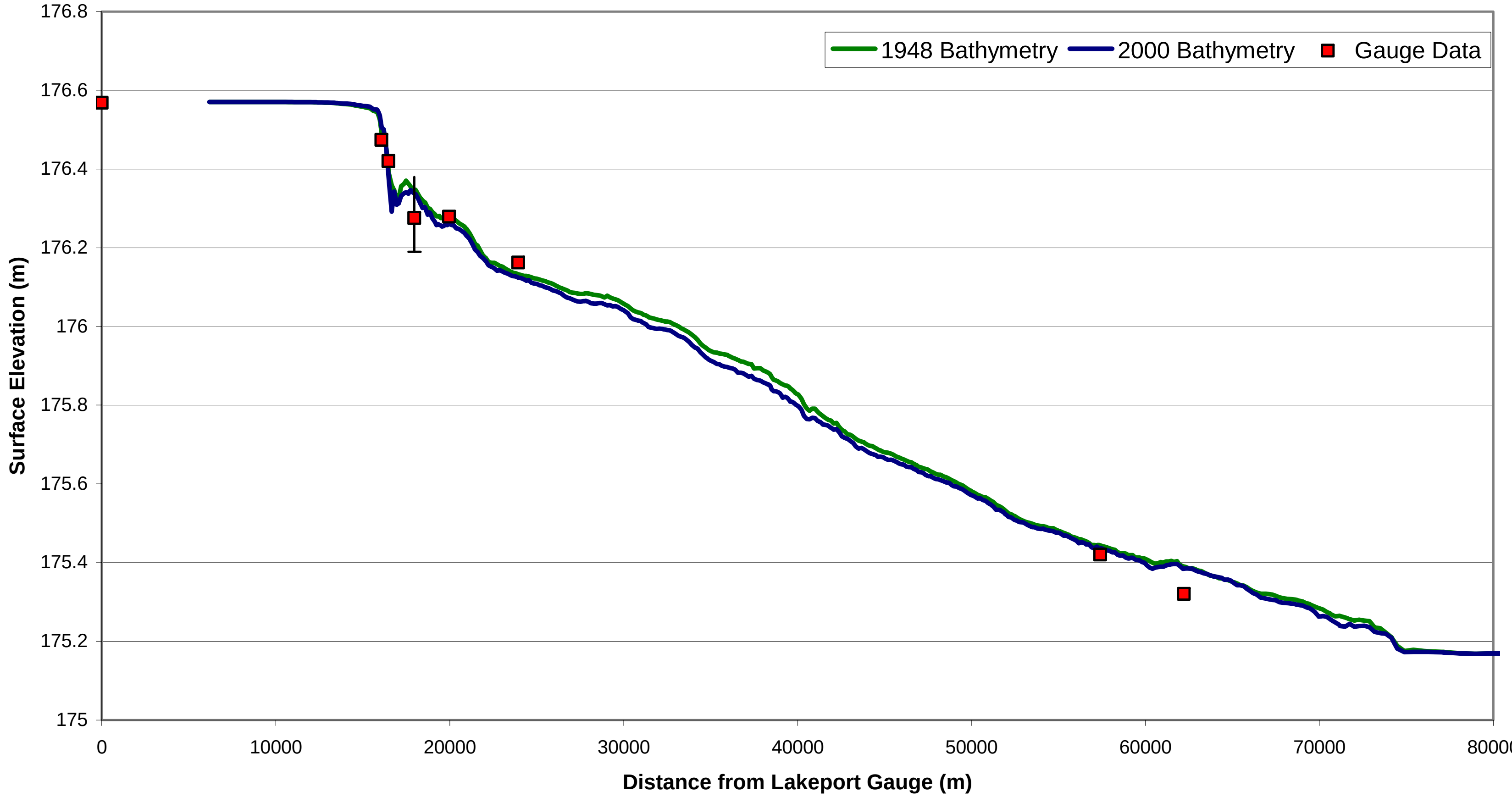


Figure 5.2 Comparison of Model Output with Gauge Data for Mean Lake Levels during August 1968

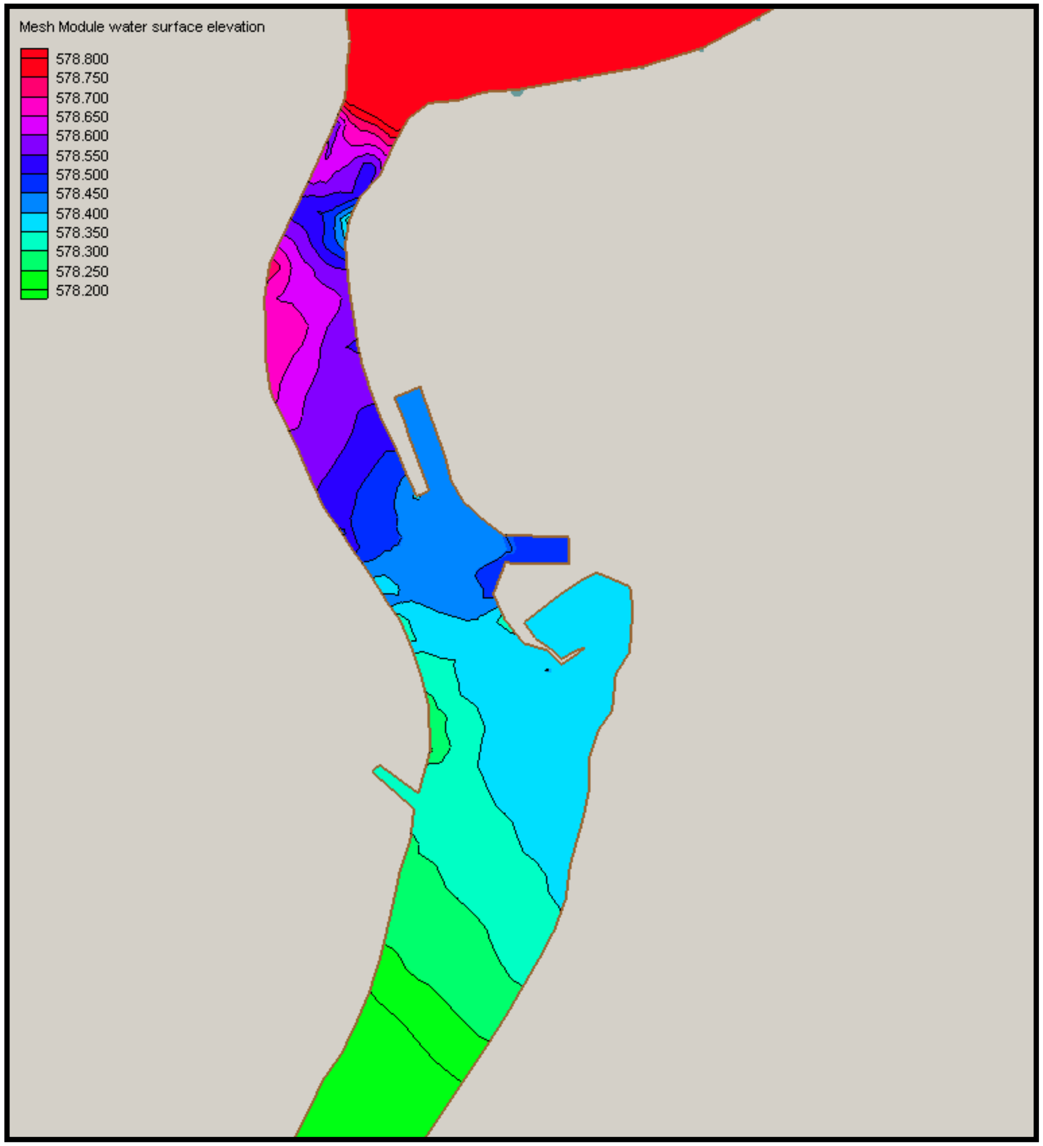


Figure 5.3 Water Surface Elevation from RMA2 Validation Run

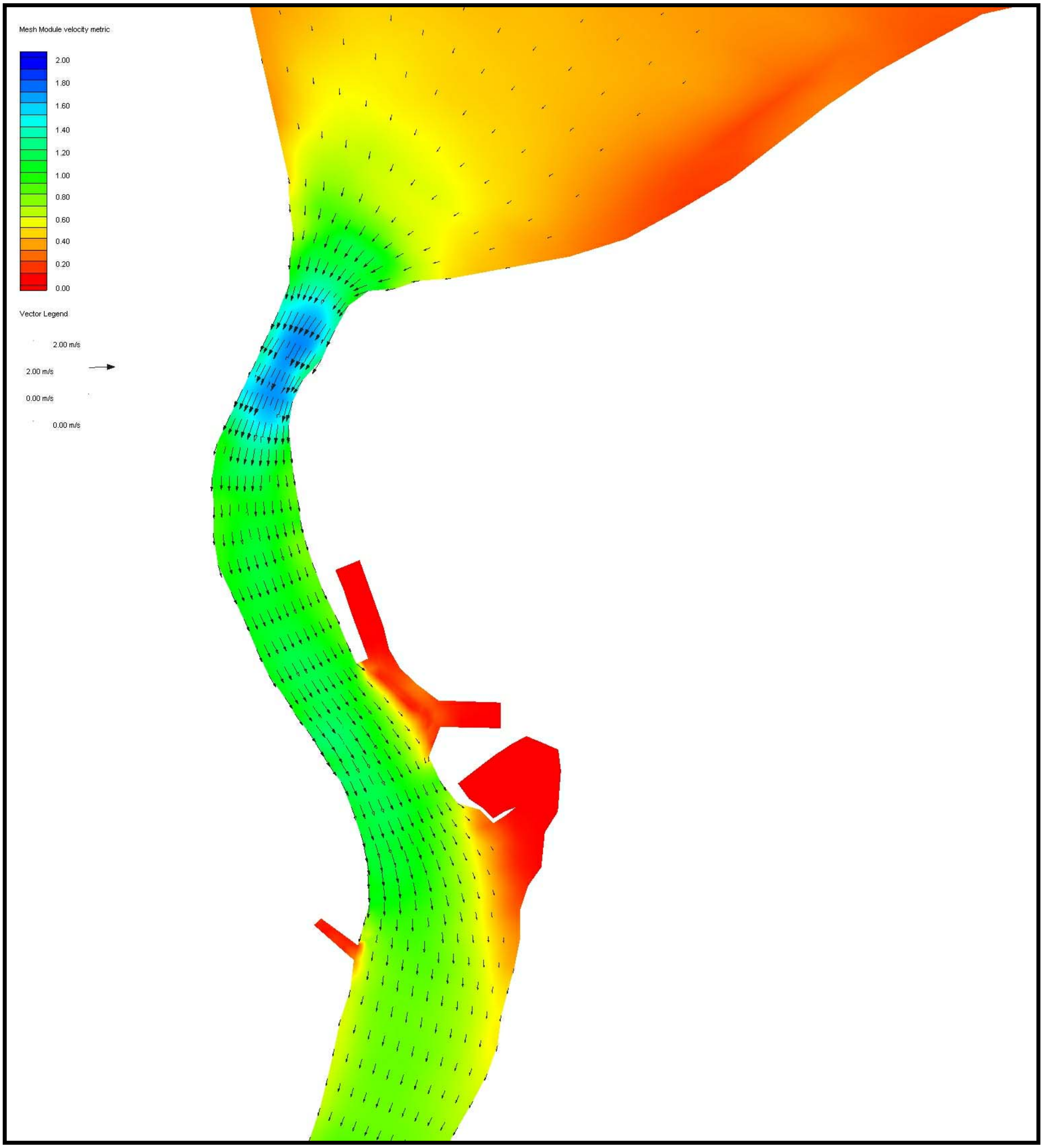


Figure 5.4 Flow vectors with 2000 Bathymetry

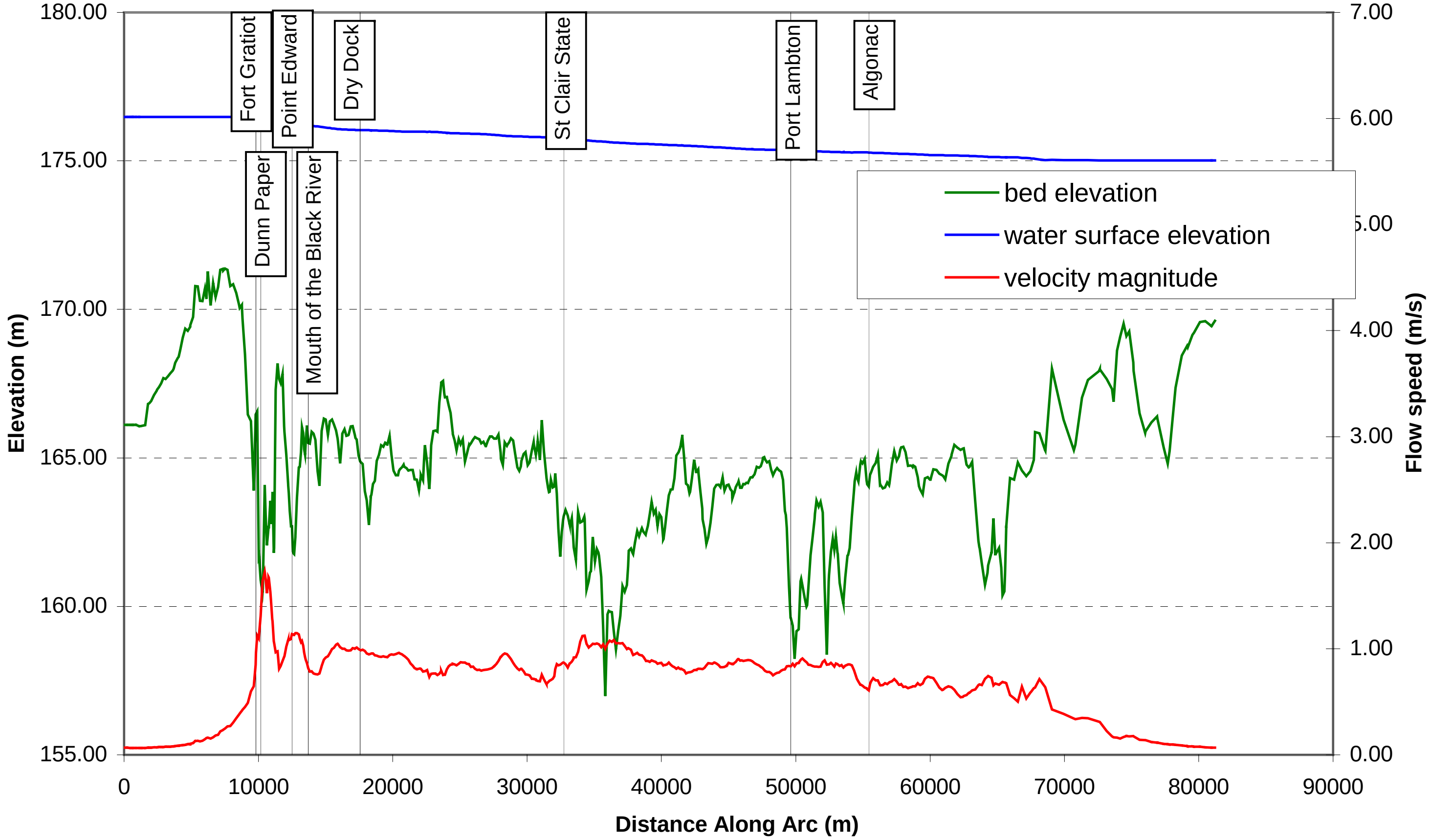


Figure 5.5 Model Output for 2000 Bathymetry, Flow = 5,200 m^3/s.

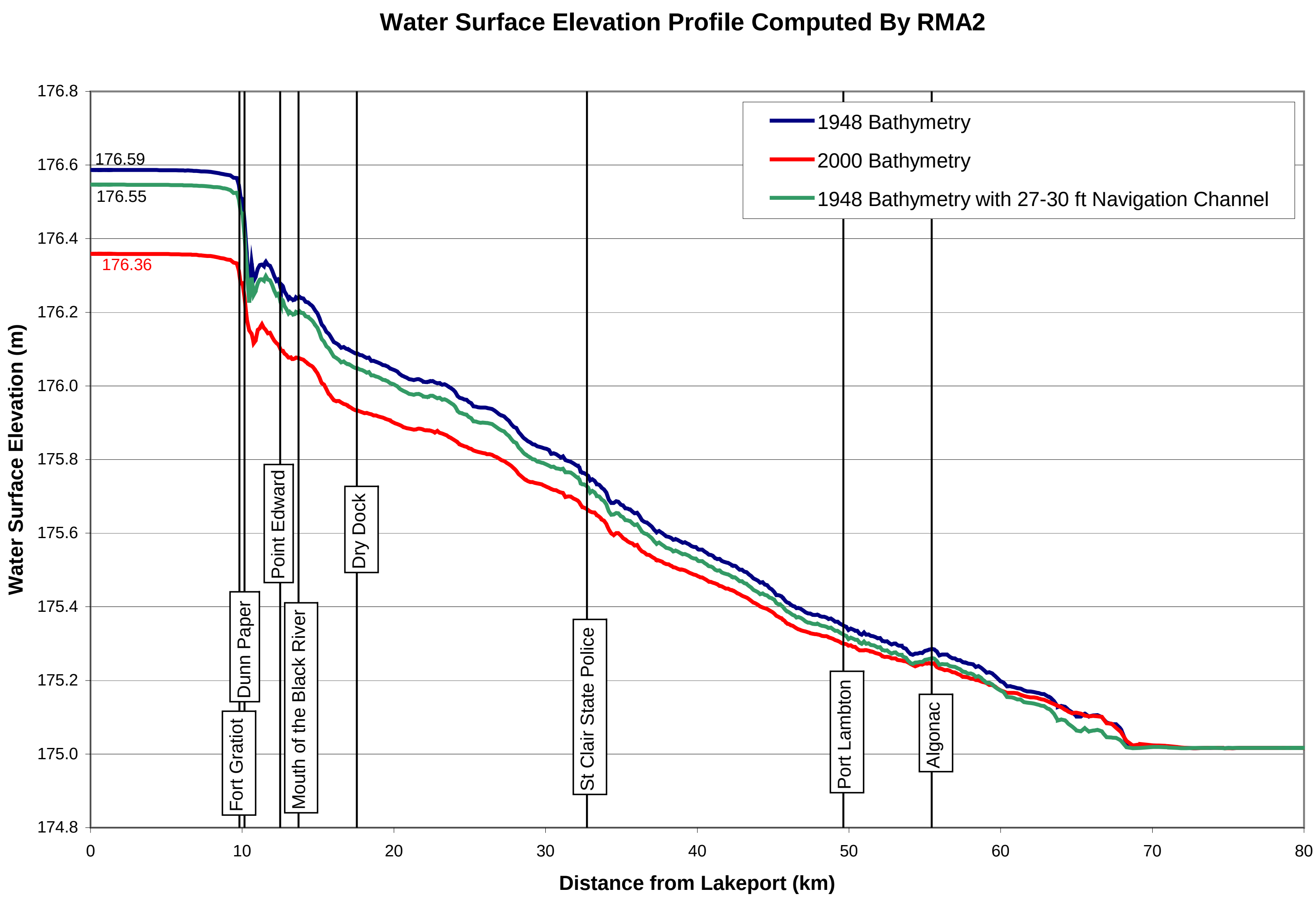


Figure 5.6 Water Surface Profile showing Head Drop from 1948 to 2000

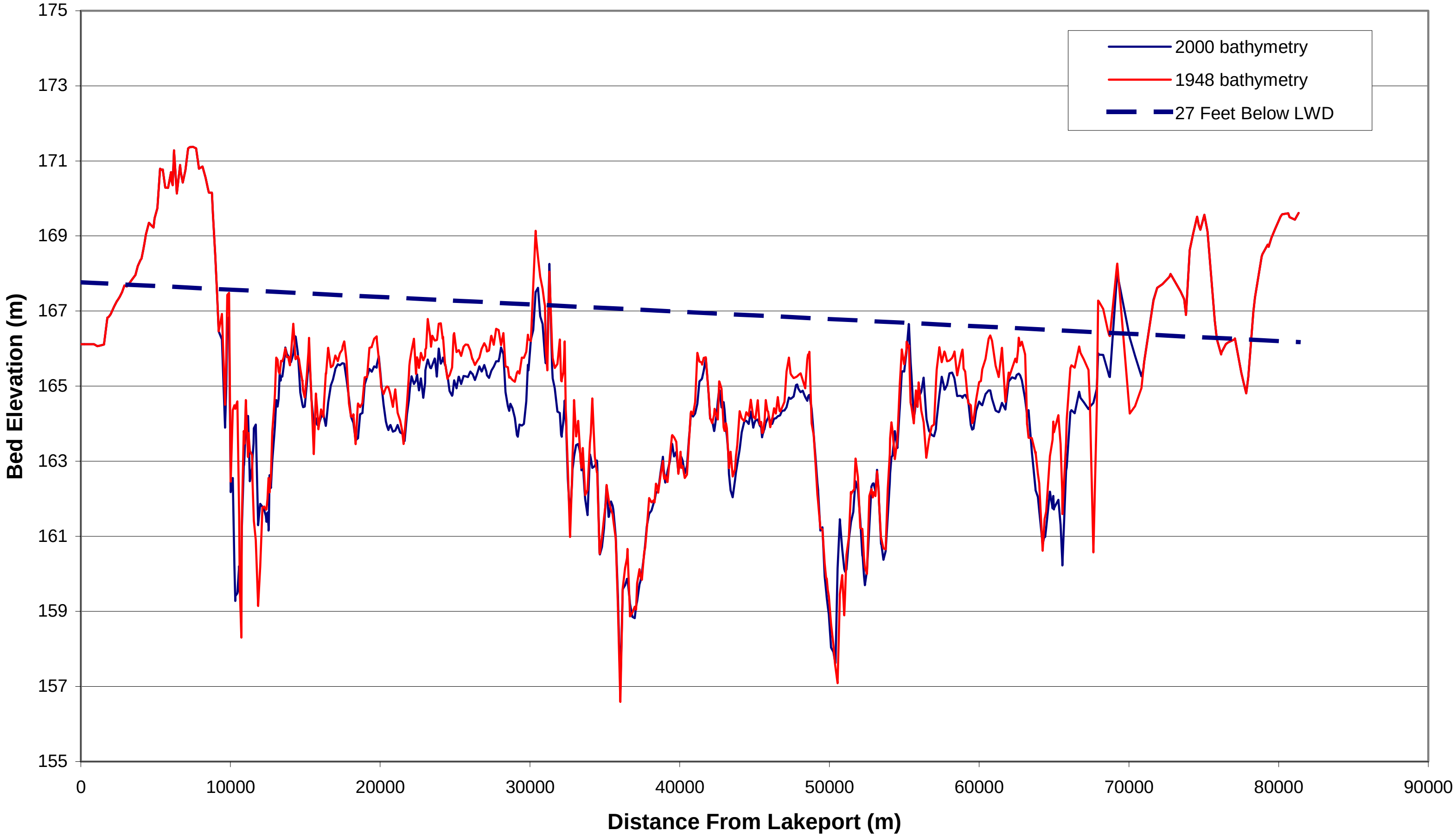


Figure 5.7 Comparison of Bed Elevation Profiles between 1948 and 2000

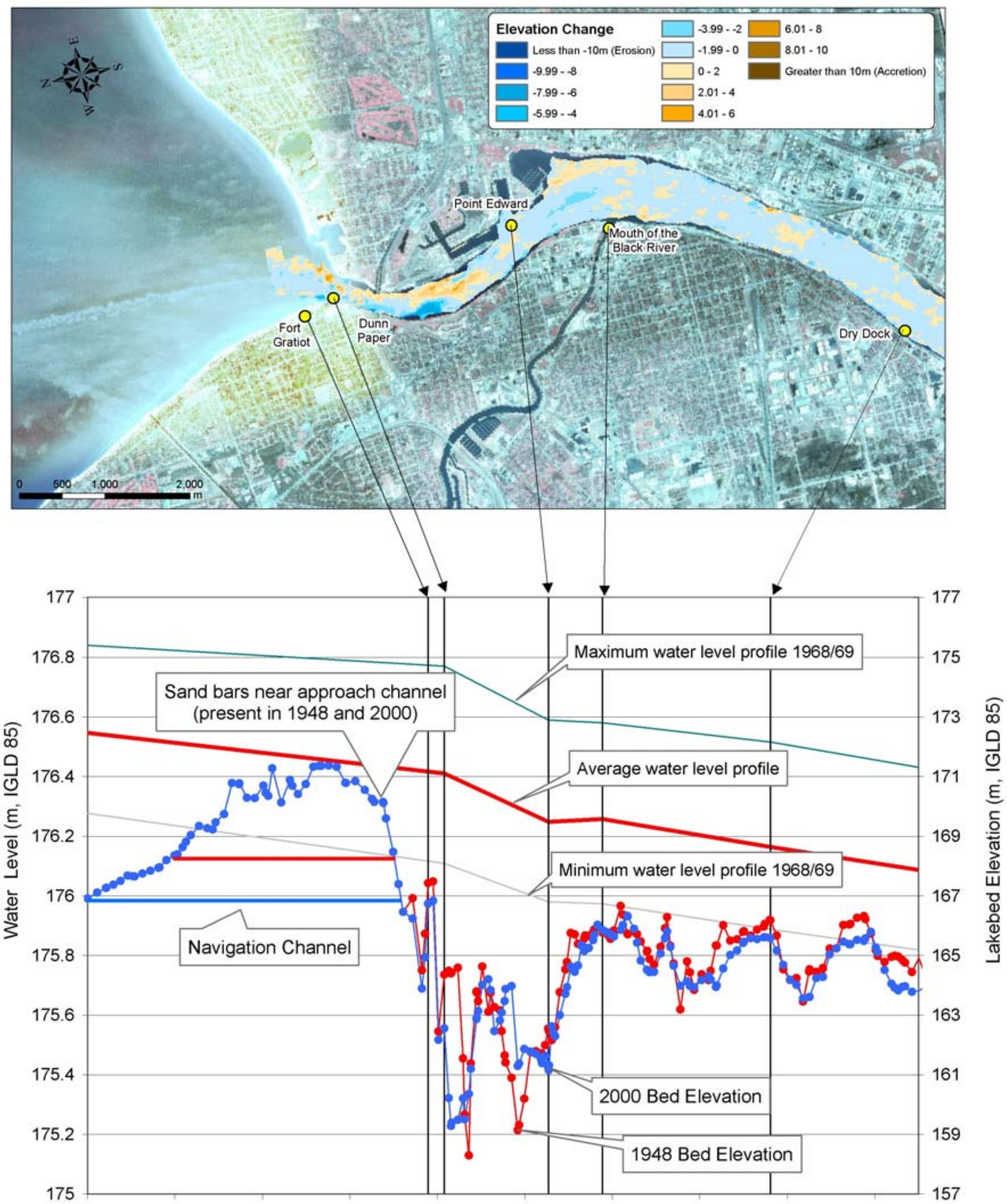


Figure 5.8 River Bed Change (1948-2000) and Water Surface Profiles in the Upstream End of the St. Clair River

6 NORMALIZATION ANALYSIS OF LEVEL DIFFERENCE

A normalization analysis was undertaken to filter out the impact of lake level variations due to changes in net basin supply, on level difference between Lake Michigan-Huron and Lake Erie. The objective was to isolate the change in level difference due to changes to the flow capacity of the river.

In Section 2 it was shown that the head between Lake Michigan-Huron and Lake Erie decreased by approximately 0.8 m (from 2.9 m to 2.1 m) between 1860 and 2003 (see Figure 2.5). A comparison of the drop in head between Lake Michigan-Huron and Lake Erie, and the actual lake level on Lake Michigan-Huron showed that there is a distinct relationship between head and lake level (see Figure 2.7). As the Michigan-Huron lake level increases due to an increase in the net supply of water to the basin, the head also increases. An important implication of the relationship between lake level and head is that periods of high lake levels (i.e. such as the extended period of highs between 1970 and 1998) would tend to mask the true extent of the head drop between Lake Michigan-Huron and Lake Erie. In other words, the head drop would have been even greater had average to low lake levels been experienced between 1970 and 1998. The influence of long term cyclical fluctuations in water levels on the Great Lakes are therefore an important consideration when analyzing historical trends.

The head data shown in Figure 2.5 represents change in head resulting from lake level fluctuations, and changes to the flow capacity of the St. Clair River induced by bathymetry changes. The head increases as the lake level increases. Since the variation in lake levels is similar in magnitude to the head change, the decrease in head due to bathymetry change alone is difficult to discern or quantify. A method was developed to isolate the head due to bathymetry change by extracting the lake level influence (i.e. the fluctuating NBS) from the head time series, leaving only the influence of dredging projects and natural erosion. This method is described in the following sections.

6.1 Derivation of Normalization Equation

For Lake Erie, the inflow from St. Clair and the Detroit River is equal to the sum of outflow to Niagara River, water storage change in the lake, and net outgoing flow to other destinations. The water balance equation can be written as

$$Q_{sd} = A\left(\frac{\Delta Z_{er}}{\Delta t}\right) + Q_{ng} + Q_o \qquad (1)$$

where Q_{sd} is the flow discharge through St. Clair and Detroit Rivers, Q_{ng} is flow discharge through the Niagara River, Q_o is net outgoing flow other than the Niagara

River (tributaries, water evaporation, and the outflow through the Canal); Z_{er} is water level on Lake Eric, A is the surface area of Lake Erie, and t is time (see Figure 6.1).

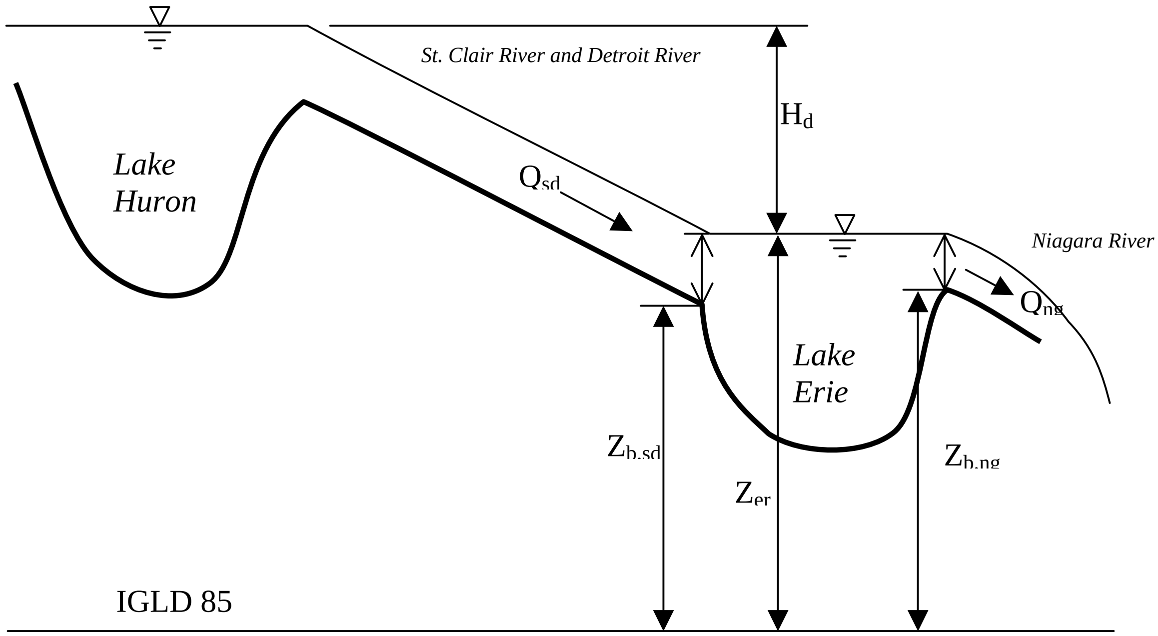


Figure 6.1 Water Balance for Lake Erie

Applying the hydraulic equation for open channel flow, the inflow Q_{sd} from the St. Clair and Detroit Rivers can be determined by the following equation:

$$Q_{sd} = C_{sd}\left(Z_{er} - Z_{b,sd}\right)^{5/3} H_d^{1/2} \qquad (2)$$

where C_{sd} is a discharge coefficient which depends on river width, roughness, and river length; Z_{er} is water surface elevation on Lake Erie; $Z_{b,sd}$ is bed elevation at the outlet of Detroit River (=167m); and H_d is head between Lake Huron and Lake Erie.

As demonstrated in this study, bathymetry changes in the St. Clair River including river bed erosion have resulted in a significant drop in water levels on Lake Michigan-Huron. The variation in lake levels on Lake Michigan-Huron includes the decrease in water levels resulting from bathymetry changes in the St. Clair River and fluctuations in water levels on the lake. The objective of this normalization analysis is to filter out the impact of lake level variations on head between Lake Michigan-Huron and Lake Erie. Therefore, the water level data for Lake Michigan-Huron could not be used in the analysis. Instead, information related to the cross-section at the outlet of the St. Clair and Detroit Rivers to Lake Erie has been used.

Niagara Falls can be regarded as a weir with a wide crest. The outflow of the Niagara River, denoted as Q_{ng} can be calculated by the following equation

$$Q_{ng} = C_{ng}\left(Z_{er} - Z_{b,ng}\right)^{3/2} \qquad (3)$$

where C_{ng} is discharge coefficient, and $Z_{b,ng}$ is bed elevation at the entry of Niagara River (=168 m).

By substituting equations (2) and (3) into equation (1) and dividing by C_{sd}, equation (1) can be rewritten as:

$$\left(Z_{er} - Z_{b,sd}\right)^{5/3} H_d^{1/2} = a\Delta Z_{er} + b\left(Z_{er} - Z_{b,ng}\right)^{3/2} + c \qquad (4)$$

where $a = \frac{A}{C_{sd}\Delta t}$; $b = \frac{C_{ng}}{C_{sd}}$; $c = \frac{Q_o}{C_{sd}}$, which should be determined by observation data.

The objective was to filter out from level difference between MH and E, the impact of the natural level variations that have occurred in E due to weather and seasonal changes. To do this, the flow coefficients C_{sd} and C_{ng} have been forced to be constant to account for just the natural volumetric balance around E caused by level variation, thus retaining in the MH level trend only the level changes that are attributable to dredging and erosion. Q_o which represents the net outgoing flow from other sources is much smaller than the main outflow through the Niagara River as verified by a regression analysis. Q_o is only about 1% of the total outflow for Lake Erie. Therefore, the coefficient *c* can also be assumed to be constant.

The coefficients *a*, *b,* and *c* can be determined using regression analysis for Equation (4) with the annual mean lake level in Lake Erie and annual mean head between Lake Michigan-Huron and Lake E, as listed in Table 6.1.

Table 6.1 Determination of Coefficients a, b and c based on Regression Analysis

Coefficient	Value	Standard Error	t Stat	Representing Term
a	9.52	1.11	8.61	Lake Level Variation
b	3.29	0.10	33.86	Flow in Niagara River
c	14.33	1.50	9.54	NBS

The correlation of the regression analysis is 0.73, which is a fairly good fit (a value 0 indicates no correlation and 1 indicates complete correlation). The *t* Stat represents how significant the "Representing Term" is for water balance in Lake Erie. If the *t* Stat value is greater than 2, the representing term contributes significantly to the lake level variation. Table 6.1 shows that the outflow in the Niagara River is the most significant contribution to level difference between Lakes Michigan-Huron and Erie.

Though the bed elevations $Z_{b,sd}$ and $Z_{b,ng}$ in Equation (4) are roughly determined from the river bathymetry data, there may be some level of error due to the complexity of river bathymetry. Sensitivity testing of the bed elevation setting was therefore undertaken. Varying the bed elevation affects the coefficients *a, b,* and *c* but it does not affect the filtered head because the coefficient *c* automatically compensates for the error induced by errors in the bed elevation. Mathematically, it can be explained as high-order terms from Taylor Series Expansion added to the coefficient *c*.

Sensitivity testing was also carried out to evaluate the impact of variations in water depth in the St. Clair and Detroit Rivers on the normalization analysis. A constant water depth was used for the term $\left(Z_{er} - Z_{b,sd}\right)^{5/3}$ on the left side of Equation (4) and therefore, the equation was simplified to:

$$H_d^{1/2} = a\Delta Z_{er} + b\left(Z_{er} - Z_{b,ng}\right)^{3/2} + c \qquad (5)$$

The results show that there is no significant difference between using constant water depth and using water depths varying with lake level, though the coefficients *a, b,* and *c* are different from that determined using variable water depth. Obviously, the variation of water depth due to lake level variation (1 m maximum) is small relative to the water depth (about 10 m). This contribution is small and can be neglected.

The coefficients of a, *b,* and *c* can be determined by using the water level records and regression analysis. The head calculated from the above equation represents the head caused by lake level variation only. Subtracting the recorded head from the head calculated using the above equation results in the head that can be attributed to the riverbed change (dredging and erosion).

6.2 Normalization Results

Figure 6.2 shows the normalized head, i.e. head that is attributed to dredging and erosion. The head due to water level fluctuations has been filtered out. As discussed in Section 2, level difference has been used in the analysis rather than actual water levels on Lake Michigan-Huron, because scatter in the data makes it difficult to identify the trend in the lake level data. The 10 year moving average has also been plotted along with the actual data. The reader should be aware that a moving average tends to skew the exact date when events occur, and it is for this reason that the 1960-62 dredging of the 8.2 m (27 ft) channel appears to occur in 1958. The moving average data shows a 0.70 m drop in head (equivalent to a decrease in Lake Michigan-Huron water levels) between 1885 and 1999. The decrease between 1948 and 1999 was 0.23 m. This is the same value that was predicted by the numerical modeling as shown in Figure 5.6. The two analyses were completely independent.

The raw data shows a larger decrease in head in the last few years, a decrease of 0.8 m from 1885 to present and 33 cm from 1960 to present.

The normalized plot shows that generally the head change between MH and E has occurred in the form of a step function with discrete responses to dredging events. Figure 6.3 shows the normalized head data and predicted head drop due to historical dredging projects and aggregate mining (IJC, 1987). There is generally good correlation between the IJC values and those predicted by the normalization method. The key differences are that this normalization method predicts a greater drop in head during the sand and gravel mining period and an ongoing drop since 1970. The steady decline since 1970 is unprecedented through the record as there is no apparent ongoing action leading to this drop. The only similar situation was through the sand and gravel mining period, but this may have been due to the ongoing nature of the dredging through that period.

The graph shows an unexplained increase in the head during the 1960's. It is possible that this apparent reduction in flow capacity may be related to changes in the lake bed morphology. The natural channel alignment for flow into the St. Clair River, evident on the 1867 and 1929 charts (Figure 4.4 and 4.5, respectively), was located in a more northeasterly alignment and to the east of the current approach channel position. The comparison of the 1948 and 2000 bathymetry shows accretion along the old channel alignment (see Figure 4.6a). It is possible that the 27 ft dredging project completed between 1960 and 1962 may have increased the over flow capacity from the lake into the river. However, this change may have contributed to the final closure of the old channel, thus eventually reducing the flow capacity (possibly explaining the increase in head drop in the late 1960's).

As explained earlier the subsequent erosion since 1970 is related to erosion of the river bed. In other words, the normalized plot also suggests that the erosion evident from comparing the 1948 to 2000 bathymetry has all occurred since 1960 (since there is no erosion response evident between 1948 and 1960). Keep in mind that the rolling mean representation tends to influence the accuracy of the dates shown on the horizontal axis of the figures.

The two main hypotheses for the explanation of the ongoing erosion (and resulting head drop) since 1970 are: 1) due to a reduction in the sediment supplied to the upstream end of the river owing to the effects of dredging, shore protection and other coastal structures; and 2) due to the influence of the change in approach channel depth and alignment and the impact to flow through the upper part of the river. These will be explored further in the final phase of our work through additional bathymetry comparisons and numerical modeling, to be completed in December 2004.

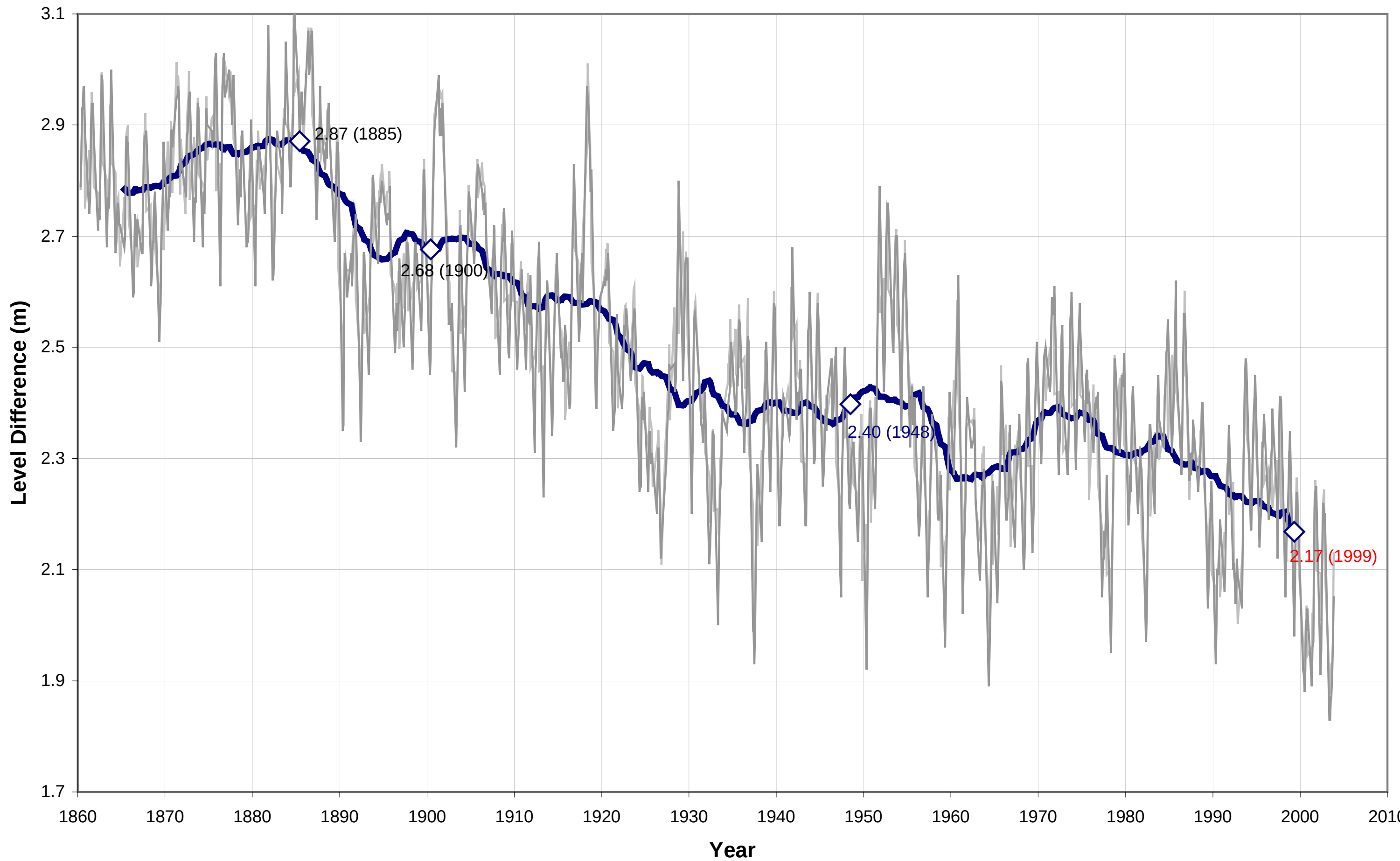


Figure 6.2 Change in Level Difference between Lakes Michigan-Huron and Erie due to Erosion and Man-Made Intervention (seasonal and weather induced changes removed through normalization)

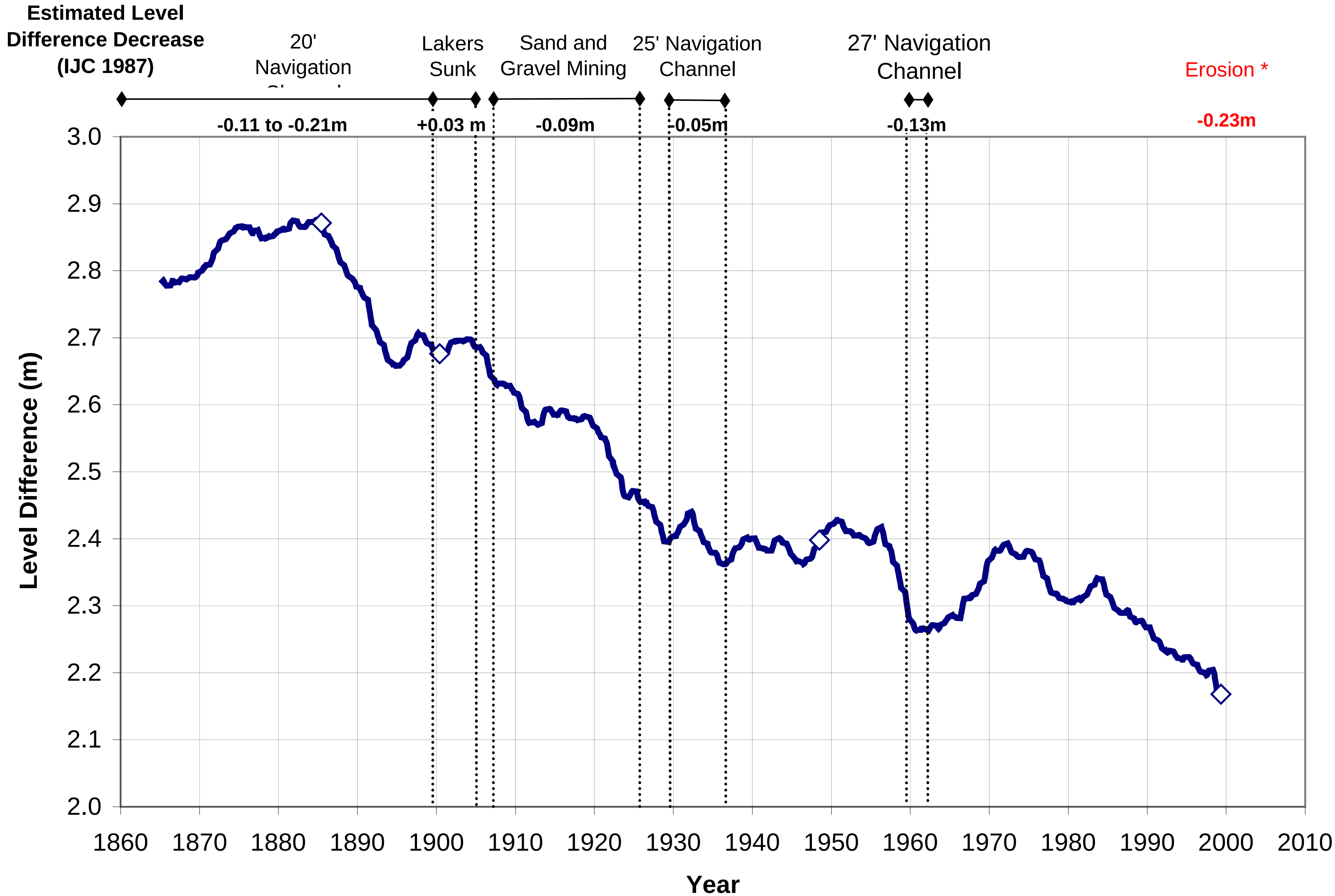


Figure 6.3 **Change in Level Difference between Lakes Michigan-Huron and Erie due to Erosion and Man-Made Intervention showing IJC Estimates (seasonal and weather induced changes removed through normalization)**

7 RIVERBED ERODIBILITY AND CAUSES OF EROSION

The numerical modeling and data analyses described in the previous sections indicate that river erosion and dredging are the main causes of the reduction of head between Lakes Michigan-Huron and St. Clair. Erosion of the river bed is a function of flow velocities in the river, the erodibility of the river bed material, and human activities in the river. This section describes the river bed geological feature, bed materials, erodibility, and the possible impact of ship propeller scour on erosion.

7.1 Geology

There are extensive clay plains on the west side and towards the downstream outlet on the east side of the St Clair River (see Figure 7.1). This region has little relief, lying between 175 and 210 m above sea level. The clay plains are a deep overburden on the underlying limestone and shale bedrock. This bedrock forms the main component of the clay. The till plain covering most of the area to the east of the channel is thought to have been deposited by Glacial Lakes Whittesley and Warren, with infilling of shallow depressions by lacustrine clay. Moranic material and dune sand found near the Lake Huron outlet are likely to contribute to the sediment load of the St. Clair River. Surface drainage in this region is nearly all to Lake St. Clair, characterized by low gradients and consequently poorly-defined drainage divides.

On a geologic time scale, the erosion of the St. Clair River outlet is believed to have caused a slow decline in Lake Michigan-Huron levels up until the natural stabilization of the outlet sometime between 2,100 years before present (Larsen, 1994) and 3,500 years before present (Baedke and Thompson, 2000).

7.2 Erodibility of the River Bed

For non-cohesive material, erodibility is a function of the grain size and density of the bed material. Borehole data collected by the USACE from 1958-1960 were used to determine riverbed erodibility. Figure 7.2 shows the locations of C25 series boreholes. The borehole C25-1 is located at the inlet of the river on Lake Huron. The borehole data indicates that the top 1.4 m of material is soft loose medium sand, which is probably new deposition supplied by longshore sediment transport from Lake Huron. Under the soft sand is dense, medium sand and gravel. Borehole C25-2 is located downstream at the Dunn Paper gauge. Similar to borehole C25-1, the river bed material is about 2 m of very soft medium sand to fine gravel over very dense medium sand to fine gravel. The distribution of bed material along the river is shown in Figure 7.3. The bed materials downstream of the Point Edward gauge generally consist of the top coarse sand to fine gravel over soft but consolidated glacial clay.

Sand on the river bed begins to move when the bed shear stress is larger than the critical shear stress. The critical shear stress is a function of grain size and soil consolidation. For non-cohesive sediment, critical shear stress increases as the grain size of the sediment increases. This means that fine sediment is easily eroded. Bed material in rivers generally consists of more than one sediment class (non-uniform bed material). If bed shear stress is sufficiently large to erode the finer sediment, but not enough large to erode coarse sediment, the finer sediments are eroded and the coarser sediments remain on the river bed. This physical process is called riverbed armouring.

On the St. Clair River, the bed material consists of medium sand to fine gravel. The critical shear stress for these sediment classes ranges from 0.2 Pa to 5 Pa. Figure 7.4 shows bed shear stress calculated from the model results for mean lake level. On the basis of the critical shear stresses for medium sand to fine gravel, the river can be classified into three distinctive river segments: upper reach from the entry to the Point Edward gauge, middle reach from the Point Edward gauge to the Algonac gauge, and lower reach from the Algonac gauge to the river delta.

In the upper reach, the bed shear stress is large enough to erode the fine gravel present in river bed material. Therefore, if the supply is not keeping up with the transport potential, the river bed will erode. However, deposition may occur in some areas as evidenced by the deposition shown along the east side of the river, where flow velocities are locally lower (see Figure 4.6a). For deposition to occur (or for long-term river bed stability), there must be a supply of sediment (from Lake Huron). The borehole data shows that under the surface layer, the material is very dense coarse sand to fine gravel that may be resistant to erosion. This dense layer will also protect the finer material below, from erosion. If the dense layer is removed, the finer material below will start eroding until a protective layer is reformed during erosion. The gravel mining conducted prior to 1925 may have removed the protective gravel layer on the riverbed.

In the middle reach, the bed shear stress is between the critical shear stress for very fine gravel and fine gavel. The fine gravels likely remain on the riverbed when the sand is washed away. Thus the fine gravels armour the riverbed and protect it from erosion. The gravel mining conducted prior to 1925 may have removed the protective gravel layer on the riverbed.

In the lower reach, the bed shear stress is below the critical shear stress for coarse sand to very fine gravel. Most sand is deposited in this reach and forms the river delta. This reach of the river is depositional as indicated by the bathymetry comparison (see Figure 4.6c).

7.3 Propeller Wash

The St. Clair River is a commercial waterway used by a large number of vessels, transporting materials through the Great Lakes-St. Lawrence. Commercial dry-bulk carriers are often laden to utilize the full channel depth, exposing the riverbed to high jet velocities produced by the propellers. Figure 7.5 illustrates the expansion of a propeller jet behind a vessel. As the propeller jet expands, its velocity decreases. Thus, the closer the propeller is to the bottom, the greater the influence of the propeller jet on the bottom. As a result, vessel draft and channel depth must be considered, along with applied horsepower, propeller diameter and the influence of a rudder.

A number of parameters are used to determine the bottom velocities and shear stresses generated by ship propeller wash. The most significant are vessel draft, power, speed, and propeller and rudder characteristics. To investigate the scour potential due to ship propeller scour, ship traffic data was obtained for the St. Clair River and representative values for the vessels identified in the vessel traffic data were selected

The calculation of bottom velocity occurs in three steps; 1) calculate the jet velocity at the ship's propeller; 2) determine bottom velocity; and 3) calculate scour. Jet velocities were calculated using the method outlined in PIANC (1997). Bottom velocities were calculated using the method outlined in EAU (1996). The current along the bottom applies a force to the riverbed, resulting in a shear stress at the surface of the riverbed. The shear stress was calculated according to Froehlisch and Shea (2000). Scour potential was calculated for the riverbed materials. Table 7.1 summarizes the bottom velocities, shear stresses and scour rates for different vessel classes. The table indicates that there is potential for significant erosion in the ship channels due to propeller scour. This may explain erosion in the ship channel but does not explain the widespread erosion outside the ship channel. In addition, erosion in the critical section of the river exceeds the rates suggested in Table 7.1.

Table 7.1 Propeller-induced bottom velocities, shear stresses, and scour.

<table>
<tr><th>Depth</th><th>Trial</th><th>Bottom Velocity</th><th>Shear Stress</th><th>Time</th><th>Scour for 40 years</th><th>Total Scour for 100 years</th></tr>
<tr><td>(m)</td><td></td><td>(m/s)</td><td>(Pa)</td><td>(s)</td><td>(mm)</td><td>(mm)</td></tr>
<tr><td>10.33</td><td>Small</td><td>2.59</td><td>92</td><td>475</td><td>38</td><td rowspan="3">729</td></tr>
<tr><td>10.33</td><td>Medium</td><td>3.89</td><td>209</td><td>1087</td><td>302</td></tr>
<tr><td>10.33</td><td>Large</td><td>5.35</td><td>395</td><td>534</td><td>389</td></tr>
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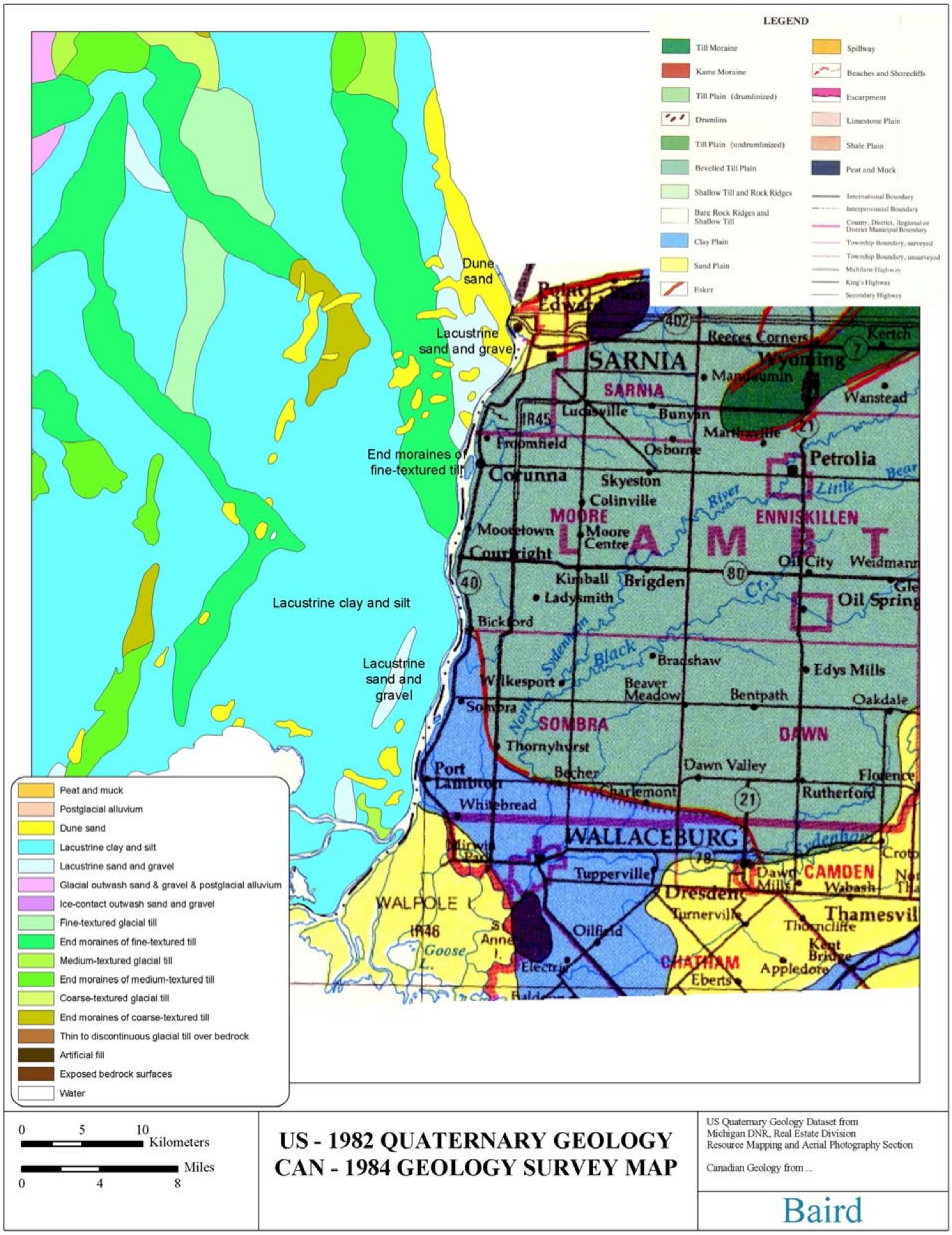

Figure 7.1 Geology along the St. Clair River

Figure 7.2 Locations of Borehole Data

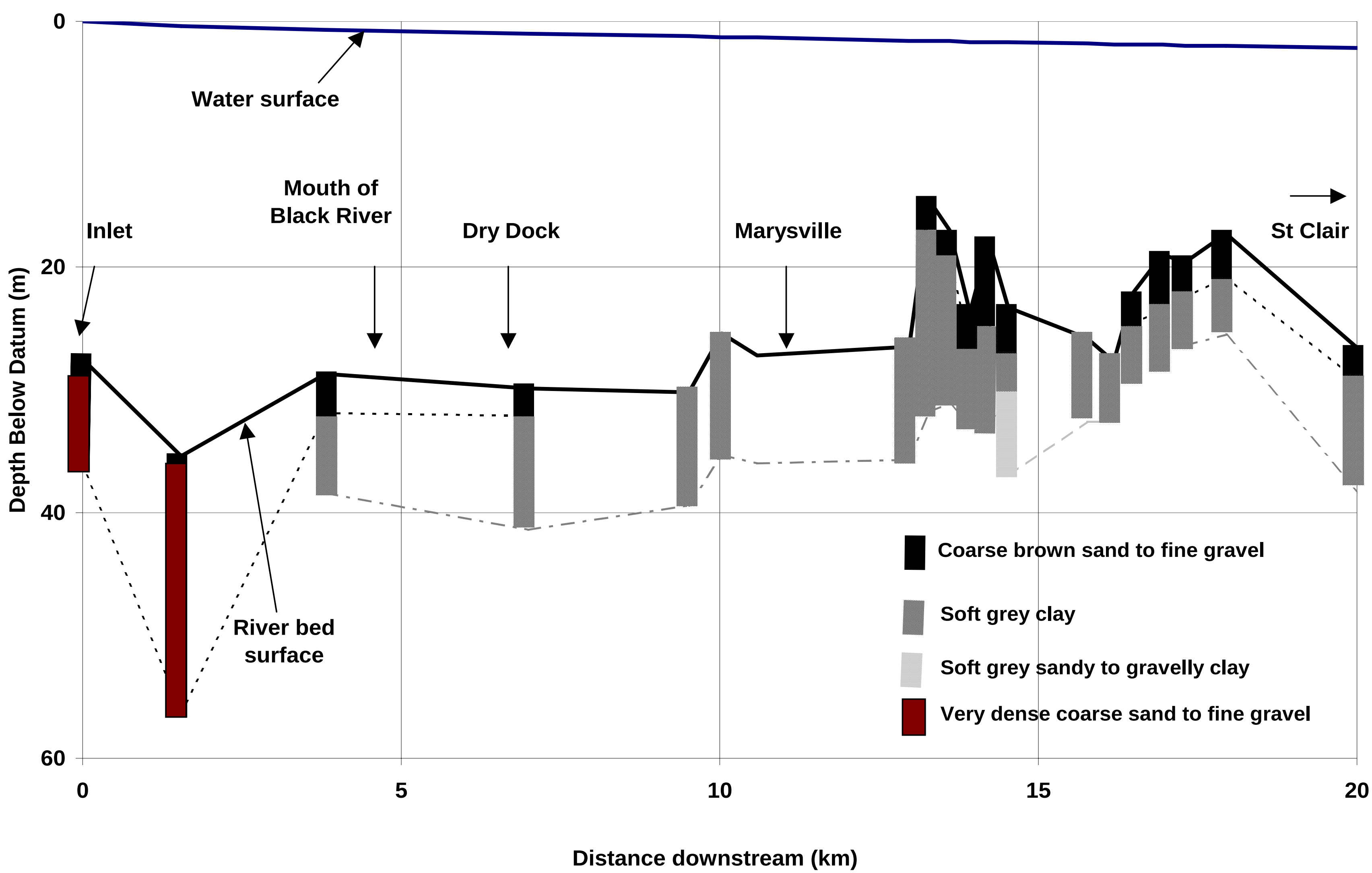

Figure 7.3 Distribution of Bed Materials Along the River based on Borehole Data

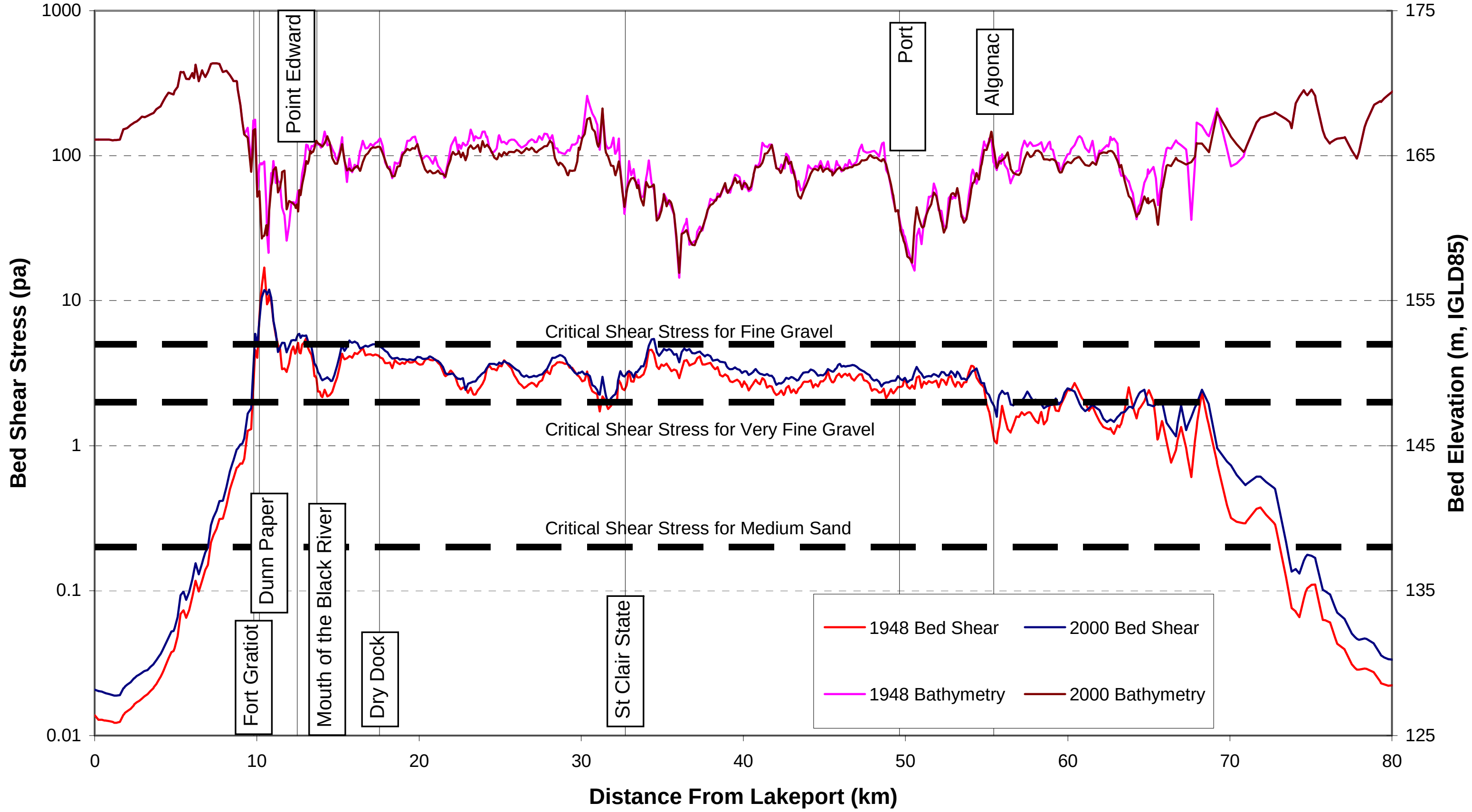

Figure 7.4 River Bed Erodibility Analysis

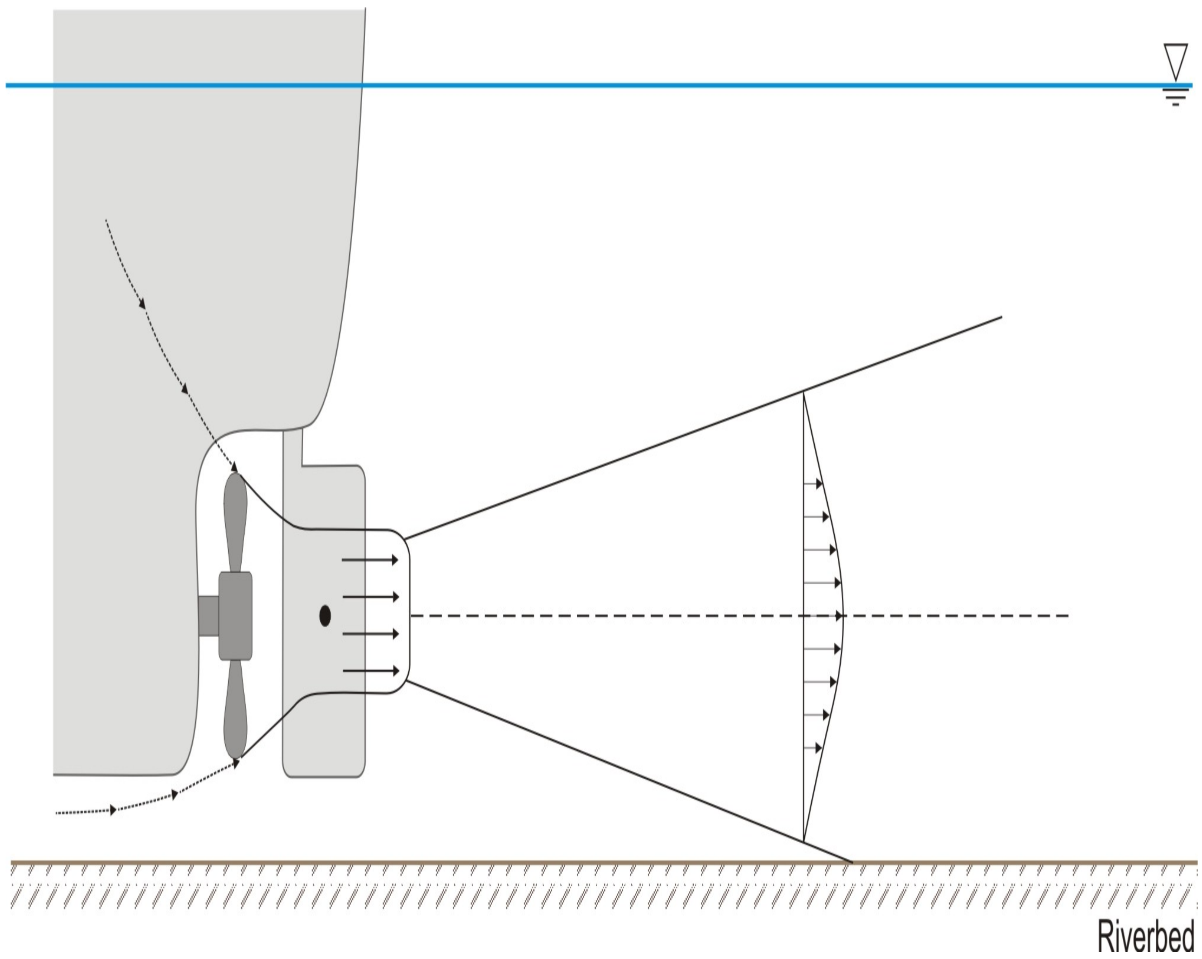

Figure 7.5 Velocity jet behind vessel.

8 SUMMARY AND CONCLUSIONS

The following summarizes the findings of this study:

1. Analysis of monthly mean lake level data for Lakes Michigan-Huron and Lake St. Clair show a decrease in the head between the two lakes from 1900 to 2003.

2. In order to obtain a longer period of record for the analysis (and thereby eliminate misleading bias that may result from lake level cycles), Lake Erie data for the period 1860 to 2003 were used in the analysis. The water level data show no long-term change in the head between Lakes St. Clair and Erie, but a decreasing head between Lakes Michigan-Huron and Lake Erie (similar to the decreasing trend between Lakes Huron-Michigan and Lake St. Clair). This justifies the appropriateness of using the Lake Erie data in the analysis.

3. The relatively constant head between Lakes St. Clair and Erie suggests that the decrease in the head between Lakes Huron-Michigan and St. Clair is a result of lower levels on Lake Michigan-Huron (as opposed to higher levels on Lakes St. Clair and Erie).

4. The trend of head drop since over the last 40 years indicates a drop of 20 cm over this period. The drop in head to the end of 2003 is closer to 33 cm and this is a more representative estimate because the high lake levels over the period from 1970 to 1998 masked the full extent of the impact. This drop represents an irreversible decline in the long-term average lake levels, without human intervention.

5. Between 1860 and present the total drop has been approximately 80 cm compared to the IJC estimate of 36 to 46 cm.

6. Possible causes of the decreased water levels on Lake Michigan-Huron were investigated including: erosion of the St. Clair River bed, relative change in net basin supply, and differential glacial rebound.

7. A review of tectonic data prepared by the coordinating Committee on Great Lakes Basin Hydraulic and Hydrologic Data (2001) suggests that although this is an important consideration when reviewing water level data, it does not explain the drop in head between Lakes Michigan-Huron and Lake Erie. The St. Clair River is in a stable region where there is minimal post-glacial rebound and gauges used in the study are in tectonically neutral locations. A second possible influence of glacial rebound relates to the effect of the tilting land and lake bed levels on the distribution of water over the surface of Lakes Michigan-Huron. Rising levels along the east shores of Georgian Bay and falling levels at the south end of Lake Michigan will cause a transfer of water from the rising to the falling side. Rather

than contributing to falling water levels on Lake Huron, the tilting of the lake could be expected to cause an increase in water levels at the outlet of lake Huron as water is moved toward the southern end of the lake.

8. Net Basin Supply is calculated by government agencies using two methods, the Residual Method and the Components Method. Data calculated using the Residual Method show a direct correlation with the head between Lakes Michigan-Huron and Erie, suggesting an apparent increase in the relative NBS (Lake Erie/Lake Michigan-Huron) between 1948 and 2000. However, the Residual NBS data are calculated directly from the stage-discharge relationships which are derived from water levels that have not accounted for changes in river cross-section and flow capacity due to bed erosion. The Components approach does not show the same trend. The Components approach does not require an estimate of connecting channel flow data to determine NBS on individual basins, and therefore is more likely to be correct. It may be concluded that it is unlikely that a significant and real shift in relative NBS between Lake Michigan-Huron and Lake Erie has occurred. Therefore, this possible cause cannot explain the large drop in head between Lakes Michigan-Huron and Lake Erie.

9. The decrease in head between Lake Michigan-Huron and Lake Erie (and St. Clair) is shown to be a result of an increase in the river cross-section through the critical flow section of the river. Because the decrease in head has been continuous, it is likely that the drop since the 1970's is due to ongoing erosion of the riverbed. Earlier and more discrete decreases in the head were attributed to specific dredging projects and operations.

10. Based on dredging records provided in Coordinating Committee (1998), it is estimated that between 1841 and 1992 approximately 22 million cubic metres of material were dredged from the riverbed including the approaches in Lake Huron and the St. Clair Flats.

11. Analysis of bathymetry data from 1948 and 2000 shows an overall erosion trend, both in the navigation channel and beyond the limits of the channel. In particular, there is significant erosion of the riverbed between Dunn Paper and Point Edward gauges. Analysis of water surface slopes and flow rates suggest that this is the critical section of the river for flow. This critical section may extend lakeward to the outer limit of the Lake Huron approach channel and downstream to the Mouth of Black River water level gauge. Changes to the riverbed in this area would cause the most significant changes to river flow.

12. Numerical modeling using the USACE RMA2 model clearly shows a reduction in water levels on Lake Huron between 1948 and 2000. The model showed a drop of 4 cm on Lake Huron as a result of dredging the 8.2 m (27 ft) navigation channel and an additional drop of 19 cm that can only be attributed to erosion of the riverbed, for a total drop of 23 cm between 1960 and 2000

13. A new normalization method was developed for isolating the effects of water level variation due to changes in Net Basin Supply, from variations resulting from changes in the flow capacity of the river (due to erosion or dredging). The results show a decrease in the head (Lake Michigan-Huron-Lake Erie) of 23 cm between 1948 and 1999. This is in agreement with the values predicted by the numerical modeling and provides an independent check on those results.

14. The normalized plot of dredging and erosion influences on the drop in head between MH and E compared well to most IJC estimates. The main differences were that the normalization approach predicts a greater drop as a result of the sand and gravel mining operations of the 1920s and it show an ongoing decline in head since 1970. The alarming observation is that all other head drops (i.e. other than the condition since 1970) could be linked to dredging events or operations. The steady and ongoing decline observed since 1970 implies ongoing river bed erosion.

15. The trend of head drop over the last 40 years indicates a drop of 20 cm over this period. The drop in head to the end of 2003 is closer to 33 cm and this is a more representative estimate because the high lake levels over the period from 1970 to 1998 masked the full extent of the impact. This drop represents an irreversible decline in the long-term average lake levels.

16. It is not surprising that this phenomenon has only recently come to light. The 2000 bathymetry data has only been made available in the last couple of years, allowing comparison to the 1948 bathymetry. Also, the lake levels have generally been high since the 1970’s, masking the drop in head. The low levels of the last three years have only recently unmasked the true extent of the underlying head drop. The new normalized approach to view the head drop caused by dredging and erosion alone, provides a method for tracking changes in the future, independent of lake level conditions.

17. These drops in water level must be considered along Georgian Bay shorelines, in addition to decreases due to glacial rebound in the order of 17 to 27 cm per century. Whereas glacial rebound cannot be compensated for, the erosion can.

18. It is widely accepted that the erosion of the St. Clair River outlet (and the associated drop in the MH level) stopped between 2,100 and 3,500 years ago. The recent erosion is unprecedented, even on a geologic time scale. Possible reasons for this recent erosion were investigated.

19. Historically, erosion may have been initiated by loss of an armour layer (coarse material), which once protected underlying erodible sediment. The armour layer may have been removed during dredging or aggregate mining. If this natural armour were removed, the underlying finer sediment would be prone to irreversible erosion for many years resulting in ongoing deepening of the channel.

This does not however explain the continuous decline in lake levels since the 1970’s (the head was relatively stable from 1930 to 1970).

20. A review of ship traffic and calculation of bottom velocities due to propeller wash suggests that there is potential for significant erosion in the ship channels due to propeller scour. This may explain erosion in the ship channel but does not explain the widespread erosion outside the ship channel. In addition, erosion in the critical section of the river exceeds the erosion rates that can be attributed to propeller scour.

21. It is evident from the 1948 to 2000 bathymetry comparison that erosion is occurring and would appear to be greater at the upstream end of the St. Clair River. This pattern of increasing river bed degradation (or erosion) moving in an upstream direction is consistent with the classic response of a river where the sediment supply has been reduced or cutoff, such as in the case of a dam. It is certain that the historic and natural sand supply to the upper end of the river has been interrupted and reduced through various actions including: dredging and sand mining and the implementation of shore protection and harbour structures along both the US and Canadian shores (trapping sand and preventing erosion that would otherwise supply the shore with sand and gravel). Most of these actions have occurred over the last 50 years where the erosion of the river bed has been detected.

22. The sediment supply deficit hypothesis fails to explain two key observations from our investigations: a) the pattern of very high localized erosion and accretion in the upper reach of the St. Clair River (i.e. in addition to the general trend of erosion); and b) the fact that after the triggering of a significant head drop with the 1960 dredging project, there was a reversal (or relaxation) of the trend in the latter half of the 1960's. These observations lead us to consider that the change in the position of the outer channel may have contributed to the recent period of erosion of the river bed, particularly above the Mouth of the Black River.

23. It is not surprising that this phenomenon has only recently come to light. The 2000 bathymetry data has only been made available in the last couple of years, allowing comparison to the 1948 bathymetry. Also, the lake levels have generally been high since the 1970’s, masking the drop in head. The low levels of the last three years have only recently allowed the true extent of the underlying head drop to be observed. The new normalization approach to view the head drop caused by dredging and erosion alone, provides a method for tracking changes in the future, independent of lake level conditions.

24. Possible explanations for the cause of recent erosion, one relating to sediment supply impacts and the other relating to the shift in the outer channel position will be investigated in the final phase of the project (to be completed in December 2004).

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REGIME CHANGE (MAN MADE INTERVENTION) AND ONGOING EROSION IN THE ST. CLAIR RIVER AND IMPACTS ON LAKE MICHIGAN-HURON LAKE LEVELS

ADDENDUM A: CORRECTION TO 1948 SURVEY DATE

Prepared for:

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JANUARY 2005

REGIME CHANGE (MAN MADE INTERVENTION) AND ONGOING EROSION IN THE ST. CLAIR RIVER AND IMPACTS ON LAKE MICHIGAN-HURON LAKE LEVELS

ADDENDUM A: CORRECTION TO 1948 SURVEY DATE

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For further information please contact
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Baird & Associates completed this investigation through funding from the GBA Foundation, a foundation of the Georgian Bay Association. The cooperation and assistance of the US Army Corps of Engineers, Environment Canada and the Great Lakes Environmental Research Laboratory (NOAA) is also gratefully acknowledged. We wish to thank Frank Quinn for his valuable input to our investigations and for his review and comments on the report.

ADDENDUM A: ERROR IN 1948 BATHYMETRY DATA

In 2004, Baird & Associates was retained by the GBA Foundation to complete an investigation into the recorded drop in the difference between lake levels on Lake Huron and Lake St. Clair, and possible relationships to historical changes in the St. Clair River. The results of that study are provided in a report titled Regime Change "Man Made Intervention) and Ongoing Erosion in the St. Clair River and Impacts on Lake Michigan-Huron Lake Levels" issued in November 2004.

In December 2004 Baird received an email from NOAA, stating that survey data on NOAA's GEODAS DVD used in the study and dating from 1961, 1970 and 1971 were incorrectly identified as 1948 data. Figures A-1, A-2 and A-3 show the surveys identified and the corrected survey dates based on the correspondence from NOAA.

NOAA believes that the data for the southern end of Lake Huron are from 1952. However, Baird's review of the 1929 field sheet suggests that some of the data are from 1929 (see Figure A1). The data for most of the river, extending to the north end of the delta, are now identified by NOAA, as 1971 data (see Figure A2). Figure A3 shows the river delta. NOAA believes that most of the data from this region date from 1961.

The implication of the correction to the date on the NOAA DVD is that erosion of the riverbed, which was originally understood to have occurred from 1948 to 2000, actually occurred for most of the river, between 1971 and 2000. This implies a higher rate of erosion. In addition, although it was previously thought that the 1948 data did not include the 8.2 m dredging project, which occurred from 1960-62, the data (from 1971 as recently indicated by NOAA) would include the 8.2 m dredging project. Any erosion identified in the comparison between the 1948 (1971) and 2000 data is solely attributable to erosion of the riverbed (as opposed to erosion and dredging).

The GEODAS CD indicates that the data originally identified as 1948 data were reduced to Lake St. Clair Low Water Datum 571.7 ft (174.3 m) International Great Lakes Datum (IGLD) 1955. It was inferred that this meant that the soundings were reduced to the sloping surface of the river corresponding to 571.7 ft on Lake St. Clair. The smooth sheet provided by NOAA in December 2004 also indicates that data are reduced to this datum. No change to the datum used in the original analysis should therefore be required and the depth difference values presented in Baird (2004) remain valid.

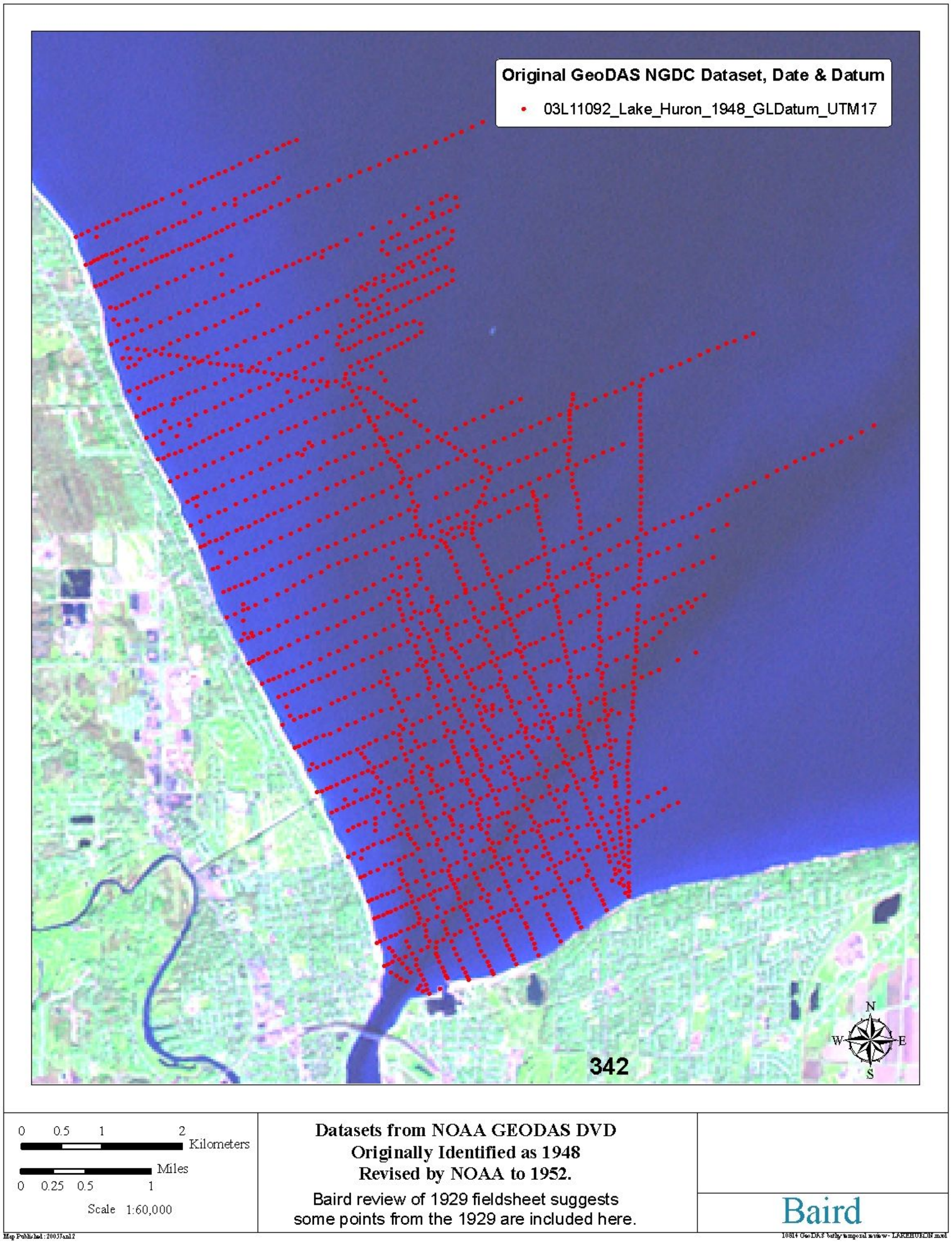

Figure A1 **Bathymetry Data from NOAA GEODAS DVD Revised from 1948 to 1952**

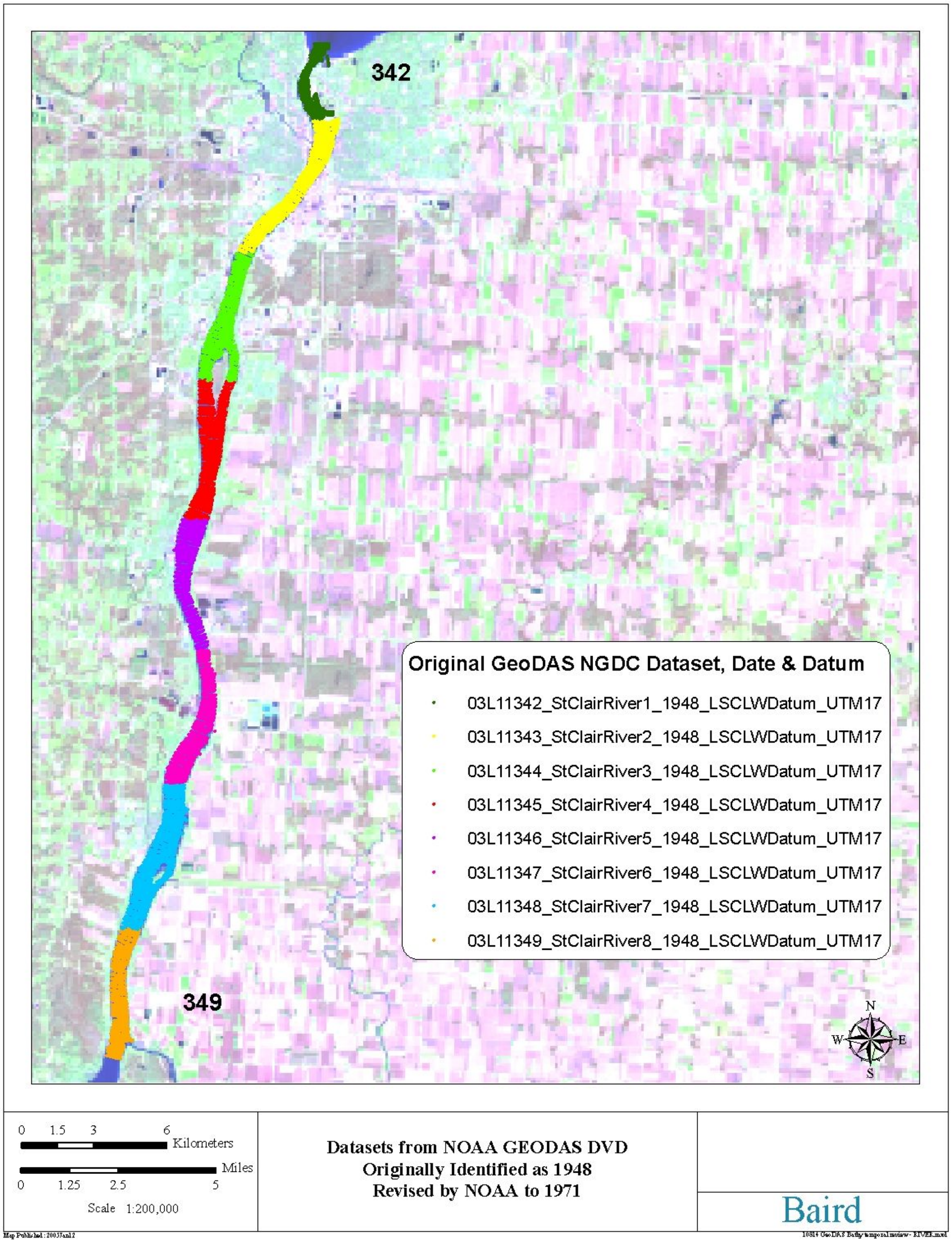

Figure A2 **Bathymetry Data from NOAA GEODAS DVD Revised from 1948 to 1971**

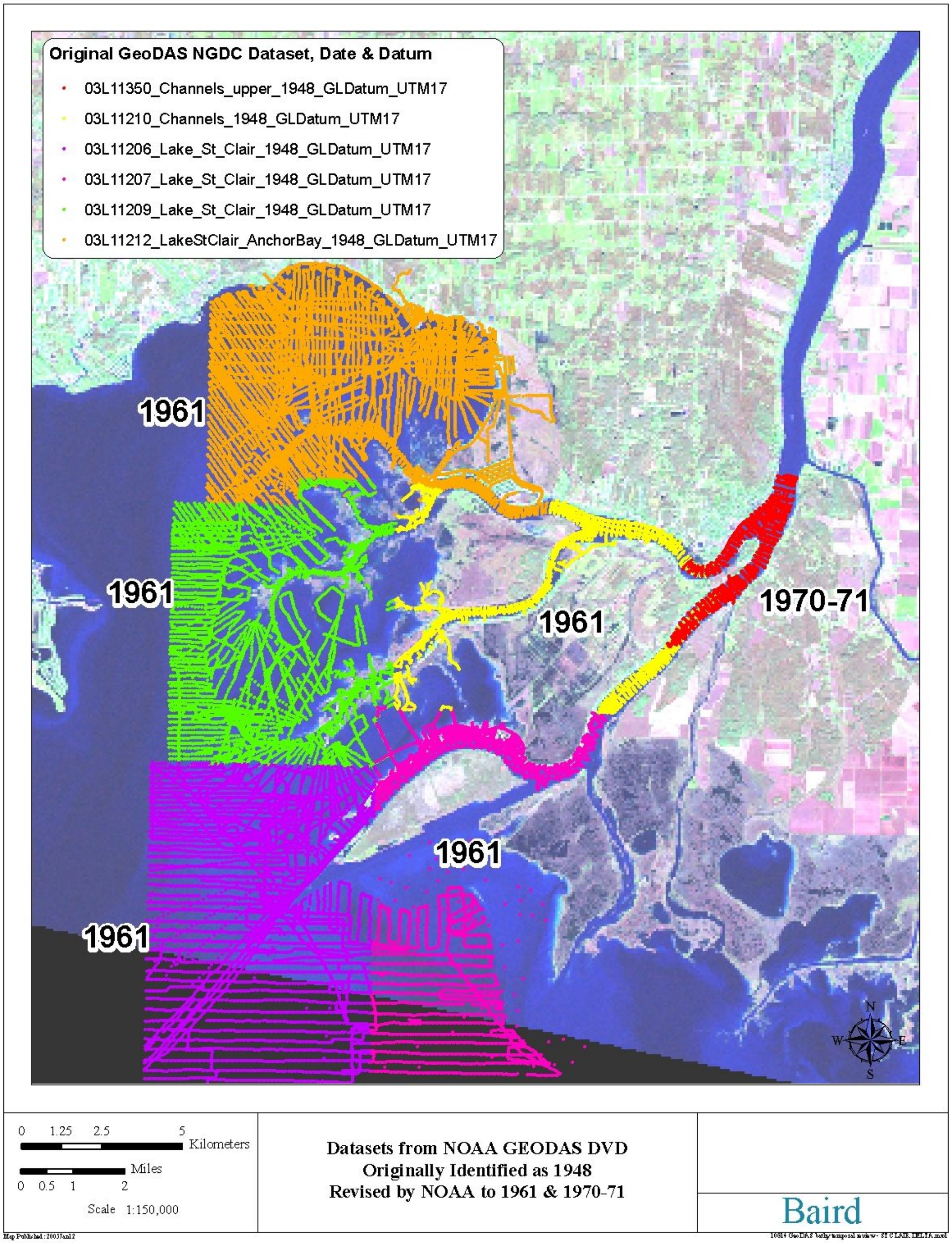

Figure A3 **Bathymetry Data from NOAA GEODAS DVD Revised from 1948 to 1961, 1970-71**

REGIME CHANGE (MAN MADE INTERVENTION) AND ONGOING EROSION IN THE ST. CLAIR RIVER AND IMPACTS ON LAKE MICHIGAN-HURON LAKE LEVELS

ADDENDUM B: CAUSES OF RIVER BED EROSION

Prepared for:

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JANUARY 2005

REGIME CHANGE (MAN MADE INTERVENTION) AND ONGOING EROSION IN THE ST. CLAIR RIVER AND IMPACTS ON LAKE MICHIGAN-HURON LAKE LEVELS

ADDENDUM B: CAUSES OF RIVER BED EROSION

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TABLE OF CONTENTS

1 INTRODUCTION

In 2004, Baird & Associates was retained by the GBA Foundation to complete an investigation into the recorded drop in the difference between lake levels on Lake Michigan-Huron and Lake St. Clair, and possible relationships to historical changes in the St. Clair River. The results of that study are provided in a report titled Regime Change (Man Made Intervention) and ongoing erosion in the St. Clair River and Impacts on Lake Michigan-Huron Lake Levels issued in November 2004. The report was issued prior to completion of all tasks in the scope of work, in the interests of allowing the government agencies to review the report as quickly as possible.

Briefly, the report showed that although the drop in lake level difference between Lake Michigan-Huron and Lake Erie (and Lake Saint Clair) has been well documented by the IJC and others up to and including the effects of the 8.2 m (27 ft.) dredging project completed between 1960 and 1962 (Derecki, 1985; IJC, 1987), the water level data show that there has been an ongoing and significant drop since the 8.2 m (27 ft.) dredging project as shown in Figure 1.1. This decrease in Michigan-Huron water levels is in the range of 20 to 33 cm (8 to 13 in.), and may be closer to 33 cm (13 in.) because the high lake levels over the period from 1970 to 1998 have masked the full extent of the impact. Also, the 1987 IJC estimate of the drop in lake level difference between Michigan-Huron and Erie since 1860 is 36 to 46 cm (14 to 18 in.), compared to the actual observed drop of approximately 80 cm (2.6 ft). Without implementation of compensation measures, this drop represents an irreversible decline in the long-term average lake level of Michigan-Huron. When compared to the range of lake level fluctuations of +/- 1 m (3.3 ft) from a mean level on Michigan-Huron, this drop in lake level is very significant with potentially extensive socio-economic and environmental implications.

It was concluded that the probable cause of the drop in Michigan-Huron was significant erosion (in the order of 2 to 6 m or 6.6 to 19.7 ft) at the outer bend of the river just downstream of the Bluewater Bridge. Numerical modeling showed that this erosion significantly increased the flow capacity of the river.

A method was developed to define the change in water level difference between Lakes Michigan-Huron and Erie attributable only to dredging and river bed erosion by extracting the fluctuating lake level influence (i.e. the impact of fluctuating net basin supply). The method is described in Baird (2004) and a plot showing the normalized water level difference is shown in Figure 1.2. This figure shows that the changes to the difference between the lake levels has generally occurred in a series of stepwise adjustments that can be explained by the major dredging and sand mining operations. The period of erosion since 1970 is well defined in this figure, which suggests that the erosion was triggered by the construction of the 8.2 m (27 ft) navigation channel in 1962 or by other factors sometime after this dredging project. The fact that the drop in the water level difference is continuing in a relatively linear fashion, apparently unabated, and so long after the 1962 dredging project, points to ongoing river bed erosion as the main sustaining mechanism.

Considering that the original erosion or incision of the outlet occurred over a period of almost three thousand years (i.e. between 5,100 and 2,100 years before present – see Larsen, 1994), the recent erosion is unusual and dramatic. Larsen (1994) suggested the erosion of the outlet, and the influence on reducing the Michigan-Huron lake level, ceased 2,100 years before present. Baedke and Thompson (2000) suggest that the Michigan-Huron lake levels stabilized within their current range 3,500 years before present. In any case, the rate of erosion over the last 30 years is unprecedented, even on a geologic time scale.

Possible causes of the onset of river bed erosion were identified as: changes to the hydrodynamic flow conditions (and the natural response of the river bottom contours) in the river due to the 8.2 m (27 ft) dredging project; a reduction in sand supply to the St. Clair River (at the outlet of Lake Huron) resulting from shore protection along the Canadian and US shores leading up to the outlet; and/or changes in the position of the outer channel in Lake Huron that may have changed the efficiency of flow into the St. Clair River. These hypotheses are explored in this Addendum, which completes our required scope of work.

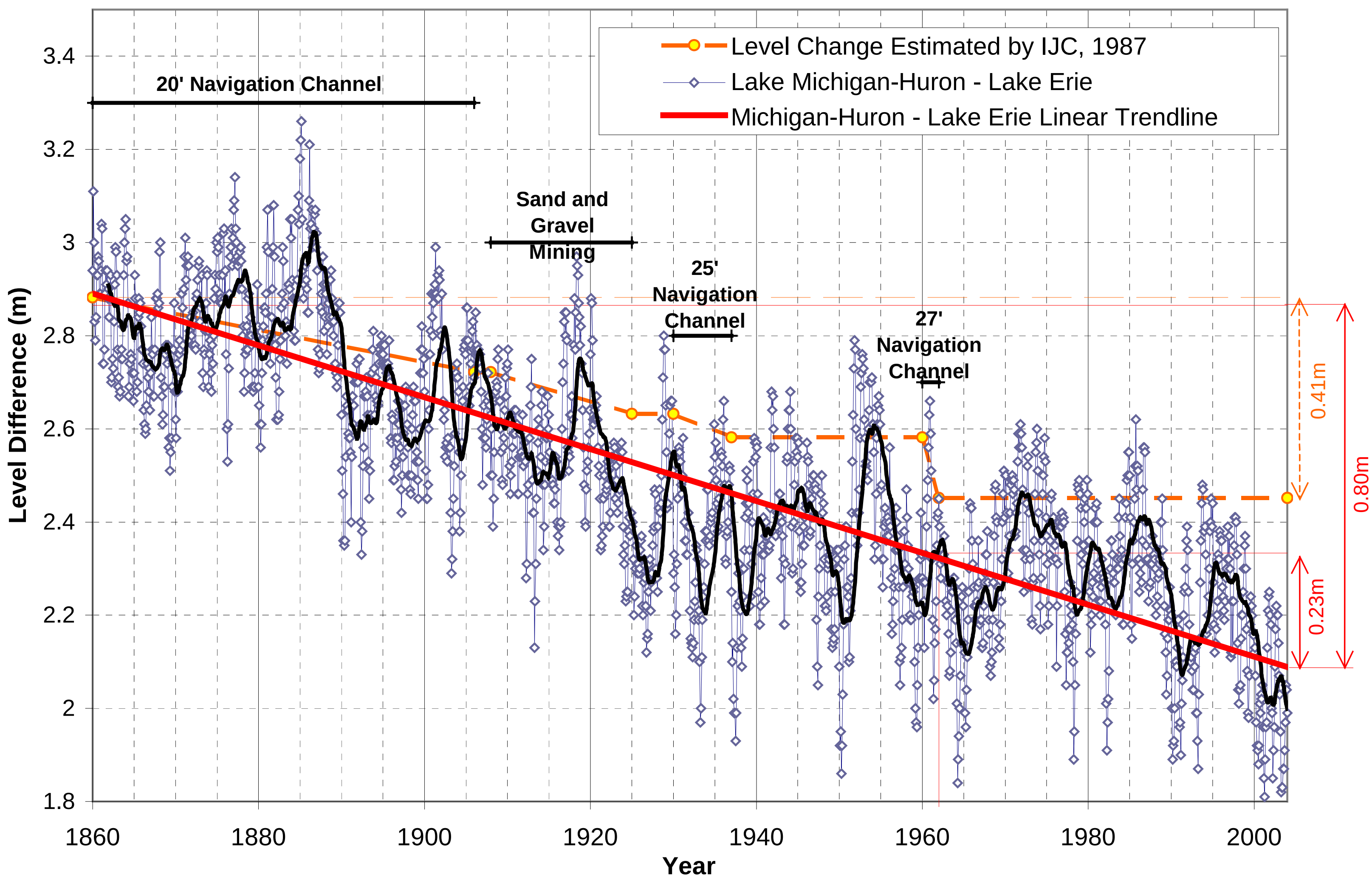

Figure 1.1 Actual Level Difference Change for MH-E vs. Level Change Estimated by IJC

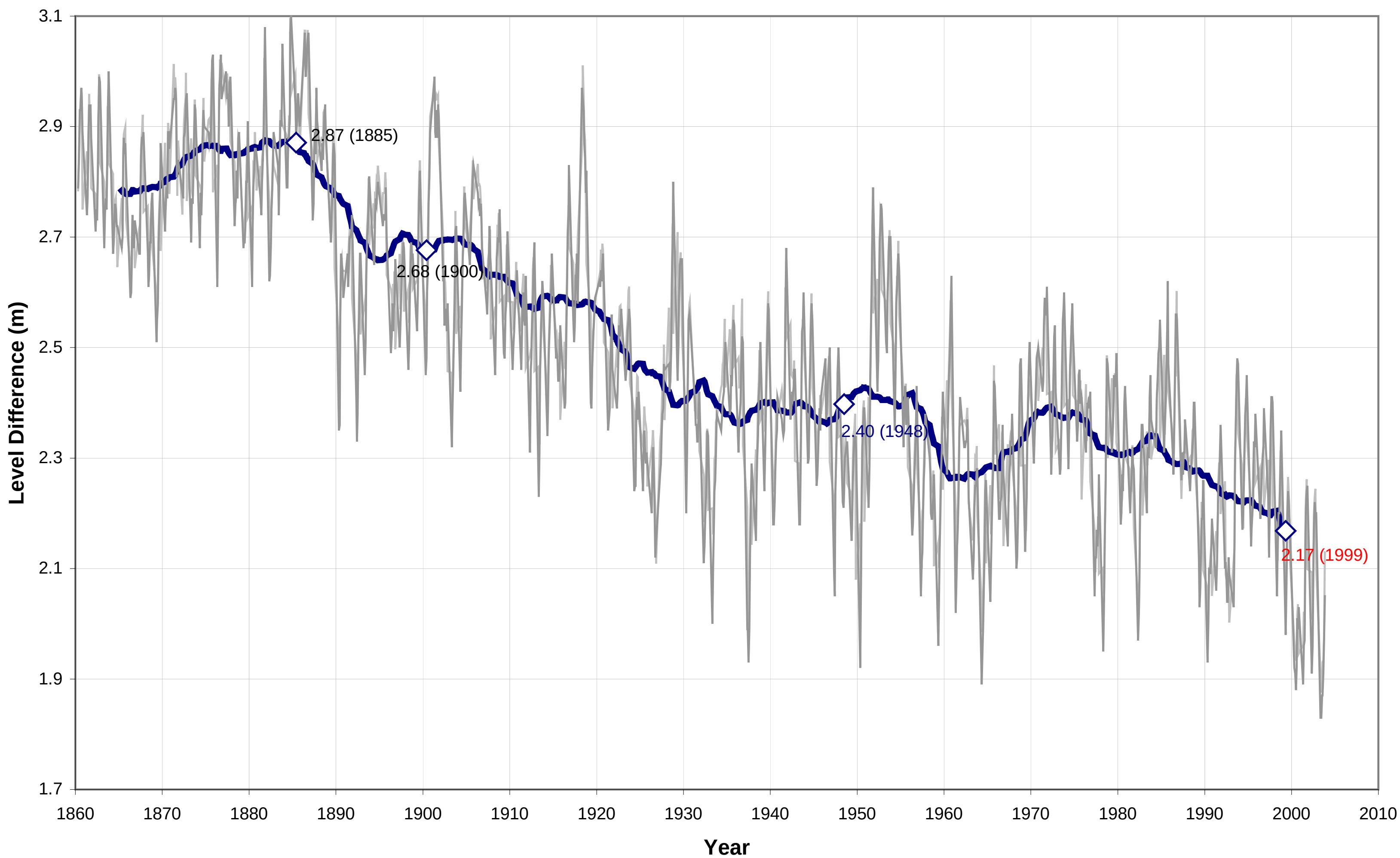

Figure 1.2 Change in Level Difference between Lakes Michigan-Huron and Erie due to Erosion and Man-Made Intervention

(seasonal and weather induced changes removed through normalization)

(annual estimate and ten-year running average are shown)

2 EFFECT OF SHORE PROTECTION ON SAND SUPPLY

Erosion of the riverbed could be in part due to a reduction in sand supply to the St. Clair River (at the outlet of Lake Huron) resulting from updrift shore protection. Shore protection works prevent the natural erosion of the shoreline. When the shoreline no longer erodes, sand that would have previously been transported to the southern end of Lake Huron and the St. Clair River, is no longer available. In addition, groynes and breakwaters trap sand that would have otherwise been transported to the river inlet. The sand supply to the St. Clair River was estimated for different time periods based on a review of air photos.

2.1 Littoral Cell Definition

A littoral cell is defined as a self-contained coastal system, for which there is no transport of sediment into or out of the system. In examining the sediment budget for the study area and the possible impacts of shore protection on the sediment budget, we therefore consider only the littoral cell within which the inlet to the St. Clair River is located. In the case of the St. Clair River, sediment is transported to the site along both the Canadian and U.S. shorelines of Lake Huron (see Figure 2.1). On the Canadian side, the St. Clair river inlet is located at the downdrift limit of a littoral cell that extends from Kettle Point to the St. Clair River. On the U.S. side, the littoral cell possibly extends from Harbor Beach to the inlet to the St. Clair River.

2.2 Shoreline Description and Historical Change in Shore Protection

Shoreline type classification data for the Canadian side were obtained from the Coastal Zone Atlas (Haras and Tsui, 1976). The following historical air photos were used to evaluate the temporal change in shoreline protection:

- Black & white 1954 aerial photos at 1:20,000 scale were acquired from Environment Canada. The photos provided coverage over most of the river except for the North and Middle Channels that are completely within US jurisdiction;
- Black & white 1973 aerial photos at 1:20,000 scale from Ontario Ministry of Natural Resources (OMNR) Ontario Great Lakes Shore Damage Survey Coastal Zone Atlas (published in 1976);
- Black & white 1985 aerial photos at 1:10,000 scale from Environment Canada's airphoto library at the Canadian Centre for Inland Waters;
- Colour infrared 1998 Digital Orthophoto Quad at 1:40,000 scale was acquired from the Michigan Department of Natural Resources. Coverage extended from the St. Clair River to Wees Beach;

- Colour 1998 airphoto previews at approximately 1:10,000 to 1:15,000. Photos were obtained from the Ontario Ministry of Natural Resources;
- Color airphoto mosaic, orthorectified comprised of individual air photos dated 1999-03-28, 1999-04-07 and 2000-04-24 was acquired from the Natural Resources Conservation Service of the US Department of Agriculture. Coverage included St. Clair County, U.S. and the Canadian shoreline; and
- Colour 2003 digital orthophotos at scale 1:20,000 with 30 cm resolution were purchased from First Base Solutions. Coverage extended from the St. Clair River to Cedar Point.

In addition, three Ontario Base Maps covering the shoreline from Wees Beach to Blue Point (scale 1:10,000) were used in the analysis.

2.2.1 Canadian Shoreline

The 26 km of shoreline from Point Edward to Blue Point is predominantly beach or dune complex rising to low plain glacial drift and high bluff glacial drift east of Errol Creek (Haras and Tsui, 1976). From the 1954 air photos it is estimated that less than 2% of the shoreline was protected at that time. Boyd (1981) estimated that 85% of the shoreline between Sarnia and Blue Point was protected in 1973. Haras and Tsui (1976) reported that between Sarnia and Brights Grove the shoreline was almost entirely protected by groyne fields and seawalls. The groynes are generally 30 m long and spaced 60 to 90 m apart. Figure 2.2 shows typical groynes at Bonnie Doon Creek. From the 1998 air photos, it is estimated that 95% of this shoreline is now protected.

The 20 km shoreline segment between Blue Point and Kettle Point changes from low and high bluff glacial till with five sand or dune complex areas west of Cedar Point to bedrock with intermittent marshy areas east of Cedar Point. Erosion of the glacial till bluffs provides sand for the sediment budget. Protection of the bluffs reduces the sand supply (see Section 2.3). In 1954, the shoreline was completely unprotected. Boyd (1981) estimated that 25% of the shoreline between Blue Point and Kettle Point was protected in 1973. From the 1998 air photos it is estimated that 35% of this shoreline is now protected. Most of the shore protection between Blue and Kettle Point is located between Blue Point and Cedar Point. Only a few harbors and seawalls are present east of Cedar Point.

The shoreline immediately east of the inlet to the St. Clair River has changed significantly over the years. The 1867 chart (shown in Baird, 2004) shows a natural shoreline with sand bars extending across much of the river. Figure 2.3 compares air photos at this location in 1955, 1973 and 2003. There appears to have been significant accretion updrift (west of the west breakwater) between 1955 and 2003. Water levels on the dates of the air photos were as follows:

- June to August 1955 average w.l. +0.86m CD
- May 1973 w.l. +1.2m CD
- June to August 2003 average w.l. +0.02m CD

There was a difference of over 1 m between the water level on the dates of the air photos with the highest water levels occurring during the 1973 air photo and the lowest levels occurring during the period in which the 2003 air photo was taken. The lower water levels in 2003 would cause the beach to appear wider. However, the beach does appear to have accreted significantly, even if water levels are taken into consideration.

2.2.2 U.S. Shoreline

A review of historical air photos for the U.S. side was beyond the scope of this study due to budget constraints. The 1998 colour infrared Digital Orthophoto Quads from the Michigan Department of Natural Resources were therefore used to evaluate the percentage of the shoreline that is currently protected. For the purposes of the sediment budget overview (Section 2.3), it was assumed that shore protection development occurred in similar time periods as on the Canadian side.

Air photos for the 30 km shoreline from Port Huron to Lexington were reviewed. The shoreline features a beach that varies in width from and estimated 10 to 60 m over its entirety. Much of the shoreline is protected by groynes: there are approximately 250 to 300 structures between Port Huron and Lexington. The groynes are typically 30 m in length with spacing varying from 20 to 200 m. These structures provide protection to an estimated 75% of the 30 km shoreline immediately updrift (north) of the St. Clair River.

2.3 Sediment Budget Overview

Sand is transported in a southerly direction from Kettle Point toward the St. Clair River on the Canadian side, and possibly from as far north as Harbor Beach to Port Huron on the U.S. side.

On the Canadian side, Philpott (1982) estimated the net potential littoral drift for the shoreline west of Brights Grove to be 50,000 m^3 per year in a westerly direction. The actual transport would be supply limited, and therefore less than the potential rate. The potential drift bypassing the groynes at Brights Grove was estimated at 12,500 m^3 per year.

Boyd (1981) estimated that erosion of the bluff shoreline between Kettle Point and Sarnia would result in 250,000 m^3 per year of sediment entering the lake. Of this, he estimated that 10,000 m^3 per year is sand sized and results in beach formation. The remainder is fine silts and clays which does not form beach or riverbed deposits. Boyd's estimate does not include input for those shorelines that were protected in 1981. This figure is in close agreement with Philpott's estimate.

A comprehensive sediment budget requires detailed analysis of shoreline data, bluff heights and bluff composition, and is beyond the scope of this work. However a rough estimate of the volume of sand that would have entered the littoral zone and made its way to the Michigan-Huron outlet, on an annual basis, prior to protection of the shoreline, may be developed from Boyd's work.

Based on the air photo review, none of the bluff shoreline between Errol Creek and Cedar Point was protected in 1954, 5% was protected in 1973, and 95% was protected in 1998. The bluff shoreline is the main contributor to the sediment budget as the shoreline north of Cedar Creek is bedrock and the shoreline south of Errol is stable beach. Beach shorelines do not provide a supply of sediment to the sediment budget; rather sediment is transported along the beach, through the littoral cell). If the sand supply was an estimated 10,000 m^3 per year in 1973 (with 5% protected), based on Boyd (1981), sand supply in 1954 would have been 10,500 m^3 per year and supply in 1998 would have been 500 m^3 per year. This does not consider sand supplied by fluvial transport and offshore sources. However it does suggest that between 1973 and 1998 the sand supply was significantly reduced.

In addition to a reduction in supply, sand that is supplied can be permanently trapped by structures such as breakwaters and groynes. The shoreline from Point Edward to Blue Point is almost entirely protected by groynes. Immediately east of the St. Clair River inlet, there is a marina with a shore perpendicular breakwater trapping sediment as shown in Figure 2.3. Detailed numerical modeling would be required to determine whether or not sediment is bypassing the marina breakwater.

We were not able to source sediment budget information for the U.S. side. As described in Section 2.2.2, much of the shoreline north of the St. Clair River is currently protected. There is a small breakwater immediately north of the river inlet at the U.S. Coast Guard Station in Port Huron, however it is significantly smaller than the breakwater at the marina entrance on the Canadian side and bypassing is more likely to occur.

2.4 Summary of Sediment Budget Implications for the St. Clair River

The sand supply to the St. Clair River from the Canadian shoreline was estimated at 10,500 m^3 per year prior to the construction of shore protection works. Before development of the marina breakwater on the west side of the river inlet, this material would have all been transported into the river. The breakwater is visible in the 1954 air photo, however the precise construction date was not available. Between 1973 and 1998, the eroding bluff shoreline that supplies the sand to the system was largely protected, virtually eliminating the sand supply. The amount of sand that would have reached the St. Clair River from the Canadian side between 1954 and 2004 is 525,000 m^3. If it is assumed that roughly the same volume of material would have come from the U.S. side, the volume of sand that did not reach the river would be approximately 1 million m^3. In fact, roughly 3 times this amount may come from the U.S. side considering the length of shoreline in the assumed littoral cell. This volume is significant in itself.

To put these volumes into context, it is estimated that between 1908 and 1925, approximately 2.7 million m^3 of sand and gravel were removed from the river bed by commercial interests. Most of the material was removed from the river bed north of Dry Dock. Between 1841 and 1993, 11.1 million m^3 material was dredged from the river head and 1.6 million m^3 was dredged from Port Huron. The total volume of material removed from the upper reaches of the river alone, between 1841 and 1993 was therefore 15.4 million m^3. The sand supply rate to the river from the Canadian side was estimated at 10,500 m^3 per year. If it is assumed that three times this amount was transported to the site along the U.S. side, it would take 367 years to replace the sediment that was removed from the river mouth.

Figure 2.1 Littoral Cell Definition for Study Area

Figure 2.2 Groynes Fields between Sarnia and Blue Point

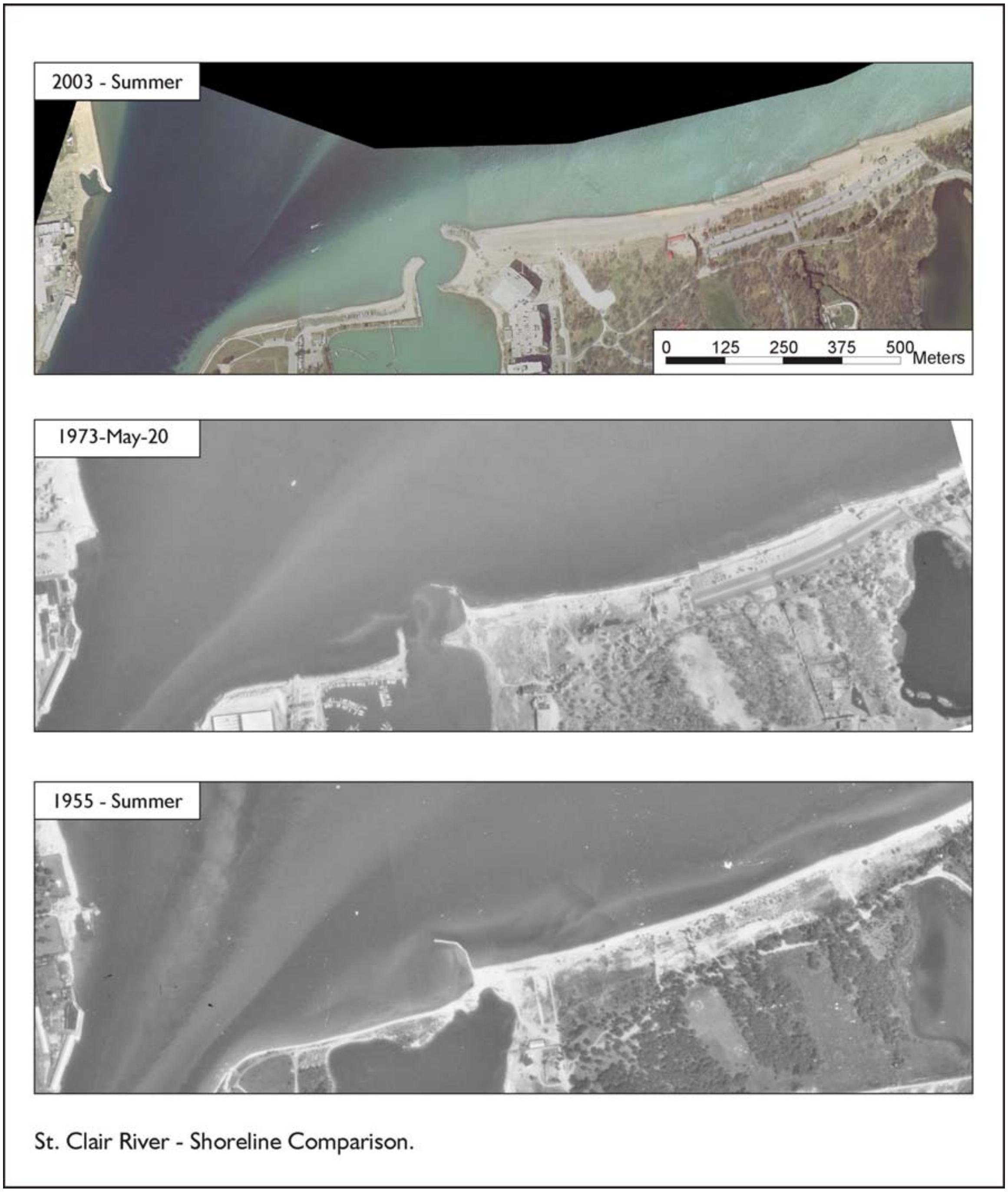

Figure 2.3 Historical Shoreline Change and Beach Development at Inlet to St. Clair River

3 CHANGES TO CHANNEL GEOMETRY

3.1 Background

A comparison of the bathymetry at the St. Clair River inlet was undertaken for four different time periods: 1867, 1929, 1971 and 2000. The purpose of this comparison was to investigate the possibility of increased flow capacity at the mouth of the river due to changes in the approach channel. In particular, the bathymetry comparison in Baird (2004) suggested sedimentation on the east side of the inlet to the St. Clair River between 1971 and 2000. There is a natural channel on the east side of the river, however the navigation channel is located on the west side of the river. A change in the distribution of flow through the natural and approach channels could potentially result in increased flow efficiency in the river. The higher flow rates and resulting higher velocities could cause erosion of the riverbed. Some profile comparisons are also undertaken in Baird (2004) including profiles in the areas where erosion rates were highest.

3.2 Data

Historical bathymetry data at the inlet to the St. Clair River is shown in Figures 3.1 to 3.4 for 1867, 1929, 1971 and 2000. The sources for the data are described in Baird (2004), however based on information provided by NOAA after the report was issued, the data in the NOAA GEODAS database identified as 1948 data, are actually a compilation of data from 1952 to 1971 (see Correction Note at beginning of this report). The data at the inlet to the St. Clair River, shown in Figure 3.3 are from 1971.

All data are referenced to the sloping surface of the river corresponding to a Lower Water Datum (LWD) for Lake Huron (176.0 m) and for Lake St. Clair (174.4 m) above IGLD 1985, with the exception of the 1867 data. No datum was provided on that chart and the data have therefore not been corrected.

3.3 Analysis and Results

Comparison of Figures 3.1 to 3.4 shows that there were sand bars at the mouth of the river in 1867 and these are not present in the later surveys (1929, 1971 and 2000). Figure 3.1 shows the sand bars extending from both Canadian and U.S. sides on the river inlet. The natural channel on the east side of the inlet is clearly visible in all of the surveys and there does not appear to be significant change in the natural channel depths between 1929 and 2000. There is some deepening on the west side of the channel (shown in Figures 3.3 and 3.4). It is not clear if this section of the river was dredged as a navigation channel is not marked on the charts for this section of the river. Depths in the natural channel exceed navigation requirements and dredging may not have been undertaken in this section of the river. This would be expected as the channel was dredged and deepened in (1930 to 1937) and (1960 to 1962).

Three profiles at the inlet to the St. Clair River were selected for a more detailed assessment of bathymetry change. Profiles A, B and C (shown in Figure 3.5), were located on transect lines from the NOAA 2000 survey. The 2000 survey included high density data along transects spaced at 100 m spacing and the irregular sampling density made the data difficult to interpolate to create a representative surface. The analysis compared the bathymetry points from the detailed 2000 survey transects with profiles developed from the interpolated surfaces for the 1867, 1929 and 1971.

The actual 2000-bathymetry data were used in the profile comparison, i.e. interpolation of data was not necessary due to the high density of the sampling points. To derive profiles for comparison from the other three time periods, surfaces were generated from the randomly dispersed survey points. A Triangulated Irregular Network (TIN) was used to generate a continuous surface for the 1867, 1929 and 1971 data. The TIN surfaces were then converted to continuous grids to support sampling of points at equal horizontal intervals of 10m. The TIN was selected over other data interpolation methods (such as a spline fit) because of the highly irregular nature of the original survey points and the high variability of the lake and riverbed surface.

Figures 3.6 to 3.8 show the 1867, 1929, 1971 and 2000 data at Profiles A, B and C. The original survey points and the interpolated values have been plotted, as well as a selection of measured individual survey points from the 1867, 1929 & 1971 surveys where points were close to the profile line.

At the outer Profile A (Figure 3.6) there was significant change in the bottom profile between 1867 and 1929. The riverbed on the east side of the river eroded up to 10 m. There was, however less change on the west side of the river between 1929 and 2000, although there is a continuous deepening trend over time, most of which occurred between 1929 and 1971. It is not clear whether this section of the river was dredged for the navigation channel as the channel is not shown on the USACE Federal Project chart (1986-644-214), for this section of the river. Although the increase in depths between 1867, 1929 and 1971 may have been due to dredging projects: 1855 to 1906 (6.1 m), 1930 to 1937 (7.6 m) and 1960 to 1962 (8.2 m), erosion after 1971 cannot be explained by dredging.

At Profile B, the most significant change occurred at the east side of the river between 1867 and 1929. This is in the vicinity of the marina development and the riverbed may have been altered during development of the marina. There is continuous deepening on the west side of the river, even after the last dredging project in 1962, as evidenced by the increase in depths of 0.5 to 1.0 m between 1971 and 2000.

At the inner Profile C, the most significant change occurred between 1867 and 1929, consisting of a shifting of the channel to the west. There was 1.0 to 2.0 m erosion between 1971 and 2000 on the east and west sides of the river and little change through the middle of the river.

There is a continuous erosion trend on the west side of the river. Although depths on this side are not as great as those in the channel to the east, increased depths on the west side of the river could result in more efficient flow (i.e. higher flows for the same lake level difference). Further investigations including numerical modeling could be used to examine in detail, flow through the approach channel at the river inlet. It is our understanding that the USACE is collecting detailed bathymetry data at this location in 2004/2005.

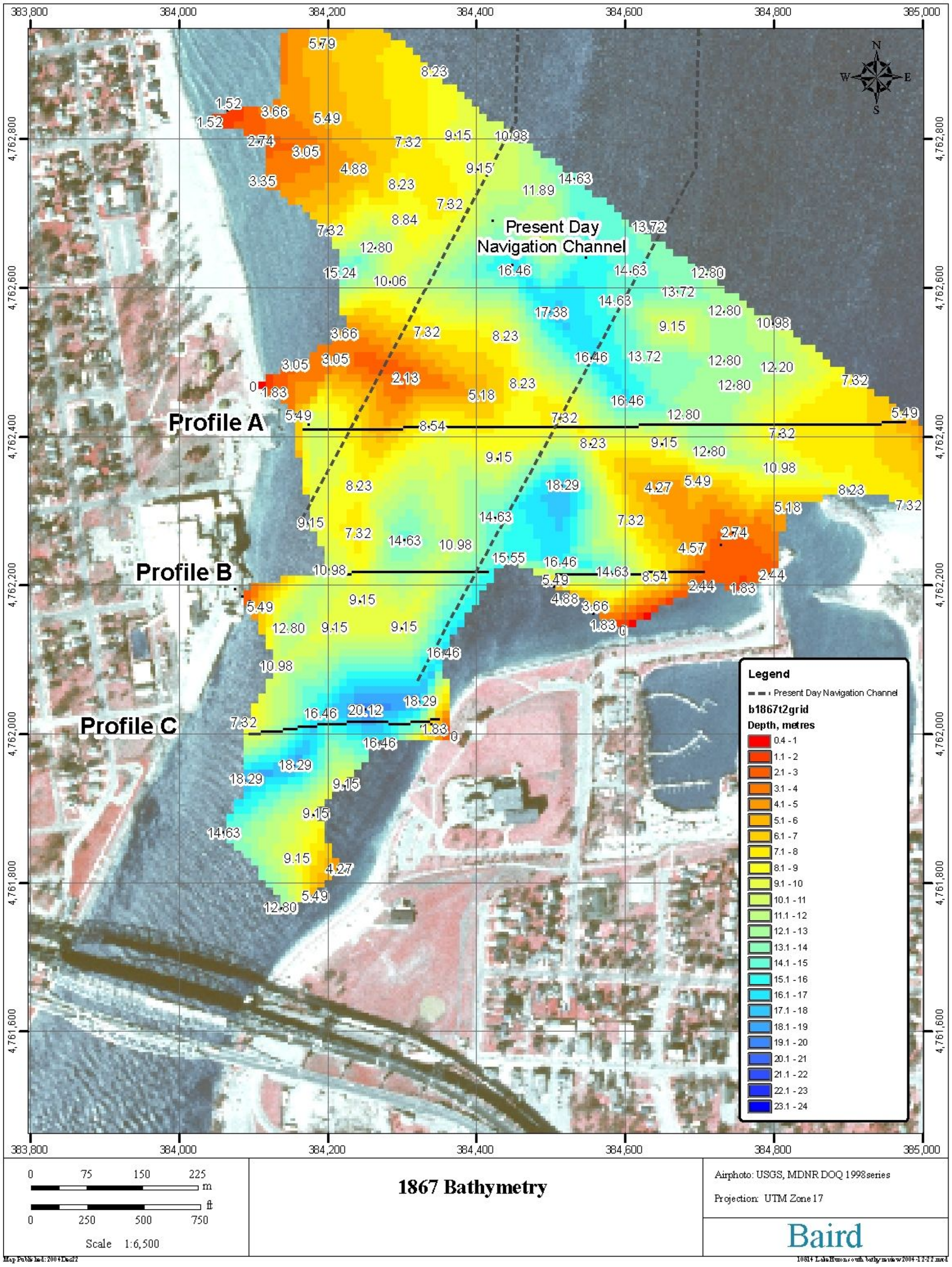

Figure 3.1 Bathymetry at St. Clair River Inlet in 1867

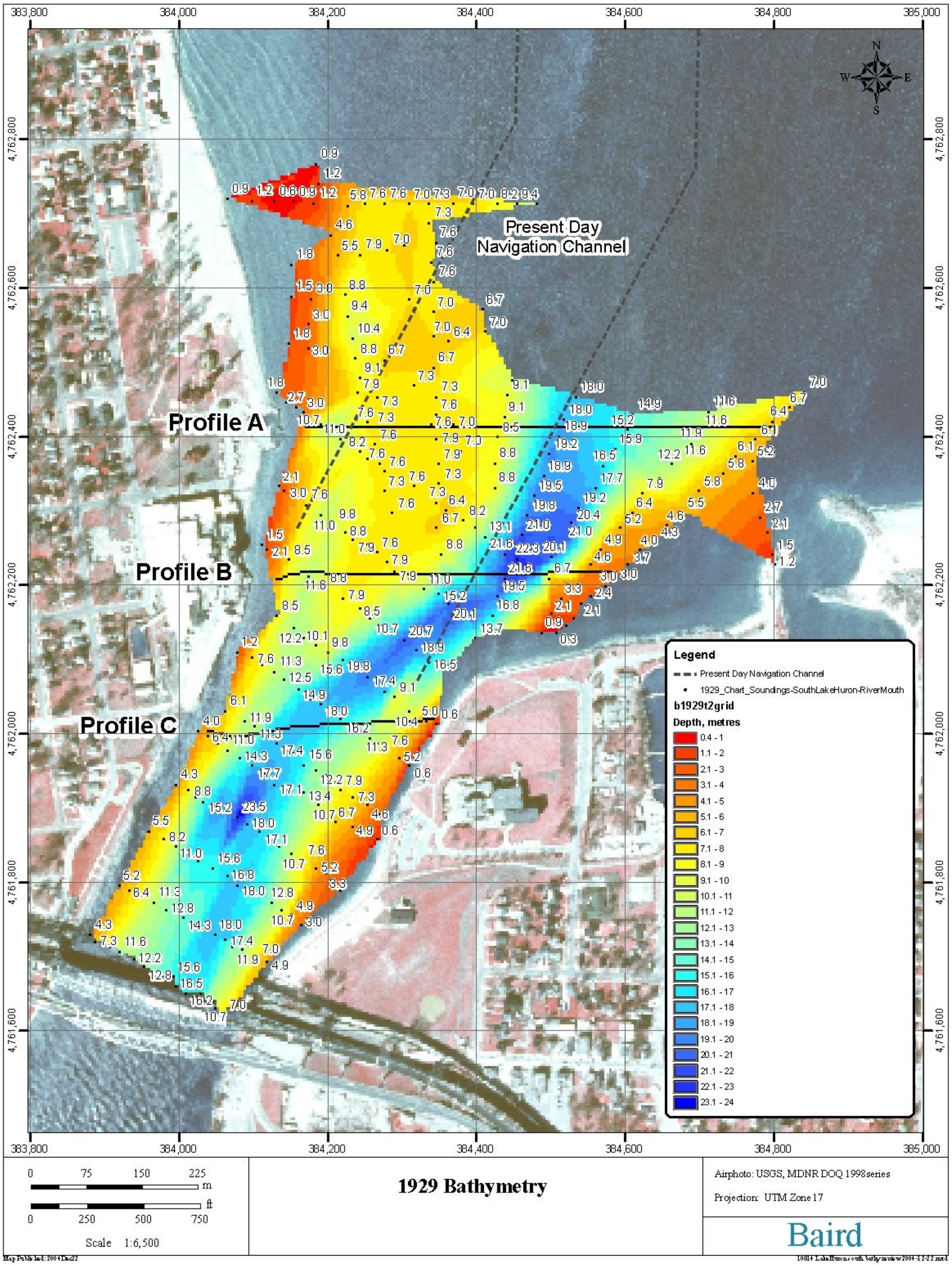

Figure 3.2 Bathymetry at St. Clair River Inlet in 1929

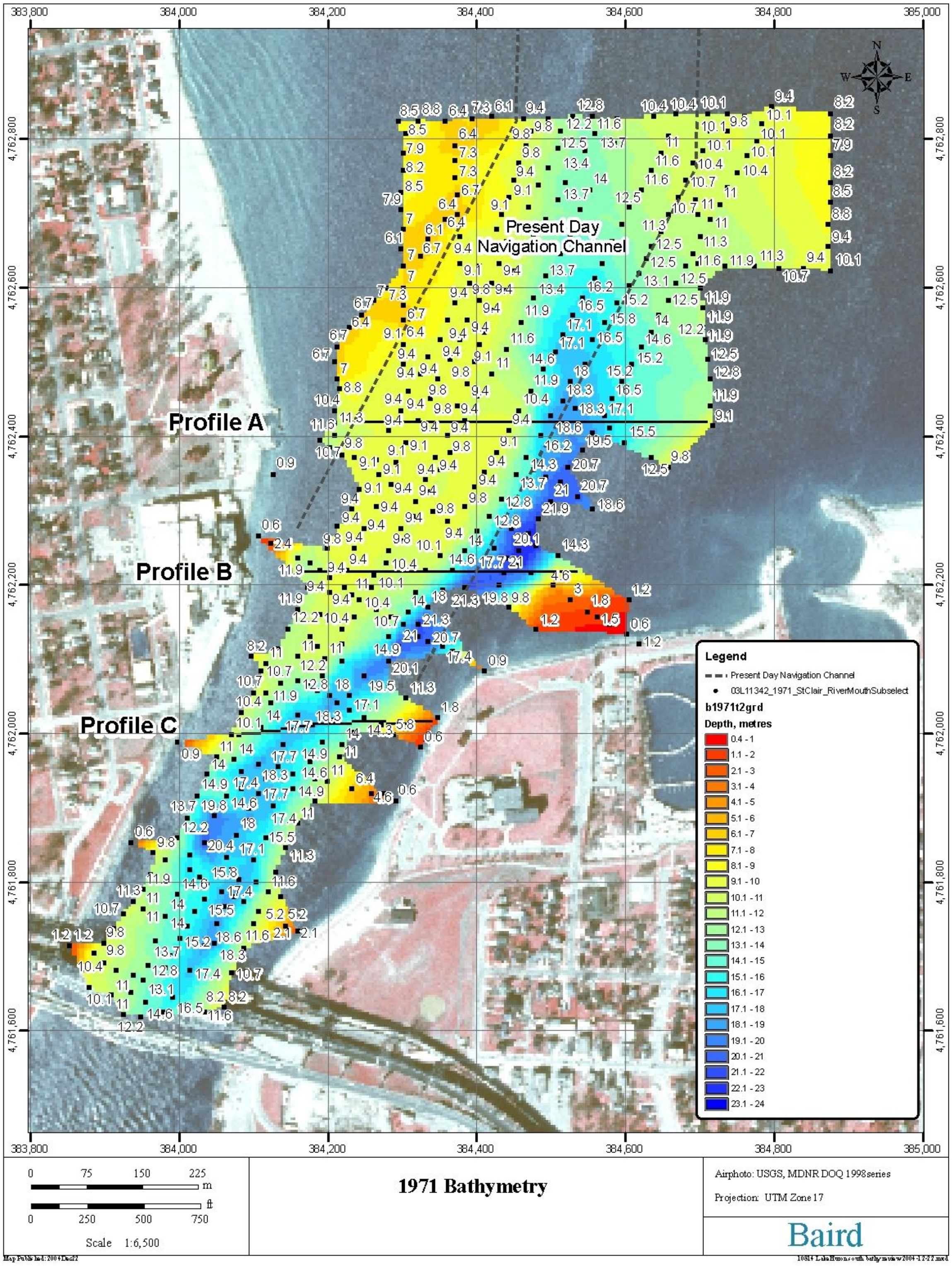

Figure 3.3 Bathymetry at St. Clair River Inlet in 1971

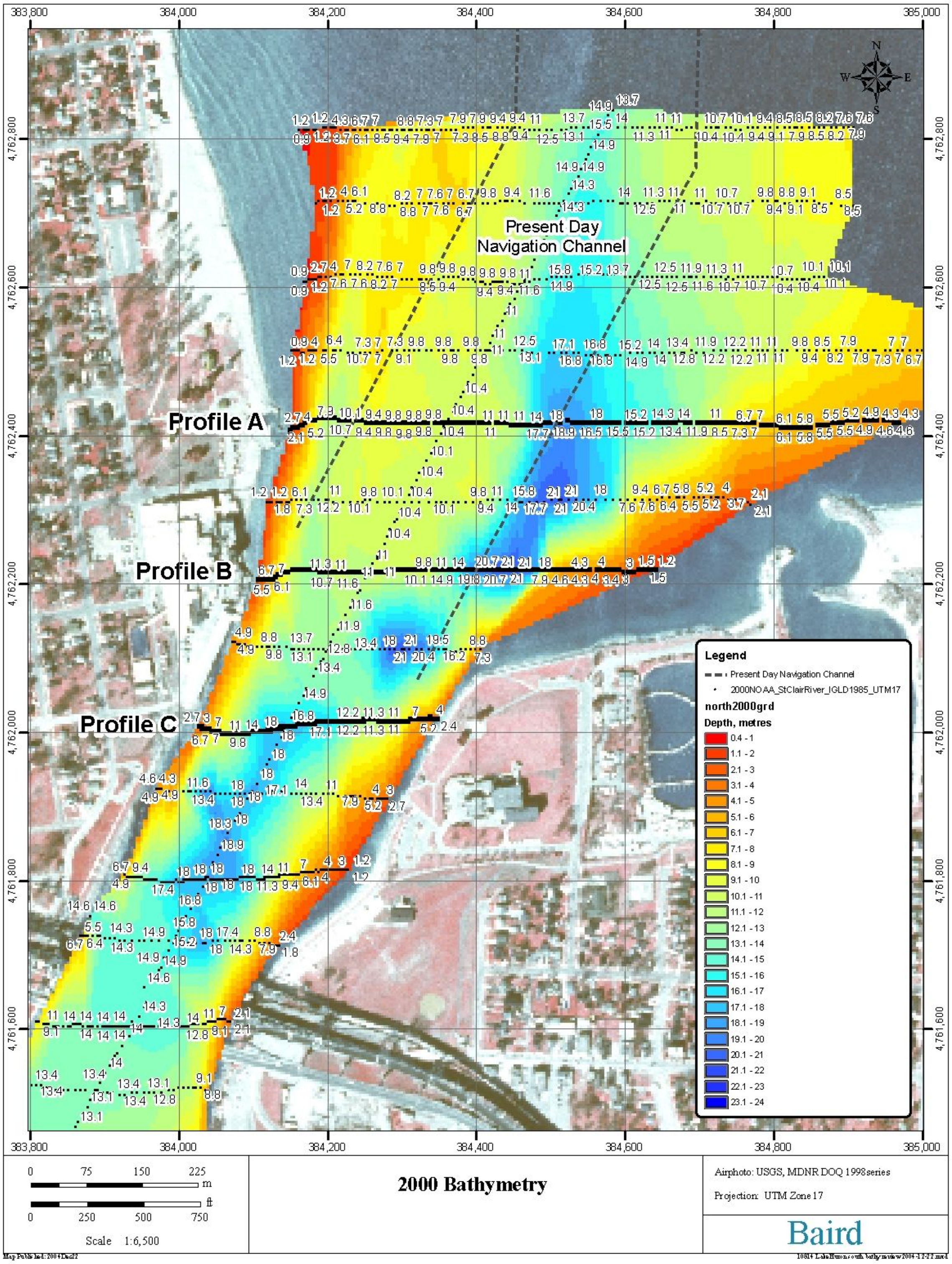

Figure 3.4 Bathymetry at St. Clair River Inlet in 2000

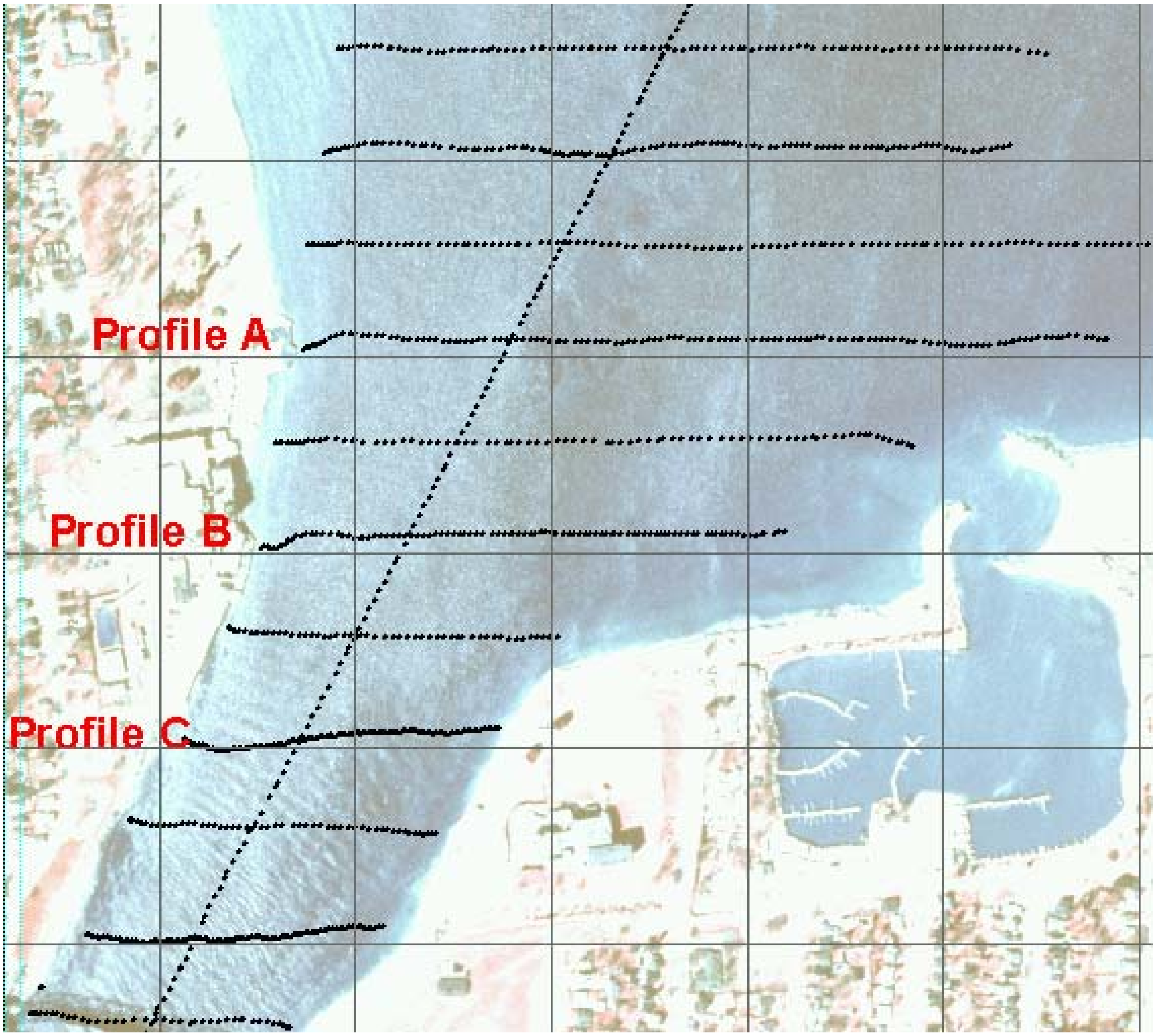

Figure 3.5 Profiles Selected for Bathymetry Comparison

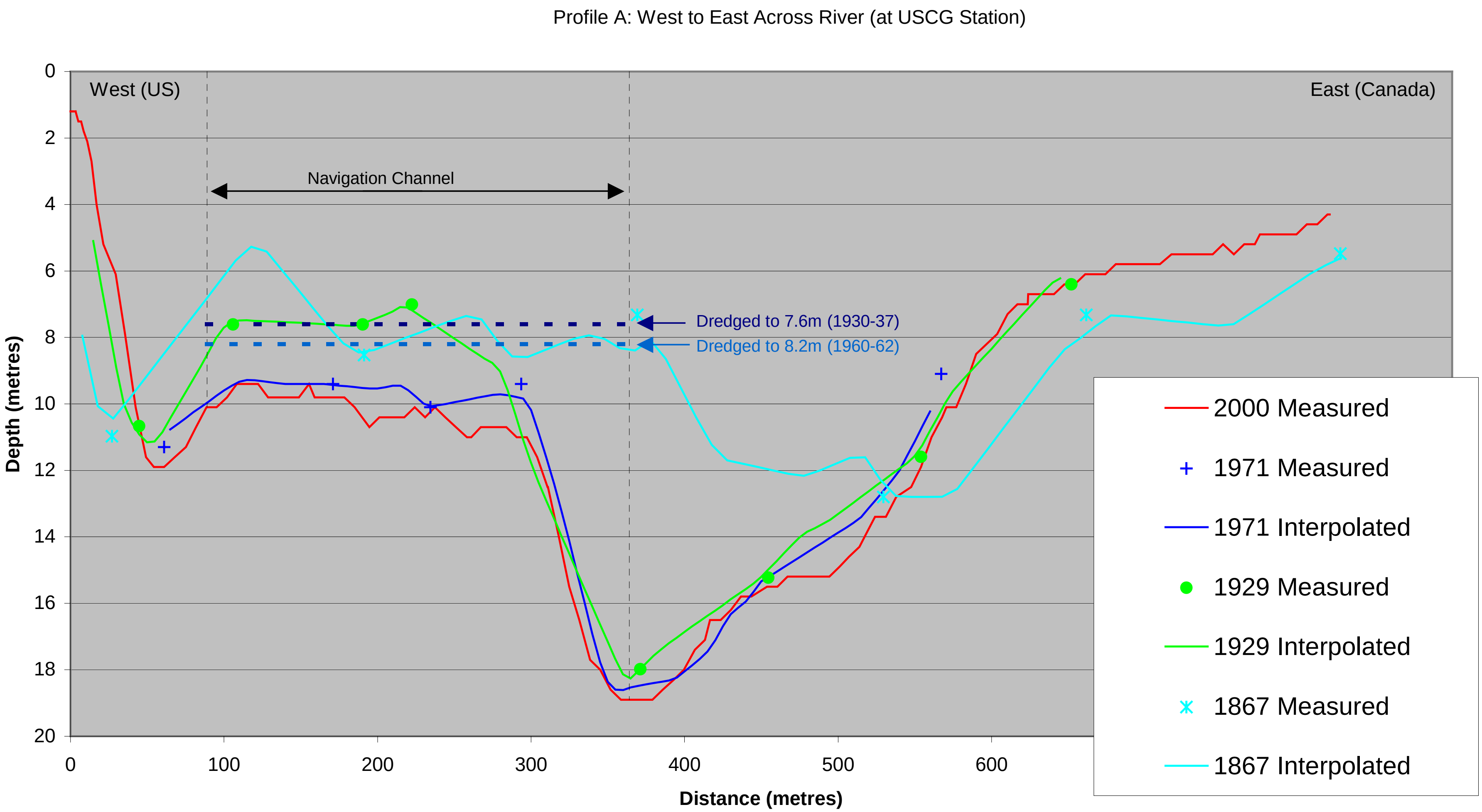

Figure 3.6 Profile A Bathymetry Comparison 1867, 1929, 1971 and 2000

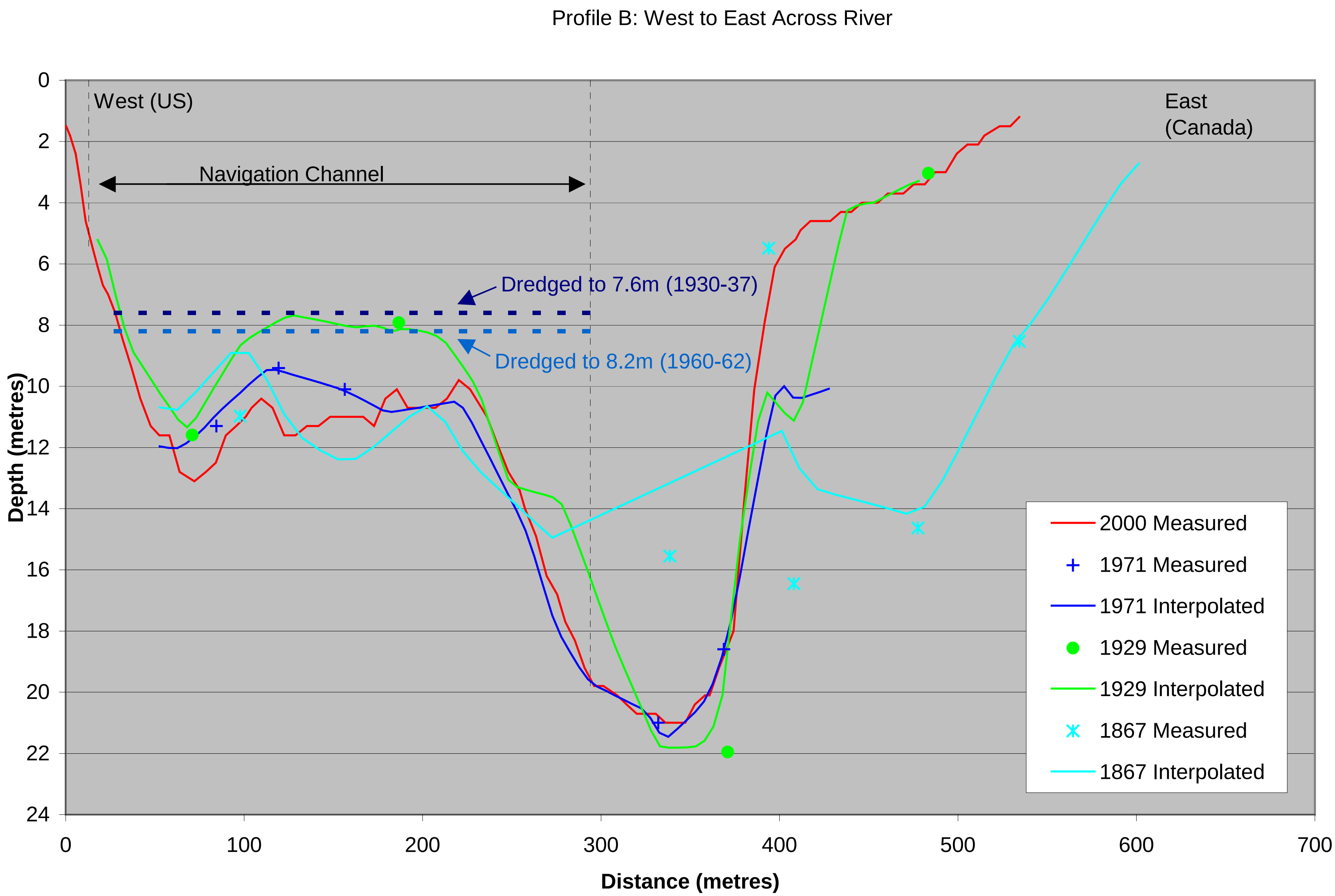

Figure 3.7 Profile B Bathymetry Comparison 1867, 1929, 1971 and 2000

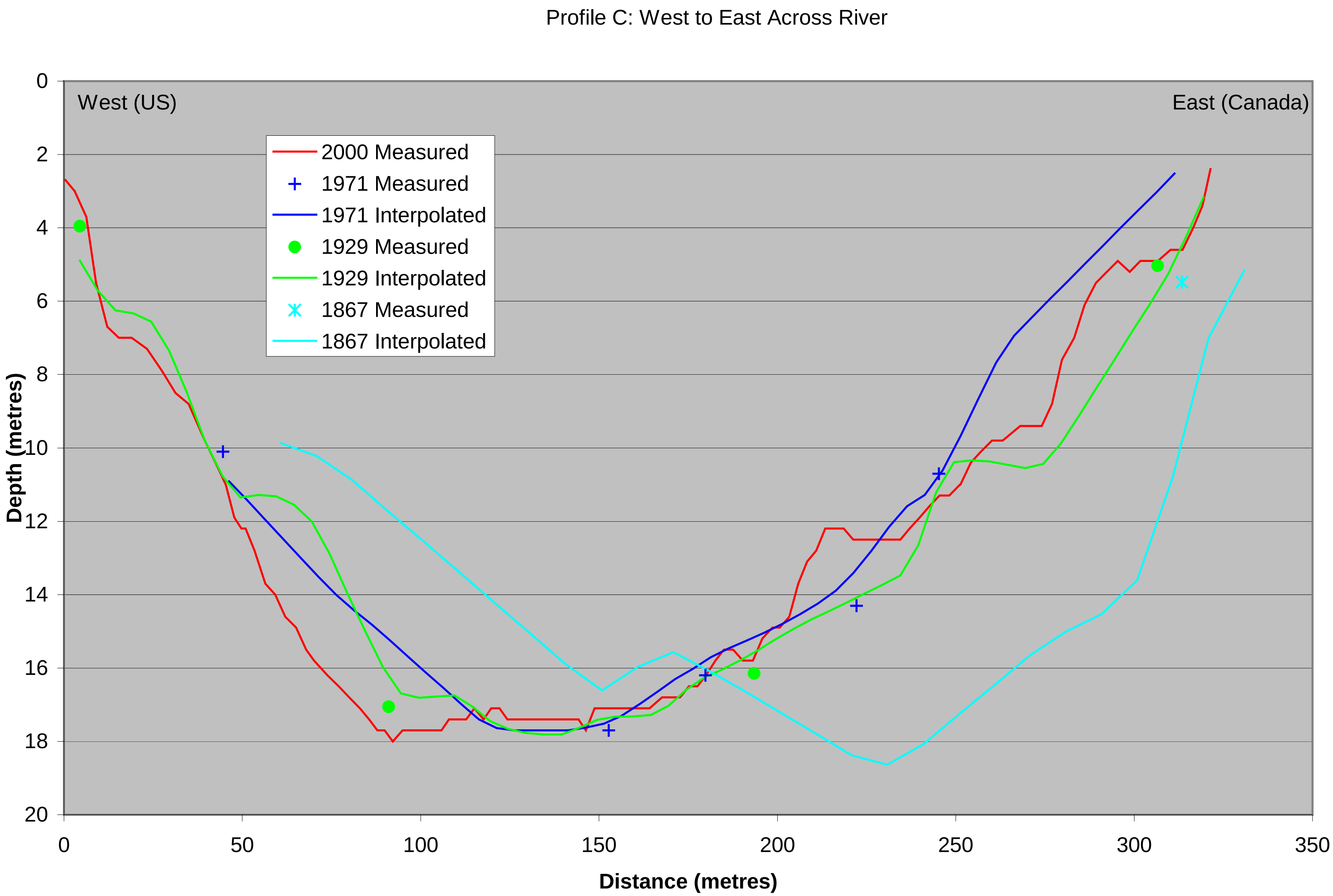

Figure 3.8 Profile C Bathymetry Comparison 1867, 1929, 1971 and 2000

4 EXPOSURE OF ERODIBLE TILL

In order to better understand the process of riverbed erosion, the riverbed material (non-cohesive or cohesive) must be known. For non-cohesive materials such as sands and gravels, erosion is a reversible process. The bottom profile is dependent on the supply of sands and gravels from upstream. If the rate of supply equals the rate at which material is transported downstream, the riverbed level will remain constant over time. If the rate of supply is less than the sediment transport rate, the riverbed will erode and if the rate of supply exceeds the transport rate, there will be deposition and depths will decrease.

For cohesive materials, erosion is an irreversible process because once eroded, the fine cohesive materials are immediately transported downstream by the current. Erosion is not dependent upon the balance of sediment supply and is triggered when the cohesive material is exposed and flow velocities exceed a critical value.

The locations of borehole data collected by the USACE from 1958-1960 are shown in Figure 4.1 (only the north section of the river is shown). Additional data and discussion are provided in Baird, 2004. Areas of erosion and deposition based on the comparison of the 1961/71 and 2000 bathymetry data sets are also shown.

Borehole C25-1 is located at the inlet of the river on Lake Huron. The borehole data indicates that the top 1.4 m of material is soft loose medium sand, which is probably new deposition supplied by longshore sediment transport from Lake Huron. Under the soft sand is dense, medium sand and gravel.

Boreholes C25-2, C25-3 and C25-4 are the nearest boreholes to the section of the river where the highest erosion rates occurred between 1961 and 2000 (up to 6m on the west side of the channel). Unfortunately, no borehole data was collected in the area of highest erosion on the west side of the river, south of the Blue Water Bridge (see Figure 4.1).

Borehole C25-2 is closest to the area of high erosion, however it is located to the east of the eroded section and the geology may differ (see Figure 4.1). A water depth of approximately 11 m is indicated at Borehole C25-2 in the drilling log and the borehole was drilled to 21 m below water level (175.6 m IGLD). The 2000 survey showed depths of 18 m (7 m erosion since the borehole was drilled in 1958-60). The borehole log indicates that river bed material is about 2 m of very soft medium sand to fine gravel over very dense medium sand to fine gravel. The very dense sand and fine gravel extend to the bottom of the borehole.

Boreholes C25-3 and C25-4 are located on the riverbank. Borehole C25-3 is approximately 2 m of fill and broken concrete over medium silty clay with a trace of sand/gravel. The silty clay extends to approximately 156.0 m IGLD ’55 (approx. 19.6 m below water level). This is underlaid by approximately 2 m of stiff clay and then shale bedrock.

Borehole C25-4 is approximately 3 m of asphalt fill over 4 m of sand. At elevation 171.0 m IGLD ’55, the borehole indicates clay, extending to 147.8 m IGLD ’55 (30 m depth).

The review of borehole data suggests that the bottom material in the erodible section of the river could be exposed clay and possibly would have been (before erosion). The clay may have become exposed as a result of aggregate mining or dredging operations. It may also have been exposed due to a decrease in the sand supply which once protected the underlying erodible clay. Additional borehole data would be required to confirm the bottom material. Borehole data and glacial geomorphic interpretation could be used to develop a 3-dimensional description of the river bed geology.

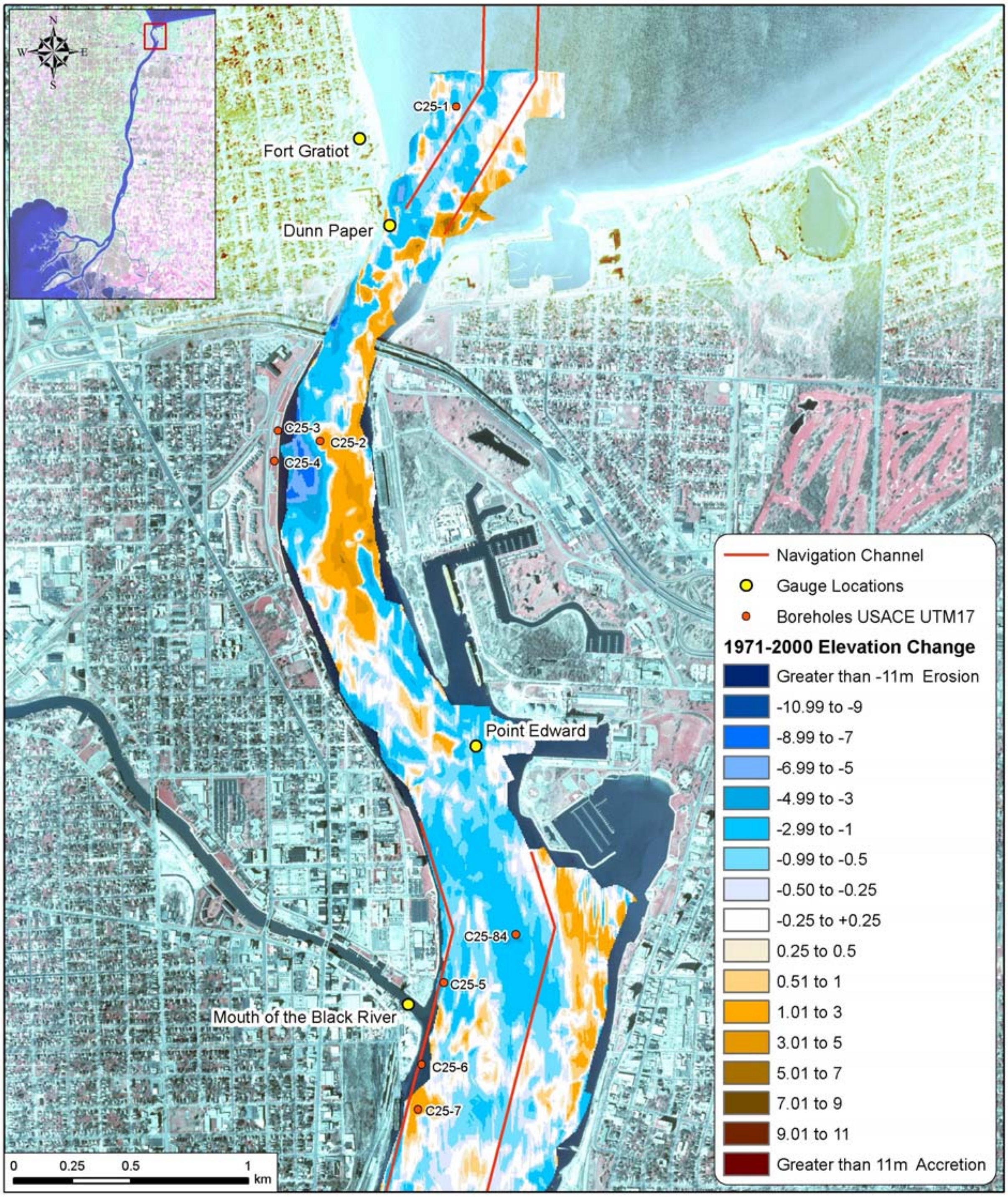

Figure 4.1 USACE Borehole Data and Erosion/Deposition Areas

5 CONCLUSIONS AND RECOMMENDATIONS

Water levels on Lake Michigan-Huron have dropped by an estimated 80 cm since 1860. 36 to 46 cm of this drop is attributed to dredging projects that increased the efficiency of the river. However, water levels have continued to drop since the completion of the last dredging project in 1962.

The continuing decrease in water on Lake Michigan-Huron is attributed to erosion of the riverbed, which has resulted increased flow efficiency (Baird, 2004). A comparison of bathymetry data from 1971 and 2000 shows erosion of the riverbed, particularly in the critical section of the river, downstream from the Blue Water Bridge where erosion of 2 to 6 m has occurred. However, Larsen (1994) suggested the erosion of the outlet, and the influence on reducing the Michigan-Huron lake level, ceased 2,100 years before present. Baedke and Thompson (2000) suggest that the Michigan-Huron lake levels stabilized within their current range 3,500 years before present. The rate of erosion over the last 30 years is therefore unprecedented, even on a geologic time scale.

This addendum has investigated possible events that may have triggered the recent erosion of the riverbed. It has been shown that there are a number of factors that could have triggered erosion of the riverbed.

These factors fall into three general categories:

1. The first is associated with reduction of sediment supply to the head of the river. As with a dam on a river, a reduction in supply at an upstream location leads to erosion (degradation) of the river bed downstream of that location.

   The sand supply to the river has been significantly reduced as a result of construction of breakwaters and shore protection along both the U.S. and Canadian shores of Lake Huron. Historical air photos show that most of the shore protection was constructed between 1954 and 1973, and likely in the early 1970's in response to high water levels during that period. It was estimated that roughly 10,500 m^3/year of sand was historically supplied to the river from the Canadian side and the supply from the U.S. side may have been three times that. In the past 30 years, the river was deprived of at least 1 million cubic metres of sand that would have historically been supplied by erosion of updrift shorelines.

   The estimated sediment transport rates also demonstrate the significance of the volumes of material removed from the river as a result of historical dredging and aggregate mining. The 1867 chart shows extensive sand bars at the river mouth that no longer exist. It is estimated that over 15 million cubic meters of material were removed from the head of the river and upper reaches between 1841 and 1993. Assuming historical transport rates of 42,000 m^3 per year from U.S. and Canadian sides, this represents over 350 years of accumulated sediment.

2. The second factor is associated with a possible change in the main driving force for erosion: the alignment of the main flow from the lake into the river.

   A comparison of the bathymetry at the St. Clair River inlet for four different time periods: 1867, 1929, 1971 and 2000, showed a continuous erosion trend on the west side of the river. Although depths on the west side are not as great as those in the channel to the east, increased depths on the west side of the river and approach channel may have focused the erosion power of the river to the outer side of the bank below Bluewater Bridge. Unfortunately, there is limited coverage of historical bathymetry to support detailed numerical modeling of the influence of these changes in the area of the approach channel on flow through the noted critical section below Bluewater Bridge. It is our understanding that the USACE is collecting detailed bathymetry data at this location in 2005. This information may assist in further evaluating this second factor.

3. Once glacially consolidated cohesive sediment (clay) is exposed on the river bed, either through the process of direct removal of overlying sand and gravel deposits (dredging or sand mining), or through reduction in supply from updrift/upstream, it will erode irreversibly under the strong flow conditions of the river. This process would continue even if the balance in sand supply was restored, and it would not abate until sufficient depth is achieved (reducing flows) or until it is protected with a sufficiently thick layer of sand, gravel or rock.

   The review of borehole data suggests that the riverbed material in the eroded section of the river south of the Blue Water Bridge, could be exposed clay. The clay may have become exposed as a result of aggregate mining or dredging operations. It may also have been exposed due to a decrease in the sand supply which once provided a sufficiently thick cover to protect the underlying erodible clay. Finally, its exposure may be related to the possible change in flow pattern discussed in the previous Point 2. Additional borehole data would be required to confirm the nature of the riverbed material. Borehole data and glacial geomorphic interpretation could be used to develop a 3-dimensional description of the riverbed geology (i.e. including for those areas already eroded).

It is possible that a combination of these factors triggered the erosion of the riverbed. It may be difficult to ascertain the precise cause due to a lack of detailed historical data.

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