Analysis of Great Lakes Volume Changes Resulting from Glacial Isostatic Adjustment

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1. Introduction

During the last glacial era, glaciers covered much of North America, including the Great Lakes region. Under the great weight of these glaciers the Earth's crust was deformed. When the ice in the Great Lakes region melted some 10,000 years ago, the crust began to rebound, and it is believed that this rebounding has continued ever since. This has been called post-glacial rebound, glacial isostatic adjustment or apparent vertical movement.

Due to variations in the thickness of the glaciers, the timing of the glaciers receding, the geology of the region and other differences, the rate of apparent vertical movement at any given location varies throughout the Great Lakes region. Nonetheless, the relative rate of apparent vertical movement around a given lake can be estimated from plots of water level differences versus time. While water level differences can not be used to estimate relative rates of movement from one lake to another, they can be used to estimate the rates of movement between gauge pairs on a single lake, including between any given gauge and a gauge at the outlet of the lake.

A consequence of these vertical movements and the distribution of them around a given lake is that each lake may be storing or decanting water with time. If most of the lake is falling relative to the lake outlet, the lake will be increasingly storing water. Alternatively, if most of the lake is rising relative to the lake outlet, the lake will be increasingly decanting water. This report presents an analysis and estimate of these effects for each of the Great Lakes.

2. Past Studies

Glacial isostatic adjustment has been studied for some time in the Great Lakes region. A report by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (Coordinating Committee, 1977a) summarizes a number of earlier studies. The Coordinating Committee compared differences between the four-month mean June to September monthly average water levels for gauge pairs on each of the Great Lakes. Linear regression lines were fit to the water level difference versus time plots, with the slope of the line indicating the relative rate of rise between the two gauges in question.

Other researchers have used similar methods, and were referenced in the Coordinating Committee (2001) report, which provides one of the most recent updates. In the 2001 study, the Coordinating Committee used monthly mean water level data from all twelve months with outliers removed as opposed to the traditional June to September average used in earlier studies. The vertical velocity rates and standard errors were calculated for all gauges from this data. The findings were also reported in Mainville and Craymer (2005).

While these past studies investigated the apparent rates of vertical movement between gauge pairs, little effort has been devoted to studying the impact of glacial isostatic adjustment on the volumes of the Great Lakes. Freeman (1926) provided an early estimate of the increase or decrease in discharge as a result of volume changes with time for each of the Great Lakes. He found that the outflow of Lake Superior and Lakes Michigan-Huron are slightly larger as a result of these two lakes decanting water with time due to glacial isostatic adjustment. On the other hand Freeman found that the outflows of Lake Erie and Lake Ontario are reduced as these two lakes progressively store water with time. Freeman's results are shown in Table 2-1.

Lake	Increase in Discharge (ft^3/s)	Increase in Discharge (m^3/s)	Decrease in Discharge (ft^3/s)	Decrease in Discharge (m^3/s)
Superior	55	1.56	-	-
Mich. - Huron	303	8.58	-	-
Erie	-	-	96	2.72
Ontario	-	-	72	2.04

Table 2-1: Rates of outflow change with time reported by Freeman (1926)

This report provides a revised assessment of volume changes of the Great Lakes over time. The rates of apparent vertical movement used include those determined in the most recent report from the Coordinating Committee (2001), as well as a set of revised rates determined for the International Joint Commission's International Upper Great Lakes Study, which include all data up to and including 2006 (Bruxer & Southam, 2008). In addition, a geographic information system (GIS) was used for interpolating the rates to the entire lake area.

3. Method

3.1. Water Level Difference Plots and Linear Regression

In this study, rates of vertical movement as determined from water level difference plots were used. As an example, Figure 3-1 shows a water level difference plot for Point Iroquois and Duluth. The downward slope of the linear regression line indicates that over time the water level observed at Duluth appears to be increasing with respect to the water level recorded at Point Iroquois at a rate of approximately 27 centimetres/century (cm/century). This in turn indicates that the land at Duluth is falling relative to the land at Point Iroquois at this same approximate rate.

Two sets of calculated rates of vertical movement were used. The first set comes from the most recent report by the Coordinating Committee (2001). The Coordinating Committee report used all twelve months of data for each year and removed outliers where appropriate. The rates were calculated and adjusted on each lake to ensure consistency between sets of gauges. A second set of revised rates from a more recent report by Bruxer and Southam (2008) were also used. This revised study was completed for the International Upper Great Lakes Study, and was done in part to specifically support this volume change analysis. Rates of movement were calculated using the June to September average water level differences. These rates were not adjusted for consistency, but inconsistencies at each gauge station individually were identified and dealt with where possible and appropriate.

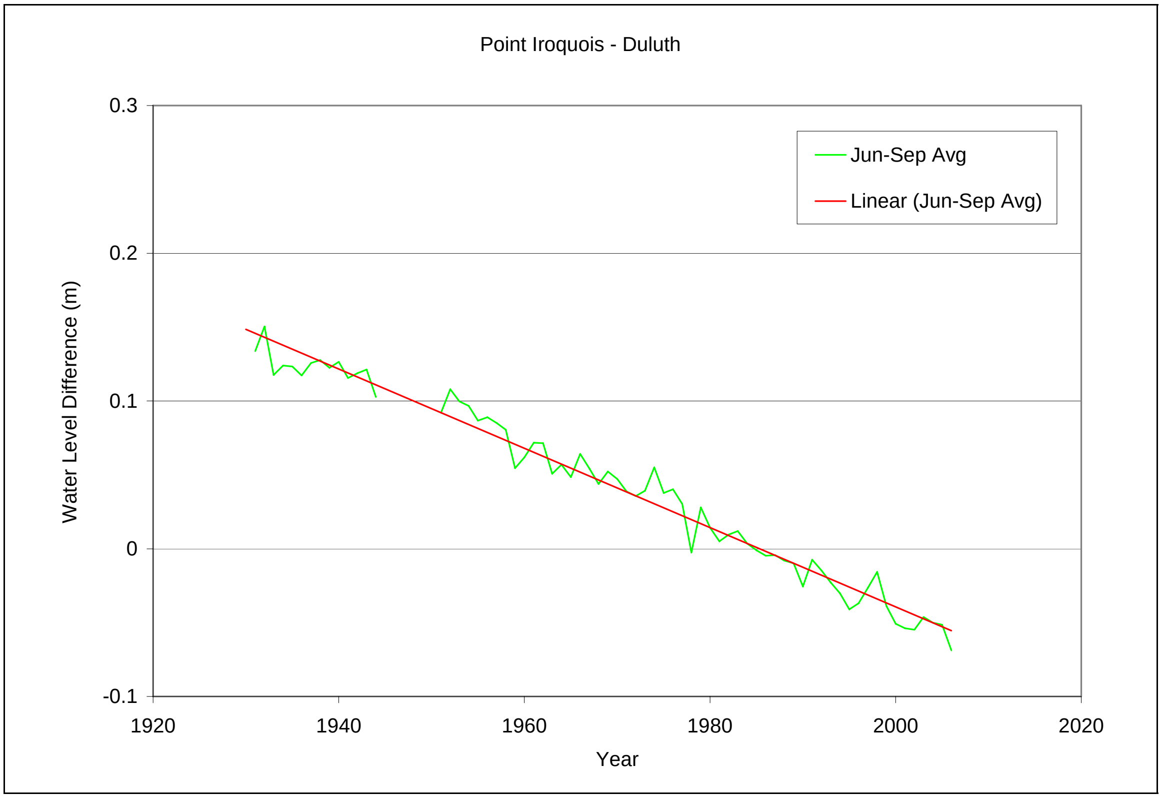

Figure 3-1: Water level difference plot of Point Iroquois minus Duluth (Lake Superior). Water levels were averaged from June to September in this case.

Three scenarios were calculated for each lake, and the rates of vertical movement used are shown below in the appropriate section. One scenario was calculated using the rates from the most recent report from the Coordinating Committee, while the other two scenarios were calculated using the revised rates from the report by Bruxer and Southam. In some instances during their study, due to inconsistencies and sources of uncertainty observed at a number of gauges, more than one rate of vertical movement was calculated. For example, if potential issues with early staff gauge data were identified in a gauge station's period of record, then it was possible that two rates of apparent vertical movement would be calculated for this gauge; one including the staff gauge data, the other with the staff gauge data omitted. A full description of other such issues and their occurrences at certain gauges is documented in the original report by the authors. The maximum and minimum rates of apparent vertical movement used to calculate storage changes over time in this report are therefore the maximum and minimum plausible revised rates calculated for each gauge in the report by Bruxer and Southam. In this way a bounded estimate is provided, since either estimate is plausible. It should also be noted that in some cases, due to an irreconcilable issue at a gauge station (such as a station with an exceptionally short period of record, for example), the rate of vertical movement calculated was inconsistent with other calculated rates on the same lake to such a degree that it was deemed inappropriate for use in this study, and was omitted from the analysis entirely. This was not done often, and where it was, it is identified where appropriate.

3.2. *Volume Change Analysis*

The volume change for a given lake over time can be estimated by determining the average rate of vertical movement for a lake from the rates of vertical movement estimated for each of the individual gauge stations, and multiplying that rate by the surface area of the lake (Eq. 3-1). The average rate of vertical movement for the entire lake must be determined by interpolating the rates at all gauge stations to the lake surface area. A direct average of the rates from the stations would not be appropriate since the gauge stations are not balanced around each lake.

$$\frac{dz}{dt}(avg) \times A = \frac{dV}{dt} \tag{3-1}$$

Interpolation was done using GIS software. Four interpolation methods were investigated, including linear, inverse distance weighted, natural neighbour and kriging methods. Detailed information on these methods can be found in available geostatistics texts (e.g. Isaaks & Srivastava, 1989).

Of the four interpolation methods evaluated, it was found that linear and natural neighbour interpolation were the two most appropriate methods for this analysis. Linear interpolation triangulates values and interpolates linearly between sets of local data points. This provides a gradual, linear transition across the surface of each lake, preserves the actual data values at these locations, and agrees with the assumption of linearity made to derive the rates of movement from water level difference plots between gauge pairs. On the other hand, since the water level gauges on each of the Great Lakes are distantly spaced, and the rates of vertical movement tend to differ significantly between stations, a "bull's-eye" effect is often observed when inverse distance weighted interpolation is used. By reducing the number of weighted values used to interpolate at any given point to only those values locally influencing the point in question, natural neighbour interpolation was found to reduce these undesirable effects. Lastly, kriging, a geostatistical method, assumes that the data being interpolated is stationary. There are significant spatial trends in the rates of apparent vertical movement for each lake, which violates this assumption. Universal kriging can be used to account for this, but the results become inexact (i.e. interpolated values at actual data points are not necessarily equal to the actual data value measured at this point) and questionable in terms of this study.

For these reasons, linear and natural neighbour interpolation methods were chosen, evaluated and compared. It was found that while natural neighbour interpolation generally produced a smoother and more visually acceptable surface image, there was little difference in the average estimated rates of vertical movement provided by the two interpolation methods. The results for each method are provided below for comparison purposes.

As mentioned, the average rates, calculated in centimetres per century, were converted to metres per century and multiplied by the surface areas converted to square metres. The surface areas of the Great Lakes used to calculate the volume change are given in Table 3-1. These values were taken from the "Coordinated Great Lakes Physical Data" report by the Coordinating Committee (1977b). In addition, the volume change calculated as a volume in cubic metres per century was converted to cubic metres per second by dividing by 3.1536 x 10^9 seconds per century.

Lake	Area (km^2)
Superior	82,100
Michigan	57,800
Huron	59,600
Erie	25,700
Ontario	18,960

Table 3-1: Great Lakes surface areas (Coordinating Committee, 1977b)

4. Lake Superior

4.1. Data Overview

Water level data from a total of ten gauge stations were used in this analysis on Lake Superior (Figure 4-1). Four of these gauge stations are located in Canada, while the remaining six gauge stations are located in the United States. The outlet of Lake Superior has traditionally been chosen as Point Iroquois, and this was similarly the case in this analysis.

The rates of vertical movement used for each of the three calculations are shown in Table 4-1. Note that the revised rates at Rossport are significantly less than the rate calculated by the Coordinating Committee. This is due to a suspected unstable benchmark at this location in the past. Furthermore, Gros Cap was omitted entirely from the maximum and minimum calculations from the revised rates, since the data is questionable at this gauge. These and other issues are documented more completely in the report by Bruxer and Southam.

Figure 4-1: Lake Superior gauge locations.

Scenario	C.C. Rates	Revised Rates	
Gauge		Max	Min
Point Iroquois	***0***	***0.00***	***0.00***
Marquette	-12	-9.78	-10.50
Ontonagon	-19	-17.32	-17.32
Duluth	-25	-26.85	-29.00
Two Harbors	-21	-19.90	-19.90
Grand Marais	-8	-10.26	-10.26
Thunder Bay	2	3.84	1.29
Rossport	28	15.41	15.41
Michipicoten	23	23.39	20.63
Gros Cap	2	0.00	0.00

Table 4-1: Calculated rates of vertical movement (cm/century) for Lake Superior relative to Point Iroquois.

4.2. Results

Lake Superior is nearly balanced in terms of areas falling and areas rising relative to the outlet at Point Iroquois. For example, Figure 4-2 shows the maximum revised rates of apparent vertical movement linearly interpolated for Lake Superior. As can be seen, the north-eastern half of the lake is rising relative to Point Iroquois, while the south-western half is falling relative to the outlet. In addition, the line of zero movement from this interpolation appears to divide the lake almost in half.

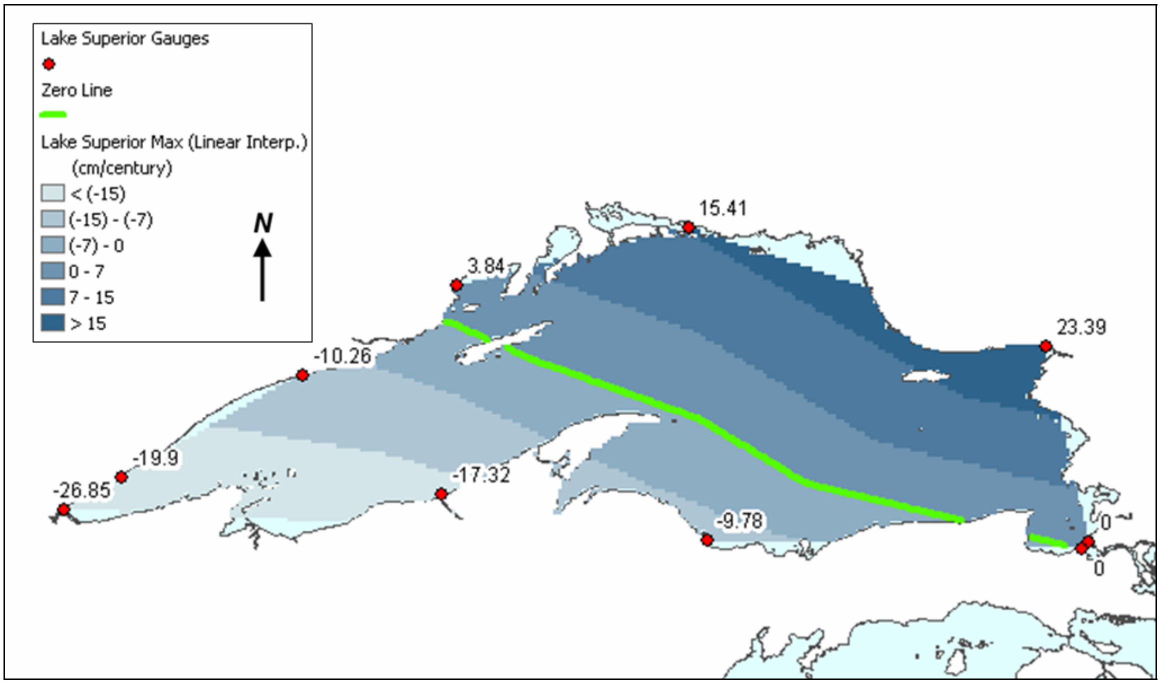

Figure 4-2: Lake Superior interpolated rates of vertical movement and zero movement line for the revised maximum rates.

Despite Lake Superior having some of the highest and lowest relative rates of movement of any lake, the average rate of movement is close to zero depending on which rates and interpolation method are used. Table 4-2 shows the average rates of vertical movement and the change in storage calculated for each scenario and each interpolation method for Lake Superior. Note that the values calculated from the Coordinating Committee rates are higher than even the maximum value calculated using the revised rates. This is mostly the result of the high rate of movement calculated by the Coordinating Committee at the Rossport gauge. As discussed, the early Rossport gauge data is suspect, and the revised rates are likely a more accurate representation of the actual rate of movement at this gauge station. Regardless, even if the Coordinating Committee rates are included, the change in storage on Lake Superior is estimated as only being between -0.23 and 0.42 m^3/s. That is, depending on which set of rates are used, Lake Superior is either storing or decanting water, respectively, but the rate at which the lake is doing either is quite small. In fact, these numbers represent only a fraction of a percentage of the average outflow of Lake Superior, which is over 2000 m^3/s.

Scenario	Avg. Rate (cm/100 years)		Difference (cm/100 years)	Q (m^3/s)		Difference (m^3/s)
	Linear	N.N.		Linear	N.N.	
Coordinating Committee	1.35	1.60	0.25	0.35	0.42	0.07
Revised Max.	0.20	-0.06	0.26	0.05	-0.01	0.06
Revised Min.	-0.78	-0.89	0.11	-0.20	-0.23	0.03

Table 4-2: Lake Superior calculated average rates of vertical movement and change in storage.

5. Lakes Michigan-Huron

5.1. Data Overview

Lake Michigan and Lake Huron are connected by the wide and deep Straits of Mackinac, which causes the two lakes to behave as one in terms of hydraulics. For this reason they were considered together in this analysis. Data from a total of eight gauge stations on Lake Michigan and twelve gauge stations on Lake Huron were analyzed. On Lake Michigan all eight gauges are located within the United States, as are six of the gauges on Lake Huron, with the remaining six gauge stations on Lake Huron being located in Canada. Figure 5-1 shows the locations of all 20 gauges on the two Lakes.

The rates of vertical movement used for each of the three calculations are shown in Table 5-1. Note that some of the revised rates are significantly different than those calculated by the Coordinating Committee. The reasons for these differences as well as other issues are documented more thoroughly in the report on revised rates by Bruxer and Southam.

Note also that the rates of apparent vertical movement reported are those calculated relative to Harbor Beach, Michigan. While Harbor Beach has traditionally been used as the outlet of Lakes Michigan-Huron due to its location and long period of record, the gauge is still located quite a good distance from the actual outlet at the head of the St. Clair River. The Lakeport gauge, on the other hand, is located much closer to the actual outlet; however, the period of record at Lakeport is not as long as at Harbor Beach, and rates of movement calculated with this gauge are more uncertain than those calculated relative to Harbor Beach.

After applying a lake-wide correction, the Coordinating Committee estimated the rate of movement between Harbor Beach and Lakeport to be zero. With the additional years of data added, Bruxer and Southam estimated from the water level difference plot that Lakeport is falling relative to Harbor Beach at -3.19 cm/century. Bruxer and Southam also found that this value is close to the average difference between rates calculated for all other gauges relative to Harbor Beach and those calculated for all other gauges relative to Lakeport, which is -3.37 cm/century.

In order to use the estimates of relative rates of apparent vertical movement with the least uncertainty, those rates calculated relative to Harbour Beach were used for all calculations. Since the Coordinating Committee estimated the rate of movement to be zero between Lakeport and Harbor Beach, the rates relative to Harbor Beach were used as is in the Coordinating Committee volume change calculation. On the other hand, for the maximum and minimum revised rate calculations, in order to transfer the average rate to the actual outlet of the lake itself at Lakeport, the average rate for Lakes Michigan-Huron interpolated from the rates relative to Harbor Beach was increased by 3.19 cm/century (i.e. by the apparent vertical movement rate between Harbor Beach and Lakeport). The result is that the final answer represents the change in storage relative to the outlet of Lakes Michigan-Huron at Lakeport for all calculations, while the uncertainty in the rates is reduced by using the more certain rates of movement calculated relative to Harbor Beach.

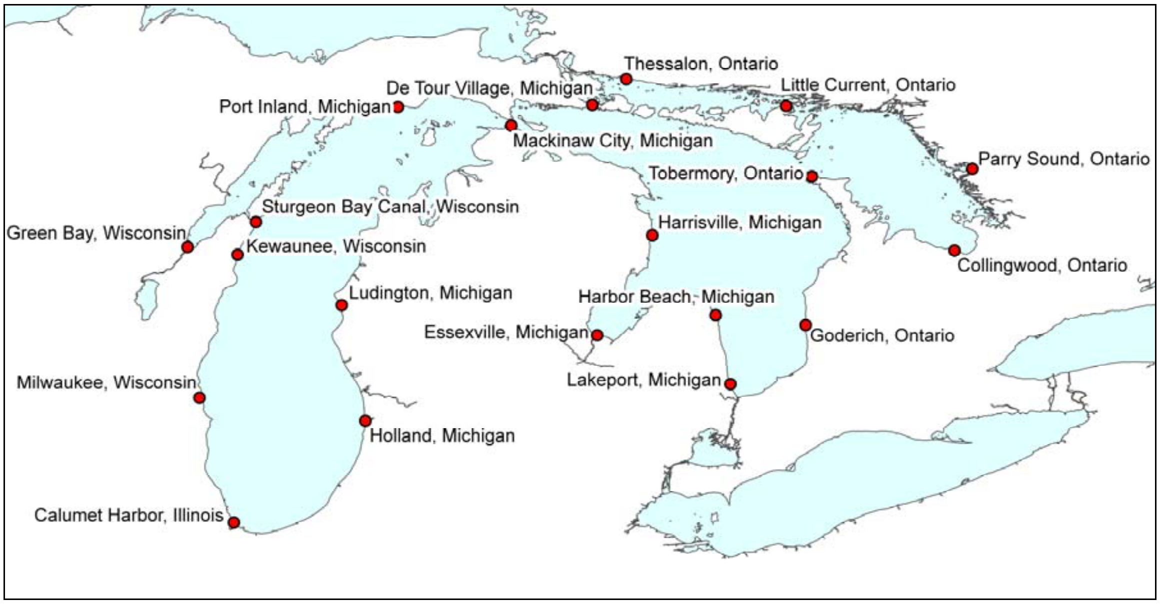

Figure 5-1: Lakes Michigan-Huron gauge locations.

Scenario	C.C. Rates	Revised Rates	
Gauge		Max	Min
Lakeport	0	-3.19	-3.19
Harbor Beach	***0***	***0.00***	***0.00***
Essexville	-1	-5.58	-5.58
Harrisville	8	5.48	5.48
Mackinaw City	10	9.22	9.22
De Tour	17	14.63	14.63
Ludington	-12	X	-17.73
Holland	-8	-11.70	-11.70
Calumet Harbor	-10	-12.12	-12.12
Milwaukee	-14	-16.14	-16.14
Kewaunee	-8	X	-11.99
Sturgeon Bay Canal	-4	-4.36	-8.26
Green Bay	-6	-9.37	-9.37
Port Inland	9	6.03	6.03
Thessalon	21	20.85	18.60
Little Current	27	21.33	21.33
Parry Sound	24	20.80	20.80
Collingwood	17	14.21	7.65
Tobermory	17	15.74	15.74
Goderich	-1	0.00	-6.51

Table 5-1: Calculated rates of vertical movement (cm/century) for Lakes Michigan-Huron relative to Harbor Beach.

5.2. Results

Similar to Lake Superior, Lakes Michigan-Huron are separated into both rising and falling areas. Figure 4-2 shows the revised minimum relative rates of apparent vertical movement interpolated for Lakes Michigan-Huron. The north-eastern half of the lake is rising relative to Harbor Beach, while the south-western half is falling relative to Harbor Beach. However, unlike Lake Superior, the proportion of the Lakes that are rising and falling is not as evenly split, and in this case it is not as obvious whether Lakes Michigan-Huron are storing or decanting water over time.

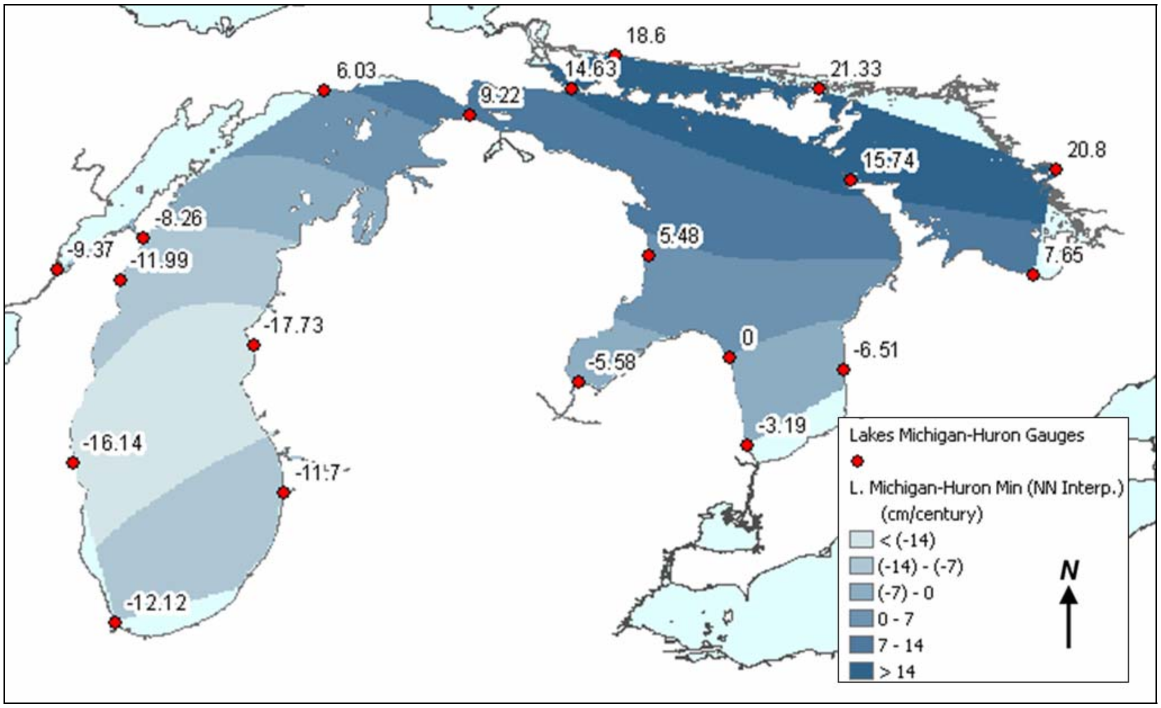

Figure 5-2: Lakes Michigan-Huron interpolated rates of vertical movement for the revised minimum rates.

Table 5-2 shows the average rates of vertical movement and the change in storage calculated for each scenario and each interpolation method for Lakes Michigan-Huron. Note that the values for the revised rates are calculated for both Harbor Beach and Lakeport, though Lakeport is the true representation of the outlet and should be used in this analysis. If the revised rates for Harbor Beach are omitted, the results show that Lakes Michigan-Huron are decanting water at a rate of between 1.35 and 2.11 m^3/s.

Scenario	Avg. Rate (cm/100 years)		Difference (cm/100 years)	Q (m^3/s)		Difference (m^3/s)
	Linear	N.N.		Linear	N.N.	
Coordinating Committee	3.64	3.71	0.07	1.35	1.38	0.03
Revised Max. Harbor Beach	2.49	2.46	0.03	0.93	0.92	0.01
Revised Min. Harbor Beach	0.46	0.5	0.04	0.17	0.19	0.02
Revised Max. Lakeport	5.68	5.65	0.03	2.11	2.10	0.01
Revised Min. Lakeport	3.65	3.69	0.04	1.36	1.37	0.01

Table 5-2: Lakes Michigan-Huron calculated average rates of vertical movement and change in storage.

6. Lake Erie

6.1. Overview

Water level data from a total of 16 gauge stations were analyzed on Lake Erie (Figure 6-1). Six of these gauge stations are located in Canada, while the remaining ten gauge stations are located in the United States. The outlet of Lake Erie is located at Buffalo, New York.

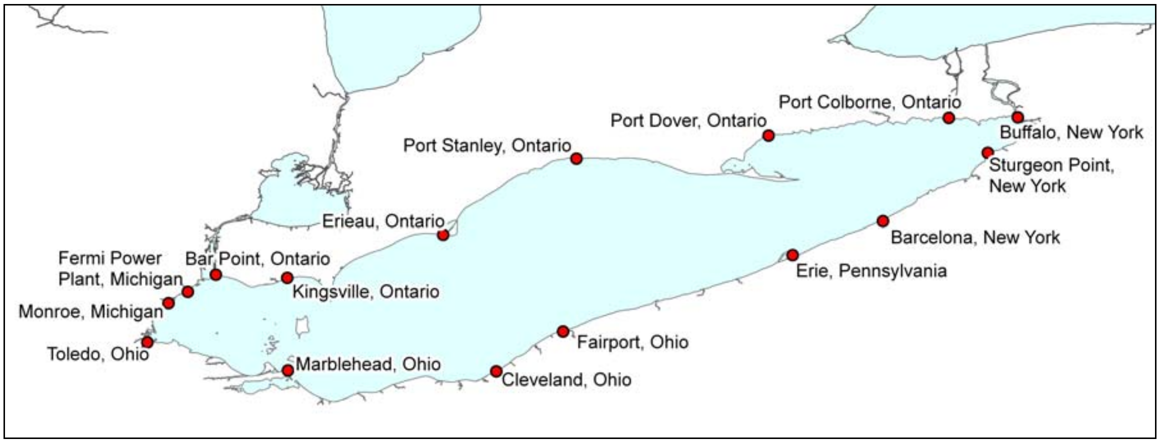

Figure 6-1: Lake Erie gauge locations.

The rates of vertical movement used for each of the three calculations are shown in Table 6-1. Note that some of the revised rates are significantly different than those calculated by the Coordinating Committee. Also, a number of gauges are not used in the calculations. Due to data issues, the Coordinating Committee chose to dismiss the rates from Fairport, Monroe and Bar Point. In addition to these rejections, the revised rates by

Bruxer and Southam do not use Sturgeon Point or Barcelona. The reason these rates are omitted is due to their high uncertainty resulting from short periods of record.

Scenario	C.C. Rates	Revised Rates	
Gauge		Max	Min
Buffalo	***0***	***0***	***0***
Sturgeon Point	2	X	X
Barcelona	-1	X	X
Erie, PA	-12	-7.69	-7.69
Fairport	X	X	X
Cleveland	-10	-6.69	-9.01
Marblehead	-8	-6.84	-6.84
Toledo	-9	-5.93	-12.64
Monroe	X	X	X
Fermi Power Plant	-10	-10.10	-10.10
Bar Point	X	X	X
Kingsville	-10	-9.80	-9.80
Erieau	-10	-6.31	-6.31
Port Stanley	-7	-2.14	-3.47
Port Dover	-2	-1.82	-1.82
Port Colborne	-6	0.34	-5.11

Table 6-1: Calculated rates of vertical movement (cm/century) for Lake Erie relative to Buffalo.

6.2. Results

Unlike Lake Superior and Lakes Michigan-Huron, all of Lake Erie appears to be falling relative to its outlet, implying that the lake is storing water over time. Figure 6-2 shows the natural neighbour interpolated rate of vertical movement for Lake Erie using the minimum revised rates. As can be seen, Lake Erie's interpolated rate does not follow as consistent a pattern as the other lakes due to uncertainty in the estimates for the rates of movement themselves, which has always been a problem on Lake Erie.

Table 6-2 shows the average rates of vertical movement and the changes in storage calculated for each scenario and each interpolation method for Lake Erie. All calculations indicate that Lake Erie is storing water. If all calculated values are accepted as plausible, the discharge at Lake Erie is reduced by a rate of between -0.65 and -0.44 m^3/s due to glacial isostatic adjustment, and is therefore storing water at that rate.

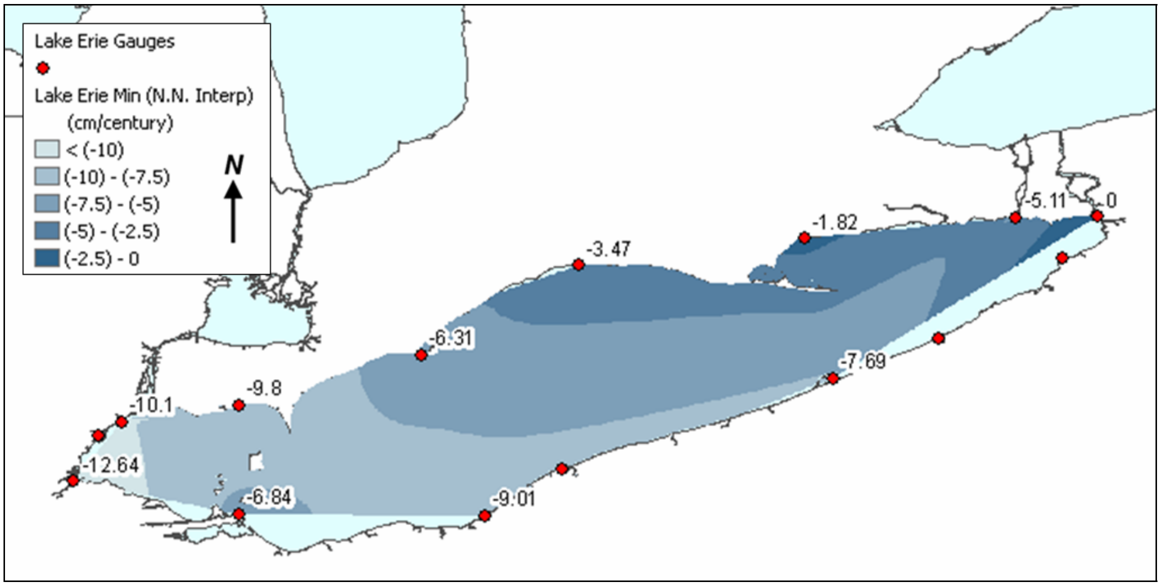

Figure 6-2: Lake Erie interpolated rates of vertical movement for revised minimum rates.

Scenario	Avg. Rate (cm/100 years)		Difference (cm/100 years)	Q (m^3/s)		Difference (m^3/s)
	Linear	N.N.		Linear	N.N.	
Coordinating Committee	-7.98	-7.99	0.01	-0.65	-0.65	0.00
Revised Max.	-5.44	-5.51	0.07	-0.44	-0.45	0.01
Revised Min.	-6.48	-6.55	0.07	-0.53	-0.53	0.00

Table 6-2: Lake Erie calculated average rates of vertical movement and change in storage.

7. Lake Ontario

7.1. Data Overview

Data from a total of ten gauge stations were analyzed on Lake Ontario (Figure 7-1). Six of these gauge stations are located in Canada, while the remaining four gauge stations are located in the United States. The outlet of Lake Ontario is normally assumed to be at Cape Vincent, New York, and this was again the case for this analysis.

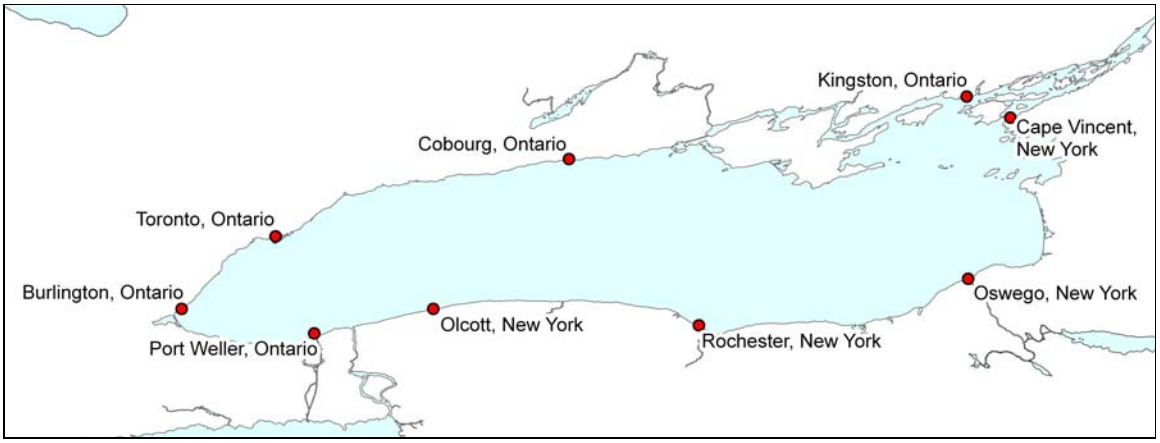

Figure 7-1: Lake Ontario gauge locations.

The rates of vertical movement used for each of the three calculations are shown in Table 7-1. Note that the rate of movement at Burlington is not used in the maximum revised rate calculation. This gauge station is located on a concrete pier close to the sand bar and filled land that divides Lake Ontario and Hamilton Harbour, and there is some question regarding its stability (Tushingham, 1992). Again, these and other issues regarding Lake Ontario relative rates of apparent vertical movement are documented in the report by Bruxer and Southam.

Scenario	C.C. Rates	Revised Rates	
Gauge		Max	Min
Cape Vincent	***0***	***0***	***0***
Oswego	-4	-3.59	-3.59
Rochester	-10	-7.91	-7.99
Olcott	-11	-12.52	-12.52
Port Weller	-15	-14.32	-17.13
Burlington	-20	X	-24.05
Toronto	-12	-10.93	-10.93
Cobourg	-8	-8.51	-8.51
Kingston	3	3.03	-2.85

Table 7-1: Calculated rates of vertical movement (cm/century) for Lake Ontario relative to Cape Vincent.

7.2. *Results*

Similar to Lake Erie, all of Lake Ontario appears to be falling relative to its outlet, implying that the lake is storing water over time. Figure 7-2 shows the natural neighbour interpolated rate of vertical movement for Lake Ontario using the minimum revised rates. As can be seen, the rate of apparent vertical movement on Lake Ontario increases significantly from east-to-west.

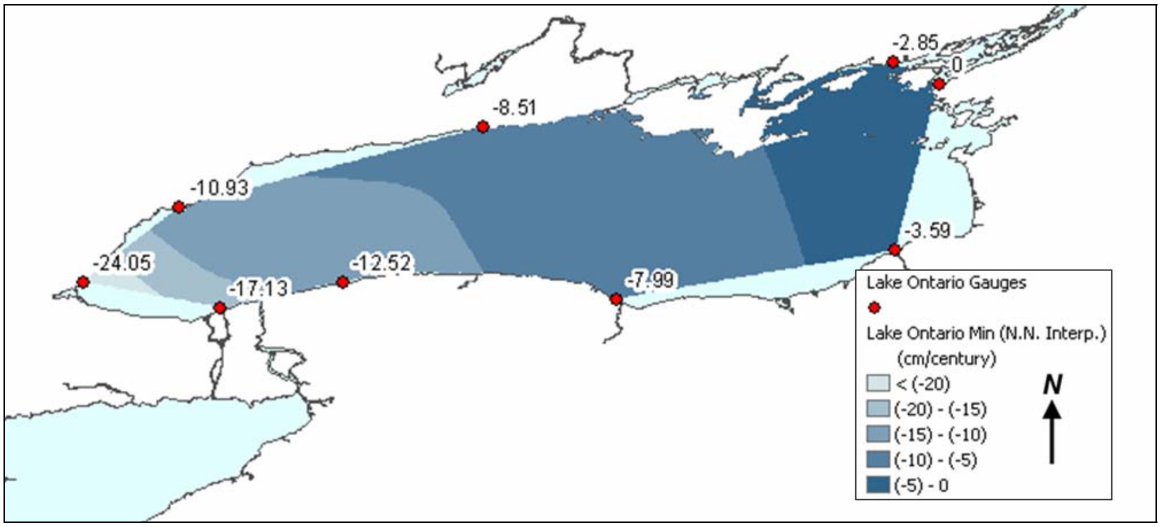

Figure 7-2: Lake Ontario interpolated rates of vertical movement for revised minimum rates.

Table 7-2 shows the average rates of vertical movement and the changes in storage calculated for each scenario and each interpolation method for Lake Ontario. All calculations indicate that Lake Ontario is storing water. If all calculated values are accepted as plausible, the discharge at Lake Ontario is reduced by a rate of between -0.50 and -0.45 m^3/s due to glacial isostatic adjustment, and is therefore storing water at that rate.

Scenario	Avg. Rate (cm/100 years)		Difference (cm/100 years)	Q (m^3/s)		Difference (m^3/s)
	Linear	N.N.		Linear	N.N.	
Coordinating Committee	-7.45	-7.53	0.08	-0.45	-0.45	0.00
Revised Max.	-7.67	-7.64	0.03	-0.46	-0.46	0.00
Revised Min.	-8.28	-8.26	0.02	-0.50	-0.50	0.00

Table 7-2: Lake Ontario calculated average rates of vertical movement and change in storage.

8. Summary

A summary of the low and high estimated rates of change in storage from all interpolation methods and calculated rates of apparent vertical movement is shown in Table 8-1. The maximum estimated rate of increasing volume (storing water) was calculated as -0.65 m^3/s for Lake Erie. The maximum estimated rate of decreasing volume (decanting water) was calculated as 2.11 m^3/s for Lakes Michigan-Huron. As a comparison of magnitude, the average discharge of the St. Clair River, which is the outlet of Lakes Michigan-Huron, is approximately 5680 m^3/s. The average discharges of the other lake outlets are of similar magnitude.

Lake	Average Rate of Movement (cm/century)		Change in Storage, Q (m^3/s)		Storing Or Decanting?
	Low Estimate	High Estimate	Low Estimate	High Estimate	
Superior	-0.89	1.60	-0.23	0.42	Inconclusive
Michigan-Huron	3.64	5.68	1.35	2.11	Decanting
Erie	-7.98	-5.44	-0.65	-0.45	Storing
Ontario	-8.28	-7.45	-0.50	-0.45	Storing

Table 8-1: Summary of average rates of movement and rates of change in storage.

9. Conclusions

As the result of differential glacial isostatic adjustment, areas of each of the Great Lakes are rebounding or subsiding at different rates relative to the respective lake outlet. As a result, each of the lakes is either storing or decanting water with time. In this study, the rates of apparent vertical movement as calculated from water level difference plots were interpolated to the entire surface of each lake. Both linear and natural neighbour interpolation methods were used and compared. The average rate for each lake was then calculated from the interpolated rates, and multiplied by the lake area to give an estimate of the change in volume of each lake over time.

It could not be inferred whether Lake Superior is storing or decanting water over time, as the calculated average rates for this lake were close to zero. Lake Huron appears to be decanting water over time, while Lake Erie and Lake Ontario are each storing water over time. Regardless, even the highest rates of change in storage are not significant when compared to the magnitude of the other terms in the water balance. The estimates presented here are less than those presented by Freeman (1926). However, the results are of the same magnitude and are similar in that his estimates were also relatively small.

10. References

Bruxer, J.K. and Southam, C. (2008). *Review of Apparent Vertical Movement Rates in the Great Lakes Region*. Report for the International Upper Great Lakes Study.

Coordinating Committee (1977a). *Apparent vertical movement over the Great Lakes.* Report by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. July 1977.

Coordinating Committee (1977b). *Coordinated Great Lakes physical data.* Report by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. May 1977.

Coordinating Committee (2001). *Apparent vertical movement over the Great Lakes - Revisited.* Report by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. November 2001.

Freeman, J.R. (1926). *Regulation of elevation and discharge of the Great Lakes: Designs for gates, sluices, locks, etc. in the Niagara and St. Clair Rivers*. Department of the Army Office of the Chief of Engineers Library. December 30, 1925 (Revised October 1, 1926), pp. 148-171B.

Isaaks, E. H. and R. M. Srivastave (1989). *An Introduction to Applied Geostatistics*. Oxford University Press.

Tushingham, A.M. (1992). Postglacial uplift predictions and historical water levels of the Great Lakes. *Journal of Great Lakes Research*. 18(3), pp. 440-455.