EVALUATING RATES AND PATTERN OF GLACIAL ISOSTATIC ADJUSTMENT IN LAKE SUPERIOR REGION

A Thesis

Presented to the Department of Earth and Environmental Sciences at the University of Waterloo in Fulfilment of the Thesis Requirements for the Degree

Honours

Bachelor of Science

Department of Earth and Environmental Sciences

Waterloo, Ontario, Canada

April 2016

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Declaration

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Abstract

Abstract

The motion of the ground beneath and adjacent to Lake Superior continues to be influenced by the long-gone Laurentide Ice Sheet. The rate and pattern of vertical ground movement, referred to as glacial isostatic adjustment (GIA), is related to many factors that include variations in ice thickness and duration during the oscillatory retreat of the Laurentide Ice Sheet. Previous research projects have recorded data of, or associated with, GIA by various methods; however, considering the different time periods examined by different research projects, the accuracy and consistency of these data is unknown. Hence, these data need to be analyzed and compiled to provide one view of GIA near Lake Superior. Data were collected from three sources, global positioning system (GPS), lake level gauges and ancient shorelines (beach ridges). Published rates of GIA from GPS stations surrounding Lake Superior were selected from a dataset covering North America. These data were then plotted and contoured to derive a rate and pattern of GIA based upon GPS data spanning recent decades. Water level gauge data for Lake Superior was updated from 2007 to 2015 and reanalyzed following methods used in the most recent International Upper Great Lakes Study. This provided a view of GIA based upon water level gauge data that extended many decades before GPS data. After each source was analyzed independently, these two results were then compared between each other. The results from the two types of data are statistically similar. These results show that ground in southwest part of Lake Superior is subsiding while that in northeast part of the lake is rising. For future work, these results can be compared with a rate and pattern of GIA provided by analyzing ancient shorelines or strandplains of beach ridges adjacent to Lake Superior over several millennia.

Acknowledgments

I would like to give my sincere gratitude to Professor John. W. Johnston, my supervisor, for his patience as well as his time and help given to me. His suggestions on data processing, results analyzing and thesis compiling were invaluable.

I also wish to thank Sean Morrison, who also helped me process and analyze data and provided me with many precious suggestions on thesis writing.

Also, I would like to thank Wesley James Campbell and Linda Chonglin Fan for their suggestions and friendliness.

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Introduction

Study Site – Lake Superior Region

Lake Superior is the largest lake among the Great Lakes in North America, which is surrounded by the Province of Ontario to the north in Canada, the State of Minnesota to the west and the states of Michigan and Wisconsin to the south in the United States. This 31,700-square-mile (82,103 km^2) (U.S. Government, 2011) lake is also considered the largest freshwater lake in the world in terms of surface area.

During the Quaternary, large ice sheets expanded and retreated multiple times. The last glaciation started about 80 000 years ago and terminated shortly after 10 000 years (Van Zee et al, 2015). During this period of 70,000 years, Lake Superior basin had started to retreat the ground. The Laurentide Ice Sheet left Lake Superior basin 10,000 years ago; since then, the ground underneath Lake Superior region has still been rebounding and adjusting due to GIA.

The elevation within the Lake Superior basin varies from zero to several hundred meters above sea level. Figure 1 is the elevation map of Lake Superior basin (Linder, 2014). The Lake Superior region can be divided into three parts in terms of topography, the upland, the lowland and the lake basins (Wadsworth, 1883). The main topographic feature is that the parallel ridges and valleys parallel to the Lake Superior syncline fold axis resulting from the long period of erosion along the folds, faults and cleavages created by the deformation of Lake Superior fold (Wadsworth, 1883).

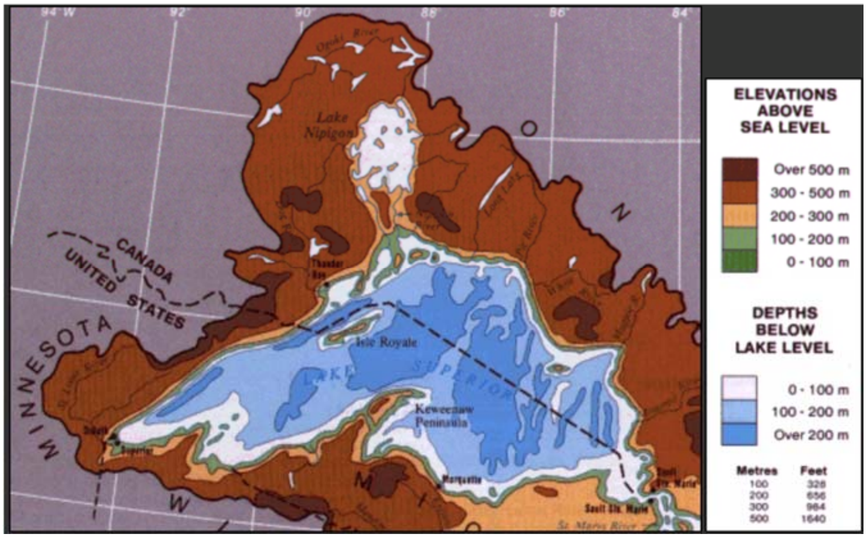

Figure 1. Elevation map of Lake Superior basin (Linder, 2014).

Water content in Lake Superior, with a volume of over 10,000,000,000,000 m^3, is larger than the combination of water content in other Great Lakes (Linder, 2014). Lake Superior flows via the St. Marys River into Lake Huron. Lake Superior and Lake Michigan flow through their tributary Lake Superior region, and then flow into the St. Lawrence River drainage system (Wadsworth, 1883). There is a total of ten water level gauge stations surrounding Lake Superior, which are Point Iroquois, Marquette, Ontonagon, Duluth, Two Harbors, Grand Marais, Thunder Bay, Rossport, Michipicoten, and Gross Cap respectively. Point Iroquois is the closest station to the current outlet of Lake Superior. Marquette is the closest station to the west of Point Iroquois. The following stations listed above are ordered clockwise along Lake Superior boundary. The bedrock of Lake Superior consists essentially of intrusive granites of the Canadian Shield (Harris et al, 2004).

Study Status/Background

Previous research projects measure rates and trends of GIA in and adjacent to Lake Superior basin with different tools and methods. For projects associated with GPS, lake level gauges and shorelines, several recent publications from each project are applicable to GIA were collected in this research.

- GPS

Research by Peltier et al (2015) accurately refines a new model, ICE-6G_C(VM5a), by applying all available data of vertical movement of crust by using GPS in three regions, North America, Northwestern Europe/Eurasia, and Antarctica. The new model is constructed by combining previously published data and methods. The above three regions were covered by the Late Quaternary ice sheet to its Last Glacial Maximum, are the main objective regions in this paper, and they also observed Greenland and the British Isles. The data were recorded as vertical movement velocity? (mm/year) for each observed site in these regions. This new model was confirmed to be feasible and reliable with respect to GIA by comparing its predictions of the rate of gravitational change with the measured results from the Gravity Recovery and Climate Experiment satellites independently.

Sella et al (2007), used GPS to record and analyze ground motion caused by GIA. Their research observed vertical and horizontal ground motion in over three hundred GPS sites located in Canada and the United States. A pattern of GIA on the North America plate was obtained. The pattern showed that the vertical-up velocity dropped from Hudson Bay to the south of the Great Lakes by 1-2mm per year; the ground was moving up along the northern shores of the Great Lakes while the ground was subsiding along the southern shores. The results of ground vertical motion were consistent with the predictions of GIA models. Their research also studies horizontal movement of ground under Canada and the United States, and obtained a pattern for the horizontal motion; however, the results showed differences with the predictions by models, which impelled further improvement of models in regard of their understanding of ice loading and mantle viscosity.

- Water level gauges

Historical water level data have been recorded for many decades to more than a century.

The most recent analyses of water level are from Mainville and Craymer (2005), Bruxer and Southam (2008) and Braun (2008).

Mainville and Craymer (2005) designed a new model of vertical ground motion for the Great Lakes region using water level data from fifty-five sites within this region. They observed 15 more gauge sites comparing with previous studies, applied data of the whole years rather than four months (June to September) in summer season in previous research, and used 8 more years' data of water level gauges in the Great Lakes region. The results of relative rates were compared with the models of ICE-3G (1991) and ICE-4G (1995) built by Tushingham and/or Peltier and show best corresponding with ICE-3G.

In Bruxer and Southam's report *Review of Apparent Vertical Movement Rates in the Great Lakes Region* (2008), water level data were recorded as monthly mean of all water level stations across the Great Lakes. For each lake, water level differences between pairs of gauges versus time were plotted. The slopes of the best-fit "least-squares regression lines" could approximately estimate the rates of relative vertical motion between the two gauges (Bruxer & Southam, 2008). They performed this analysis process for each pair of gauges for each lake. For the pairs with one gauge considered as outlet, the slopes of these pairs were considered to be the rates of vertical ground motion for their corresponding lakes. The collections and analyses were updated to 2006.

In Braun's research in 2008, a dataset of observation rates of GIA were compared with another dataset of prediction rates by models. The observation rates of vertical ground motion were obtained from two methods: one is an improved GPS network, and the other is a combination of tide gauges and satellite altimetry. The prediction rates of GIA were computed from 70 different GIA models. After comparison and analyses, the results showed that both datasets could be valuable methods to obtain data and evaluate the accuracy of GIA in Great Lakes region.

- Shorelines

Johnston et al (2012) constructed four paleohydrographs for Lake Superior providing water level changes during historical time, GIA and the optimal outlet. 321 basal foreshore vertical motions and 56 optically stimulated luminescence ages were obtained to constrain the chronology of these paleohydrographs. These published data are new and different compared with previous shoreline data. A linear approach was used to calculating GIA between paleohydrographs. They obtained a pattern of GIA in Lake Superior region and compared this pattern to the results estimated by water level gauges data (Mainville and Craymer 2005).

Methods

This research collected data from three different sources, which are GPS, lake level gauges, and shoreline respectively. For each set of data, different methods have been used to analyze.

GPS Data

GPS data were collected from the supplementary original datasheet in Space geodesy constrains ice age terminal deglaciation by W. R. Peltier et al (2015). Their data sheet includes horizontal and vertical velocities of ground surface movement with errors of all observed sites in North America, Northwestern Europe/Eurasia, and Antarctica. Because this research only concerns vertical ground motion under or near Lake Superior, we selected latitudes, longitudes, and vertical velocities of the sites beneath Laurentide Ice Sheet. Based on their latitudes and longitudes, and their corresponding velocities, Google Earth was applied to analyze this set of GPS data. In order to submit above data onto Google Earth, for sites positioning, the online GPS Visualizer (http://www.gpsvisualizer.com) was used to convert the series of “sites name, latitude, longitude” into Google Earth KML file; again, the GPS Visualizer converted the series of “vertical velocity, latitude, longitude” into Google Earth KML file to provide each site with its corresponding velocity of vertical ground movement. After submitting these two files into Google Earth, the observed sites were positioned on Google Earth (Figure 2) as well as their vertical movement velocities (Figure 3).

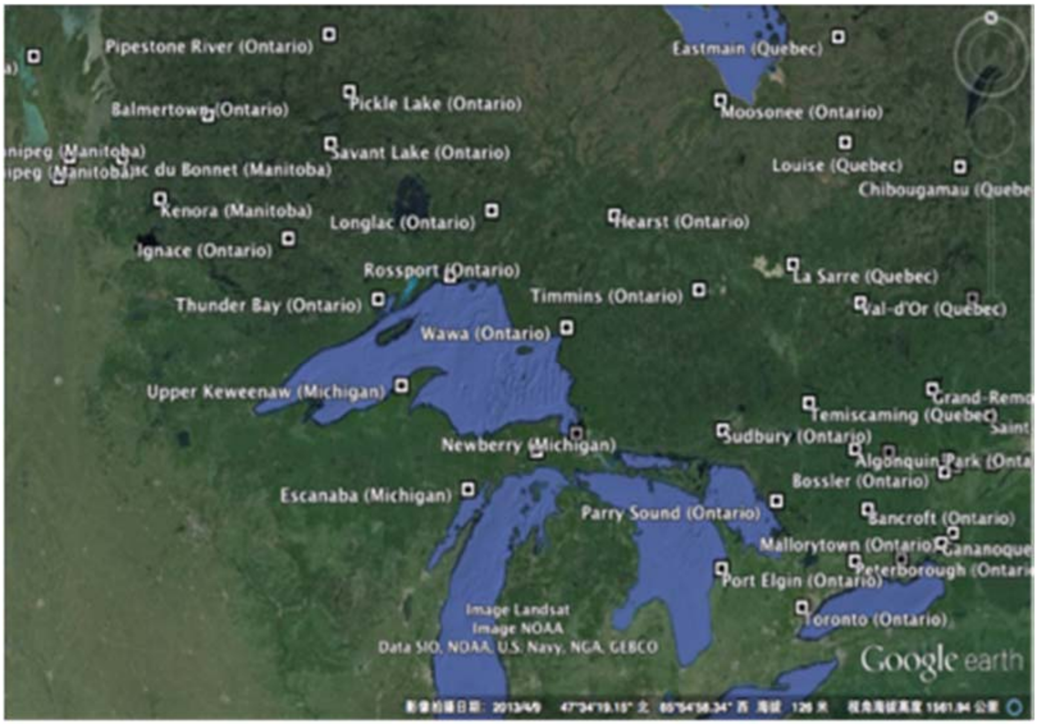

Figure 2. The observed sites beneath Laurentide Ice Sheet on Google Earth.

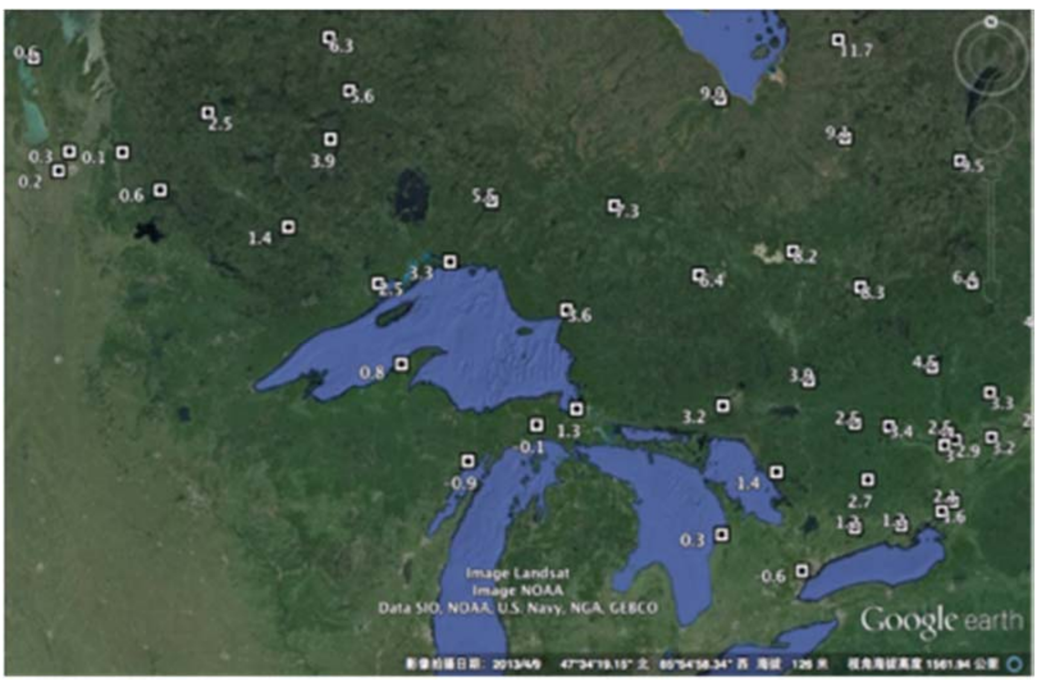

Figure 3. The corresponding vertical velocities of ground motion for observed sites beneath Laurentide Ice Sheet. The unit of these velocities is mm/year.

In order to contour the rates on the map (Figure 3), 0.5 mm/year is chosen as the contour interval based on the difference between the highest and lowest rate values on the map (Figure 3). Next, some auxiliary lines are built by connecting every two adjacent observation sites. Assuming the velocities change linearly, the linear rates of GIA between all observation sites can be calculated by dividing these auxiliary lines based on the distance (Figure 4). Then, all points with velocities of 0.5n mm/year (n= -1, 0, 1, 2, 3, … , the following n has the same meaning and range if mentioned) in this region can be determined. Some points with the rates of 0.5n mm/year are the observation sites with the rates of 0.5n from Peltier et al (2015). Other points with 0.5 mm/year are the linear rates estimated between every two adjacent locations with velocity difference greater than 0.5 mm/year or including 0.5n mm/year if smaller.

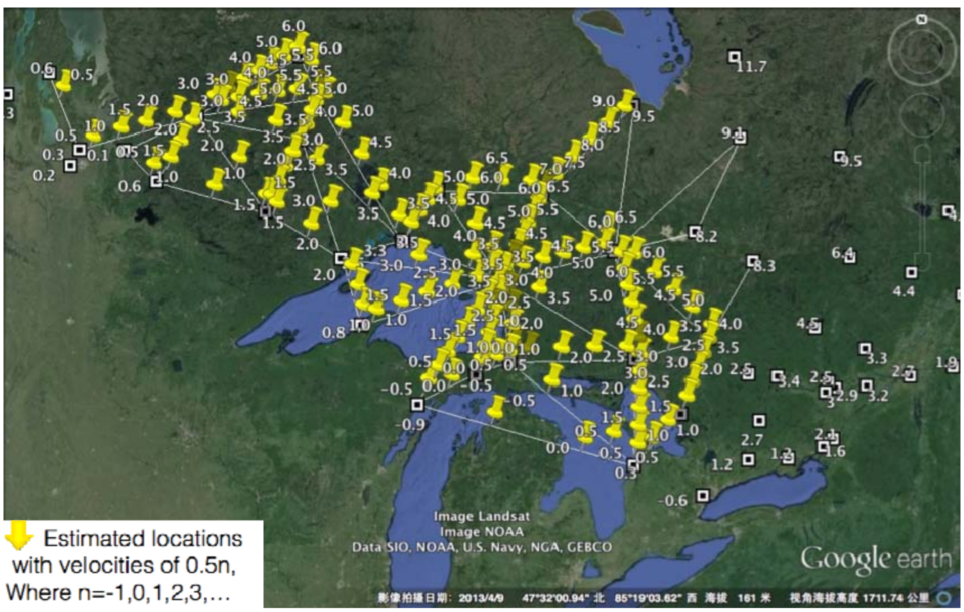

Figure 4. The estimated locations with velocities of 0.5n mm/year on auxiliary lines or polygonal boundaries.

Then, after connecting locations with same velocities on the auxiliary lines, the isobases of 0.5n mm/year are generated. In order to differentiate the isobases with the auxiliary lines, the auxiliary lines are supposed to be eliminated.

Water Level Gauges Data

Because the apparent vertical movement rates of Lake Superior region are collected and analyzed in regards to GIA by Bruxer and Southam (2008) from 1900s to 2006, the rates and the analyses should be updated to present.

- Collecting data

From 2007 to 2015, there are a total of twelve lake level gauge stations operating on Lake Superior, which are Duluth, Marquette C.G., Ontonogan, Grand Marais, Thunder Bay, Rossport, Michipicoten, Gros Cap, Sault Ste Marie (10980), Sault Ste Marie (10010) and Point Iroquois. For the seven Canadian gauges, the data was obtained from the Canadian Hydrographic Service; for the other five gauges in the United State, the data was obtained from the U.S. National Ocean Service. These data collected from the two media recorded daily means. They were then used to calculate monthly means of water levels from 2007 to 2015. Considering impacts of meteorological factors, monthly means of June to September are used to calculate annual average for each year. (Bruxer & Southam, 2008)

- Converting water level data into vertical movement velocities

The eastern corner of the lake Superior is the Point Iroquois station, which is the closest gauge to the outlet of the Lake Superior. Since Point Iroquois is nearest the outlet, it is used as a reference when calculating rates of GIA for other water level gauge stations surrounding Lake Superior. Take the station Duluth for instance, if the water level observed at Duluth became lower than that observed at Point Iroquois after a certain period of time, the earth crust under Duluth could be basically considered to fall vertically compared to the crust under Point Iroquois (Bruxer & Southam, 2008). Therefore, the relative rate (mm/year) to Point Iroquois of all individual stations surrounding Lake Superior except Point Iroquois, which is the absolute rates of vertical ground motion at the stations except Point Iroquois minus that at Point Iroquois, can be obtained by subtracting the annual average water level of each station from that of Point Iroquois station for the same year. After calculating all the subtractions for 2007 to 2015 for an individual station, a series of water level differences for 2007 to 2015 for this station was obtained. For every station, after plotting the water level difference (meter) over time (year) and finding a best-fit line of its pattern, the slope of the line can be considered as the vertical movement rate. Performing this process for each station compared to the Point Iroquois station, the vertical motion velocities of all the other eleven stations can be obtained.

GPS Data

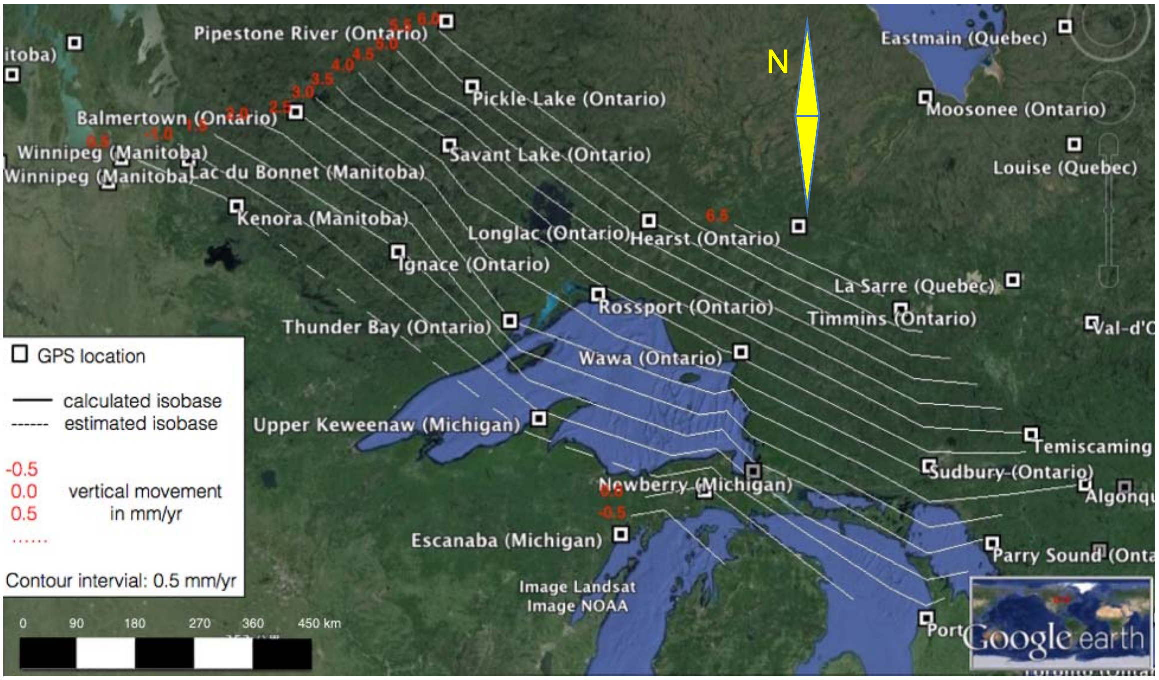

Figure 5. Isobase profile map on Google Earth.

- Rates

The final isobase profile is shown above (Figure 5). The minimum rate of vertical ground movement equals to or is less than -0.9 mm/year. The minimum value can be smaller than -0.9 mm/year because of lack of GPS data at the southwest part of Lake Superior. The maximum of the rate is about 3.6 mm/year. The rate difference between maximum and minimum values is 3.6 - (-0.9)= 4.5 mm/year.

- Pattern

The majority of the ground under Lake Superior is rising, only the southeast corner of the lake is dropping. The separation between the uplift and subsidence, i.e. the isobase of 0.0mm/year, is about 150km away from the southwest corner of the lake along a direction of around 60° from north to west.

The highest rate is at the northeast part of the Lake Superior while the lowest rate is at the southwest of the lake. The rate gradually decreases from the northeast end to the southwest end. The rate gradient (= rate difference / the distance perpendicular to the isobase lines) of the whole Lake Superior region is (4.5 mm/year)/ 223.65 km = 0.02 mm/year /km. The isobase lines are in the direction of approximately 65.81°SE (i.e. strikes 114.19°N).

Water Level Gauge Data

- Rates

The Point Iroquois station was used as a reference to compare water level changes of other stations surrounding Lake Superior because this is the closest station to Lake Superior's outlet. Water level difference plots are shown below starting with the closest station to the west of Point Iroquois and then following clockwise around Lake Superior. For the water level difference plots, only summer months (from June to September) are used to calculate the annual water level difference average for each year considering the meteorological effects.

For each station, a water level difference plot with all data of water level difference is plotted and provided, followed by another water level difference plot with 95% confidence interval constructed and removed some data. These data removed are based on decisions include visually significant outliers or outliers significantly influence linear regressions, variable data in certain period of record, discontinuous data or a gap of data record, dramatic changes in certain single years (Bruxer & Southam, 2008). According to Bruxer & Southam (2008), no single outlier significantly impacts the slope in the dataset for this water level difference plot analysis considering the error in statistics view. Therefore, the following plots would not remove any single outlier in dataset if the plots were plotted to remove some data.

The plot of water level difference between Point Iroquois and Marquette is shown in Figure 6. The water level data of Marquette used for calculating water level difference is combined the data observed by the station "Marquette" (909-9016) from 1860 to 1980 with the data observed by the station "Marquette C.G." (909-9018) from 1980 to 2006

(Bruxer & Southam, 2008). Data was updated from 2006 to 2015 using observations recorded by the station "Marquette C.G." (909-9018) as well. Because Point Iroquois only have data record since 1931, although the dataset for Marquette has data since 1860, the plot of water level difference between Point Iroquois and Marquette starts from 1931. The equation for the linear regression line is y= -0.00103x + 2.1433 (R^2 = 0.88839) (1931 – 2015). The negative slope indicates that the water level at the Marquette station increased compared to that at the Point Iroquois station. Hence, the ground is considered to subside vertically at Marquette compared with Point Iroquois. The relative rate to Point Iroquois is -0.00103 m/year or -1.03 +/- 0.026 mm/year (1931 – 2015) at the Marquette station, which is determined by the slope of the linear regression line.

Considering the missing data from 1945 to 1950, we removed the data from 1931 to 1944 and plot a new water level difference plot from 1951 to 2015 in order to use a continuous dataset. The new water level difference plot of Point Iroquois minus Marquette, which a 95% confidence interval constructed, is shown in Figure 7. From this new plot, we can see that almost all water level difference values are within the predicted interval with 95% confidence. Only one point with water level difference of -0.011 m in the year of 1978 is outside the predicted interval. This point is potentially an outlier, but because it is in the middle of the dataset, it may not greatly influence the slope. Therefore, since the point does not significantly influence the slope, it is not necessary to remove this point according to Bruxer & Southam (2008). For this plot post 1951, the slope is -0.00098 m/year (1951 – 2015), which gives the vertical ground motion rate of -0.98 +/- 0.035 mm/year (1951 – 2015) for Marquette relative to Point Iroquois.

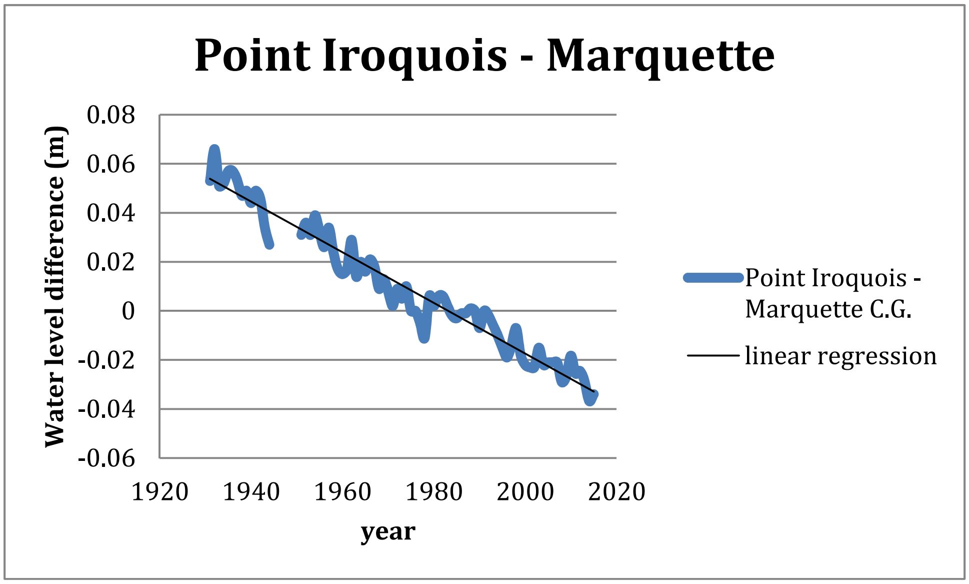

Figure 6. Point Iroquois minus Marquette water level difference plot from 1931 to 2015.

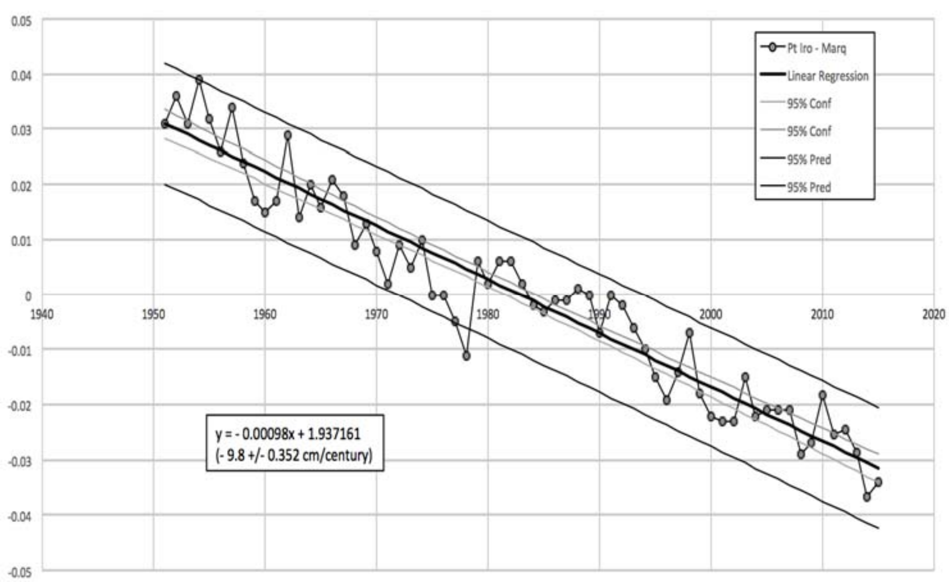

Figure 7. Point Iroquois minus Marquette water level difference plot from 1951 to 2015 with variable data removed.

The plot of water level difference between Point Iroquois and Ontonagon is shown in Figure 8. Water level data recorded by Point Iroquois started in 1931 while by Ontonagon started in 1960, so the water level difference plot starts in 1960. The equation for the linear regression line is y= -0.00169x + 3.3511 (R^2 = 0.86163) (1960 – 2015). The negative slope indicates that the water level at Ontonagon station increased compared to that at the Point Iroquois station. Hence, the ground is considered to subside vertically at Ontonagon compared with Point Iroquois. The relative rate to Point Iroquois is -1.69 +/- 0.092 mm/year (1960 – 2015).

Again, two potential outliers were found in the middle of the plot in Figure 8. However, according to Bruxer & Southam (2008), there is no need to remove outliers because the impact of outliers does not do a significant effect on the slope. Since the dataset is continuous without any record gaps or dramatic changes, no data would be removed for this plot in terms of the other decisions of removing data mentioned above. Hence, for Figure 9, we constructed a 95% confidence interval to evaluate the water level difference plot without removing any data.

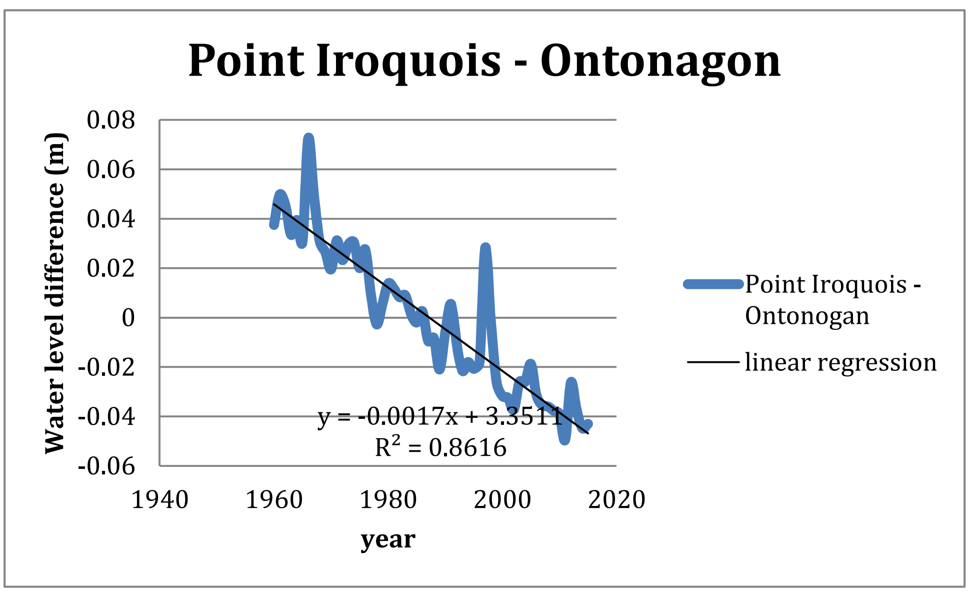

Figure 8. Point Iroquois minus Ontonagon water level difference plot from 1960 to 2015.

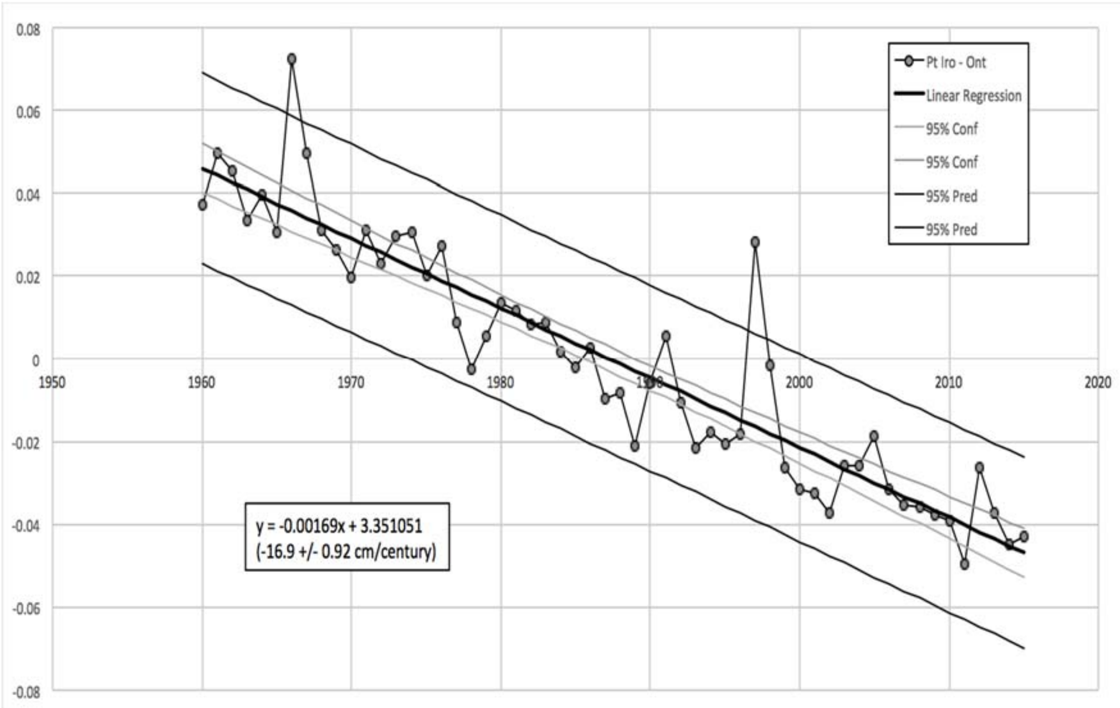

Figure 9. Point Iroquois minus Ontonagon water level difference plot from 1960 to 2015 with a 95% confidence interval constructed.

The plot of water level difference between Point Iroquois and Duluth is shown in Figure 10. Water level gauges data for Point Iroquois and Duluth are from 1931 to 2015 due to the same period of data record (1931 – 2015) for the two stations. The equation for the linear regression line is y= -0.00267x + 5.3035 (R^2=0.97858) (1931 – 2015). The slope is negative, which indicates that the relative water level at the Duluth station increased after 1931 compared to the Point Iroquois station. This increased rate is associated with vertical ground movement of 0.00267 +/- 0.000045 m/year or 2.67+/- 0.045 m/year (1931 – 2015) between these stations. The relative rate of vertical ground motion to Point Iroquois is -2.67 +/- 0.045 mm/year (1931 – 2015) at Duluth.

Noticing there is a time gap from 1945 to 1950, the new water level difference plot of Point Iroquois minus Duluth, which is shown in Figure 11, removed the data from 1931 to 2015. The slope computed determines the relative rate to Point Iroquois at Duluth is -2.82 +/- 0.061 mm/year (1951 – 2015).

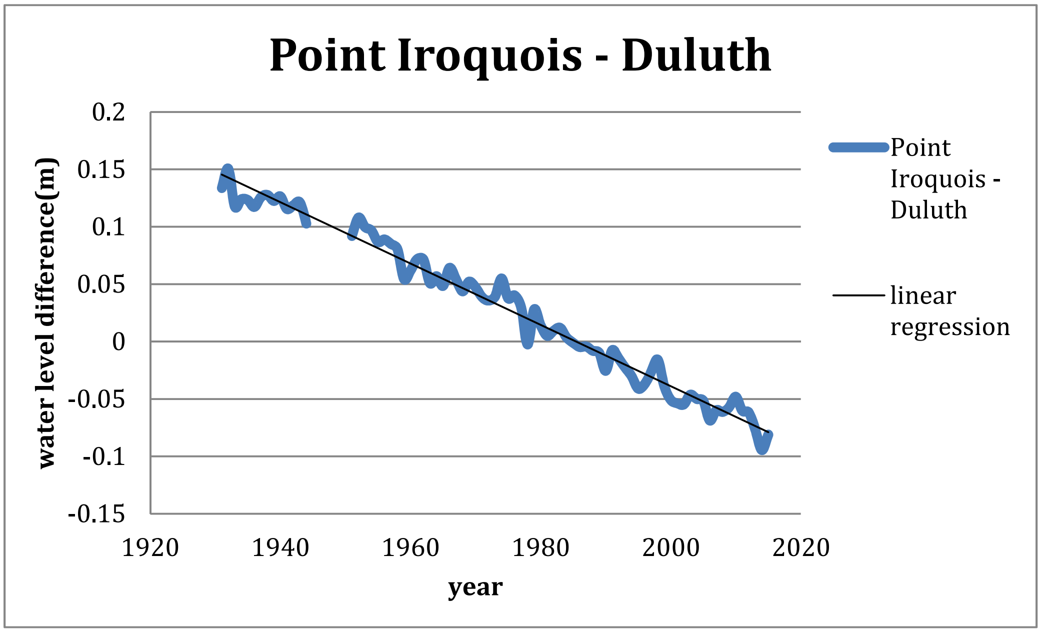

Figure 10. Point Iroquois minus Duluth water level difference plot from 1931 to 2015.

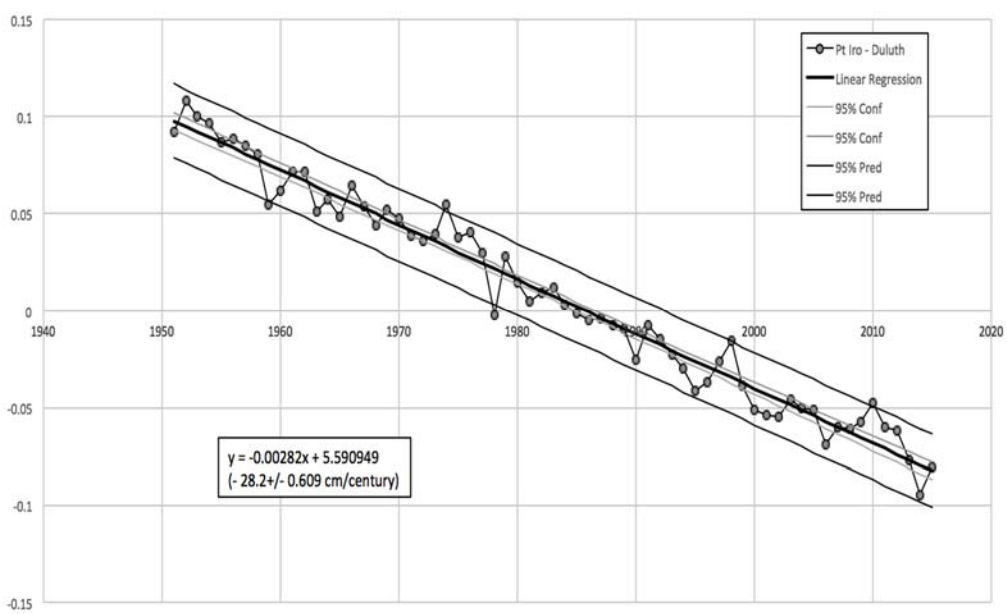

Figure 11. Point Iroquois minus Duluth water level difference plot from 1951 to 2015.

The plot of water level difference between Point Iroquois and Grand Marais is shown in Figure 12. Water level data has been recorded since 1966 at the station Grand Marais, so the water level difference plot starts in 1966 although the data record at Point Iroquois is from 1931. The equation for the linear regression line is y= -0.00092x + 1.8187 (R^2 = 0.73593) (1966 – 2015). The negative slope indicates that the water level at Grand Marais station increased compared to that at Point Iroquois station. The relative rate of vertical ground motion to Point Iroquois is -0.92 +/- 0.079 mm/year (1966 – 2015) at Grand Marais.

There are three potential outliers in the middle of the plot, -0.0175 m in 1978, 0.00825 m in 1998 and -0.00725 m in 2010, but they are not supposed to influence the slope of linear regression. Therefore, we ignored the impacts of outlier according to Bruxer & Southam (2008). Again, the same as Ontonagon, no data need removing in terms of other data-removing decisions listed above. Hence, for this station, all data are used into water level difference plot. The plot with 95% confidence interval is shown in Figure 13.

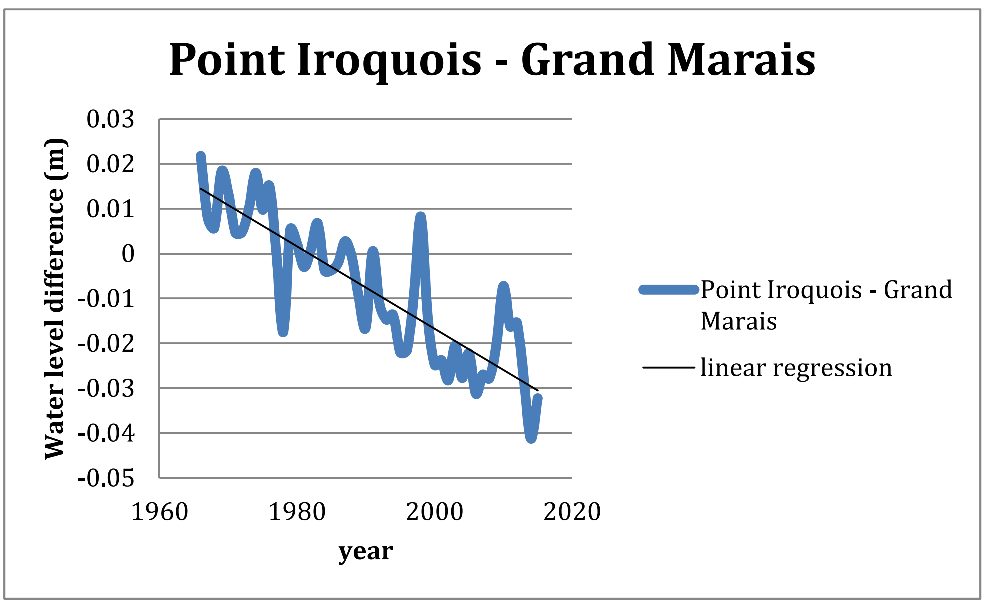

Figure 12. Point Iroquois minus Grand Marais water level difference plot from 1966 to 2015.

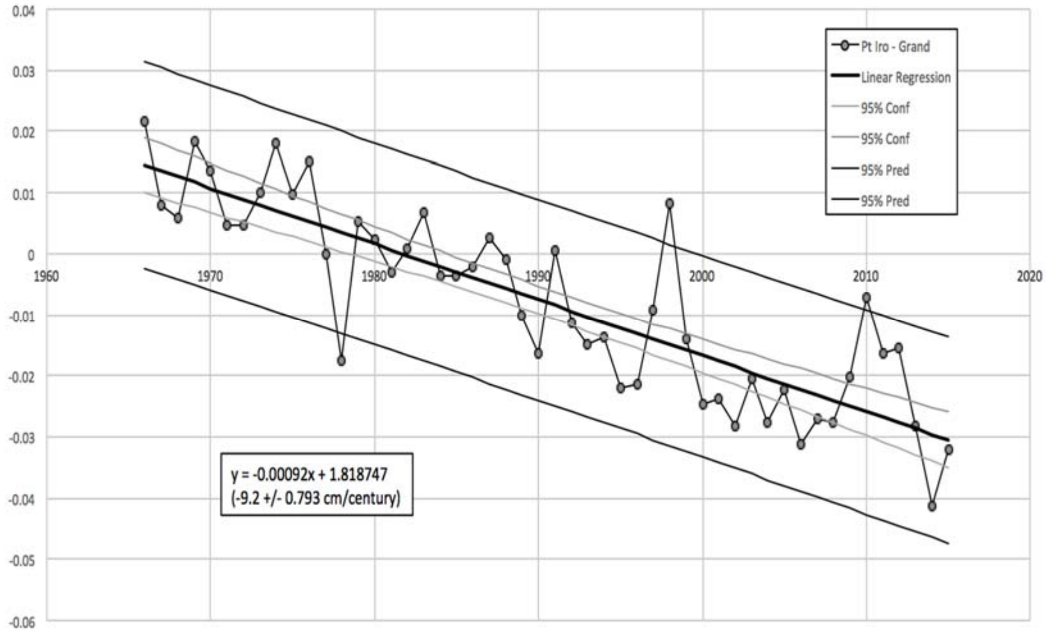

Figure 13. Point Iroquois minus Grand Marais water level difference plot from 1966 to 2015 with a 95% confidence interval constructed.

The plot of water level difference between Point Iroquois and Thunder Bay is shown in Figure 14. Both of the two stations started their water level data records in 1931, so the water level difference plot begins with 1931. The equation for the linear regression line is $y= 0.00035x – 0.7006$ ($R^2 = 0.32305$) (1931 – 2015). The positive slope indicates that the water level at Grand Marais station decreased compared to that at Point Iroquois station. Hence, the ground at Thunder Bay is considered to rise compared with that at Point Iroquois. The relative rate of vertical ground motion to Point Iroquois is 0.35 +/- 0.058 mm/year (1931 – 2015) at Thunder Bay.

Considering the line gap of the years from 1945 to 1950, after constructing a 95% confidence interval and removing data from 1931 to 1944, the relative rate to Point Iroquois is given by the slope of plot in Figure 15, which is 0.15 +/- 0.082 mm/year (1951 – 2015) at Thunder Bay. Based on Bruxer & Southam (2008), it is no need to remove the two potential outliers in the middle of the plot, 0.03475 m in 1976 and -0.036 m in 1978.

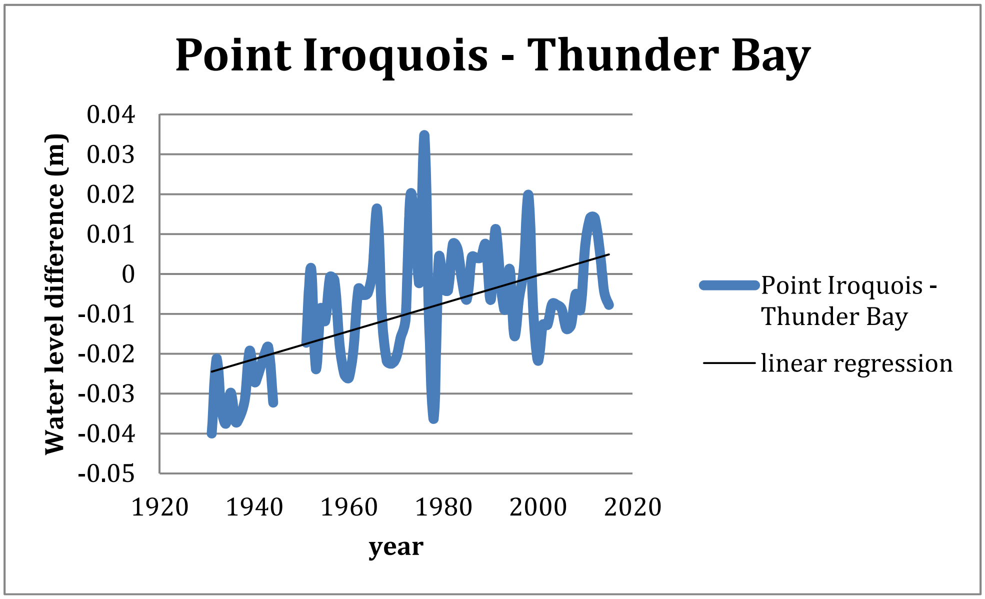

Figure 14. Point Iroquois minus Thunder Bay water level difference plot from 1931 to 2015.

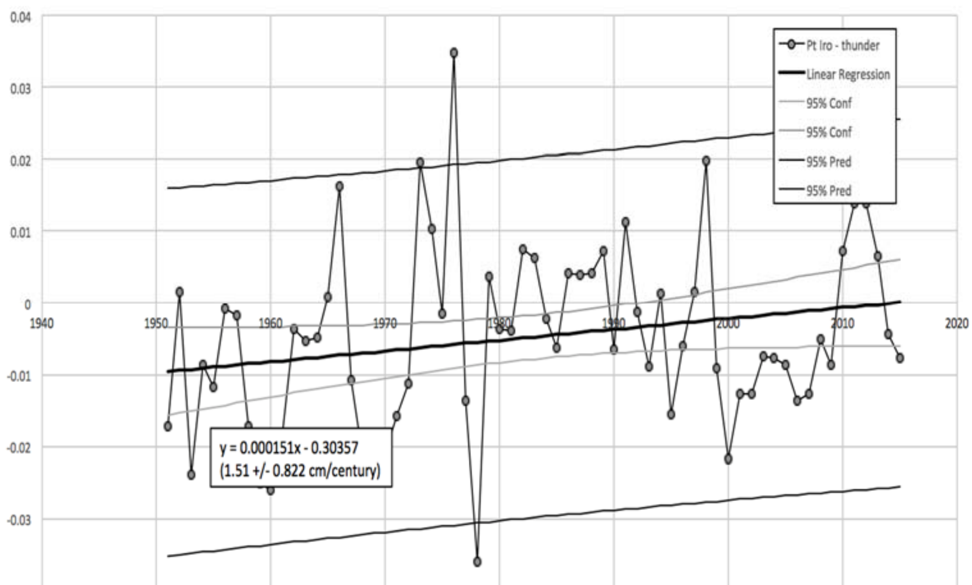

Figure 15. Point Iroquois minus Thunder Bay water level difference plot from 1951 to 2015.

The plot of water level difference between Point Iroquois and Rossport is shown in Figure 16. Water level data record started in 1967 at Rossport, so the water level difference can only be calculated from 1967 although the earliest data record are in 1931 for Point Iroquois. The equation for the linear regression line is y= 0.00242x – 4.5732(R^2 = 0.75621) (1967 – 2015). The positive slope indicates that the water level at Rossport station decreased compared to that at Point Iroquois station. Therefore, the relative rate of vertical ground motion to Point Iroquois is 2.42 +/- 0.149 mm/year (1967 – 2015) at Rossport.

Considering the obvious jumping happened in 1973, we only plot data from 1973 to 2015. The new water level difference plot is shown in Figure 17. The slope is 0.00185 +/- 0.000121 m/year or 1.85 +/- 0.121 mm/year (1973 – 2015), which gives the relative vertical ground motion rate to Point Iroquois 1.85 +/- 0.121 mm/year (1973 – 2015).

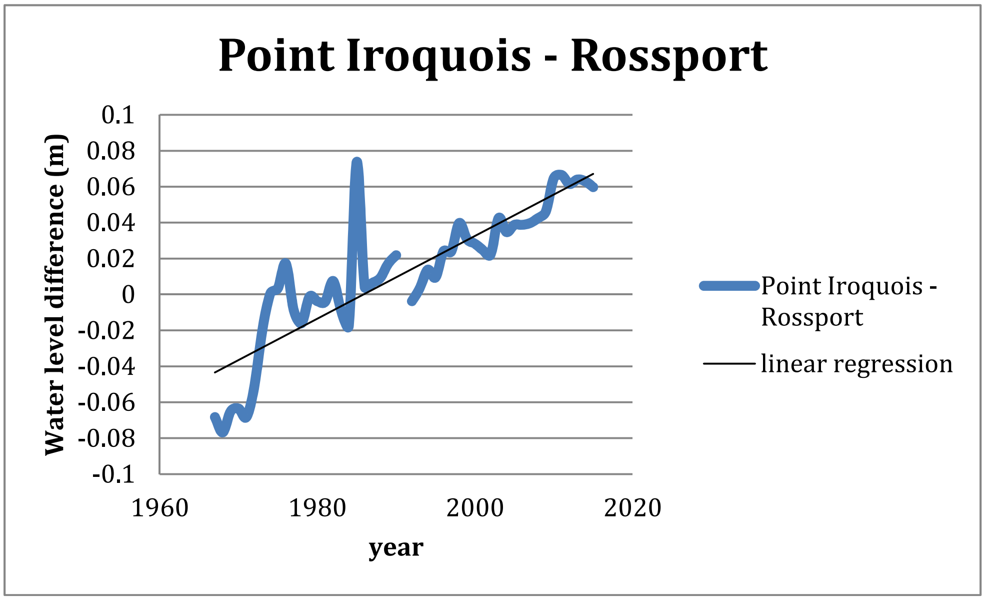

Figure 16. Point Iroquois minus Rossport water level difference plot from 1967 to 2015.

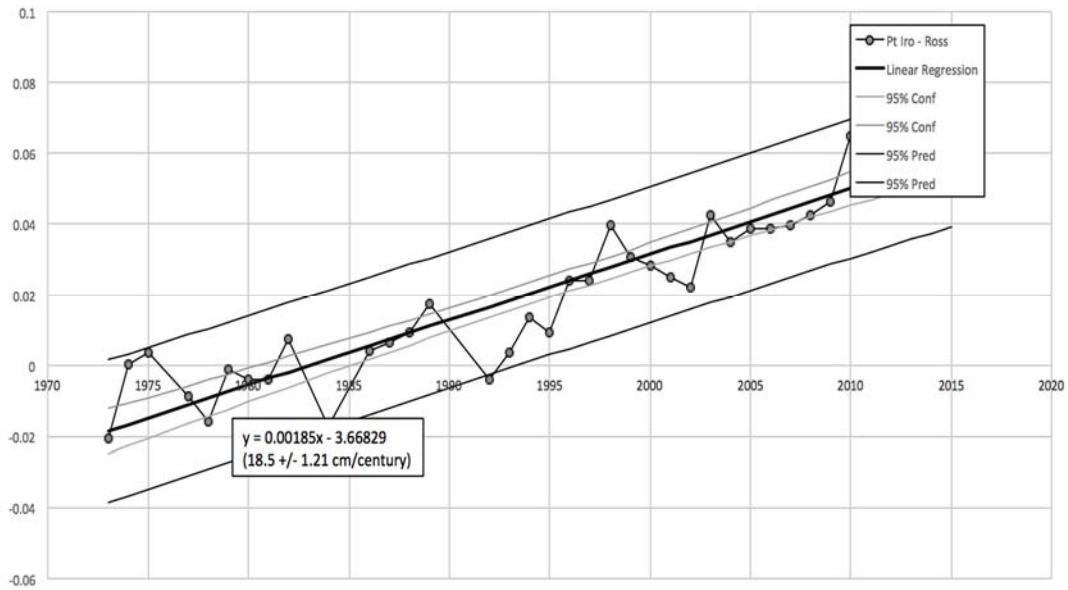

Figure 17. Point Iroquois minus Rossport water level difference plot from 1973 to 2015.

The plot of water level difference between Point Iroquois and Michipicoten is shown in Figure 18. Both of the two stations started their water level data record in 1931, so the water level difference can be calculated from 1931. The equation for the linear regression line is y= 0.00225x – 4.5162 (R^2 = 0.96555) (1931 – 2015). The positive slope indicates that the water level at Michipicoten station decreased compared to that at Point Iroquois station. Therefore, the relative rate of vertical ground motion to Point Iroquois is 2.25 +/- 0.044 mm/year (1931 – 2015) at Michipicoten station.

Considering there is no data from 1945 to 1950, the data of 1931 to 1944 were removed in order to make a continuous curve. The relative rate to Point Iroquois defined by the slope in Fiugre 19 plot is 2.01 +/- 0.053 mm/year (1951 – 2015).

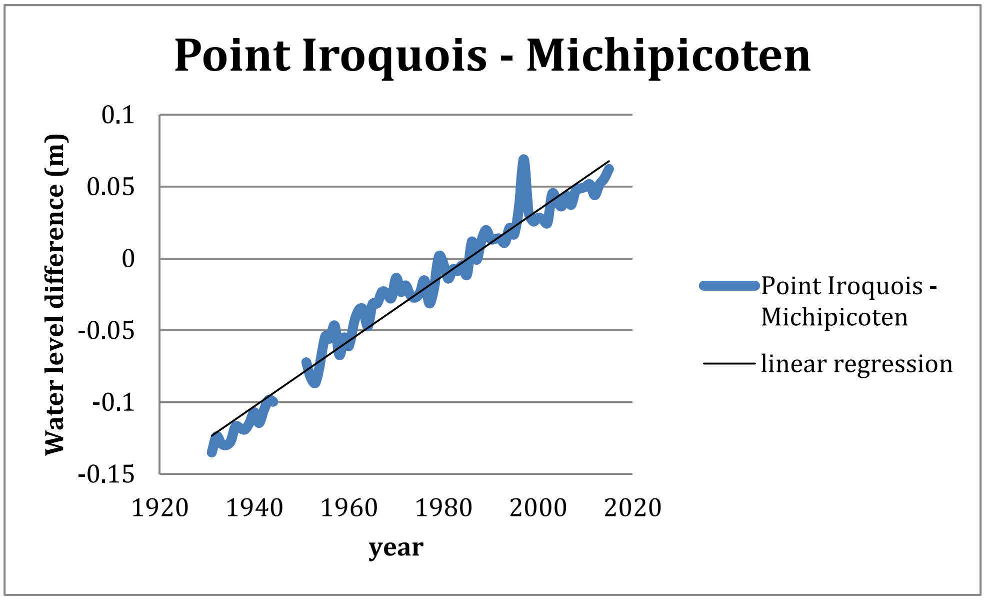

Figure 18. Point Iroquois minus Michipicoten water level difference plot from 1931 to 2015.

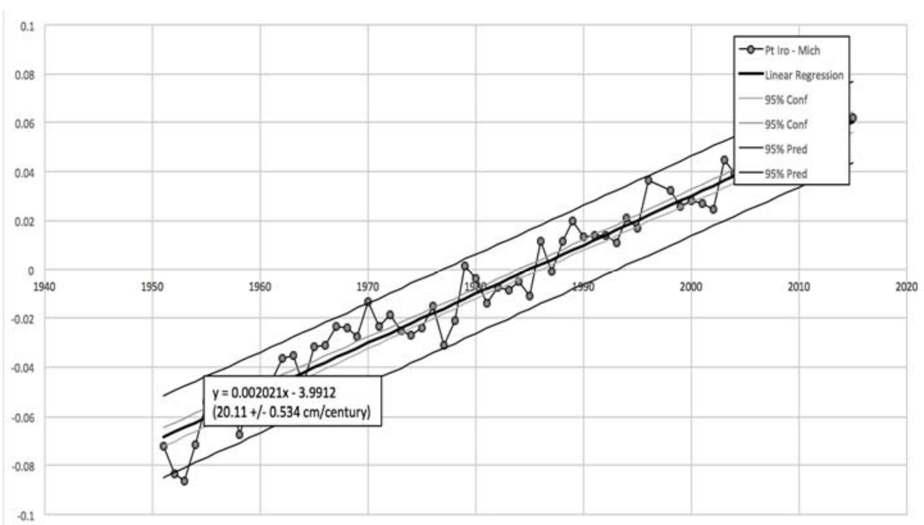

Figure 19. Point Iroquois minus Michipicoten water level difference plot from 1951 to 2015.

The plot of water level difference between Point Iroquois and Gros Cap is shown in Figure 20. Water level data record started in 1961 at Gros Cap, so the water level difference plot is from 1961. The equation for the linear regression line is y= -0.00021x + 0.3298 (R^2 = 0.0165) (1961 – 2015). The negative slope indicates that the water level at Gros Cap station increased compared to that at Point Iroquois station. The relative rate of vertical ground motion to Point Iroquois is -0.21 +/- 0.176 mm/year (1961 – 2015) at Gros Cap.

As mentioned before, there is no need to remove any single outlier of this method to analyze the water level data (Bruxer & Southam, 2008), so the potential outlier of 0.13075 m in 1968 can be still plotted into the refined water level difference plot, shown in Figure 21. However, the recent year since 1986, the water level data observation has become stable; therefore, in Figure 21, the plot removed water level difference from 1961 to 1985. From the plot with outliers removed, the relative rate to Point Iroquois, which is determined by the slope of this water level difference plot, is 0.04 +/- 0.076 mm/year (1986 – 2015).

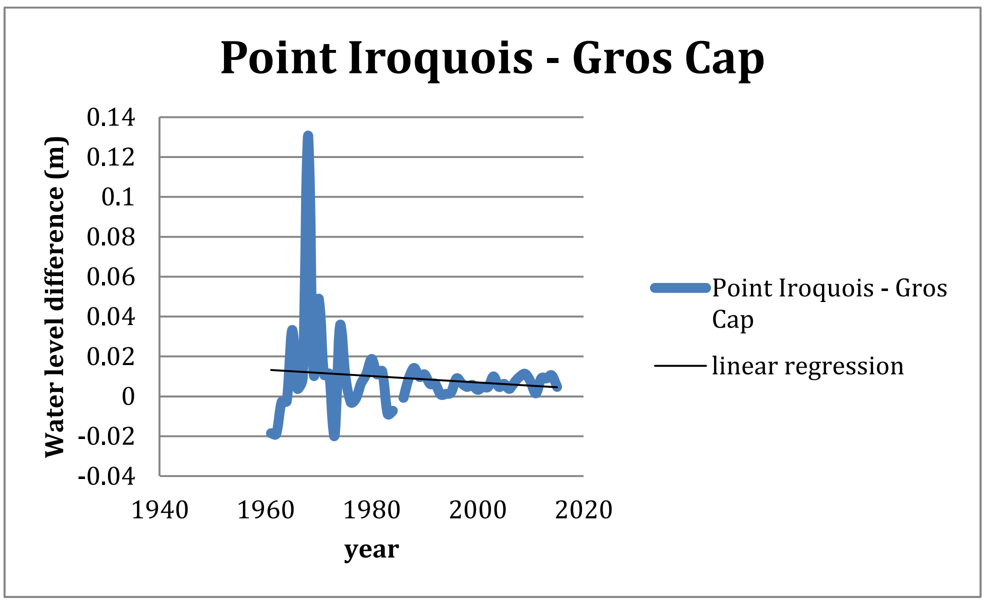

Figure 20. Point Iroquois minus Gros Cap water level difference plot from 1961 to 2015. The data in the years of 1971, 1973, 1983 and 1985 are missing.

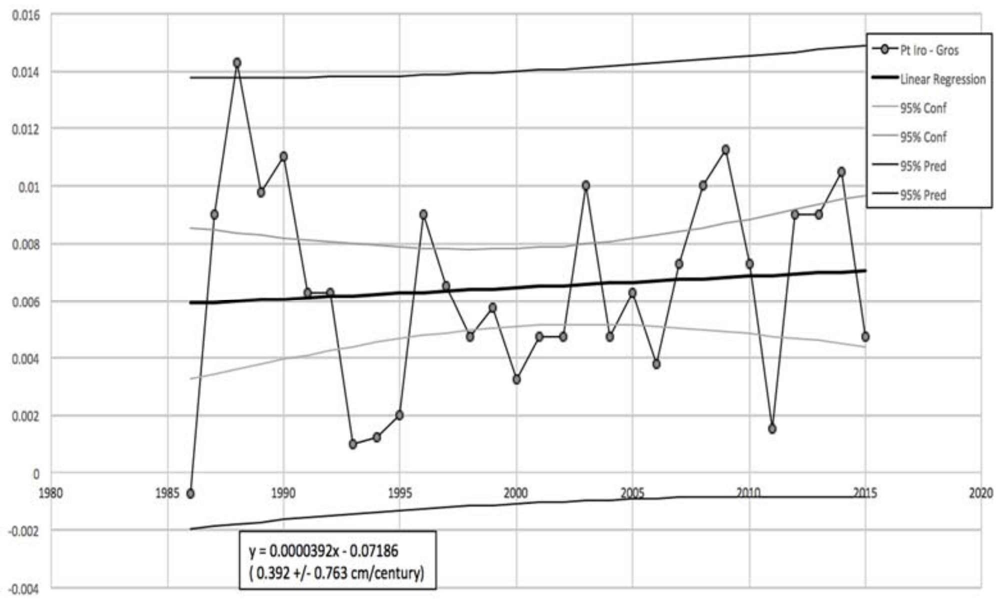

Figure 21. Point Iroquois minus Gros Cap water level difference plot with data before 1986 removed. The plot is from 1986 to 2015.

To summarize the rates associated with GIA obtained by water level gauge data, the following Table 1 shows all the relative rates to Point Iroquois, which is the closest station to the outlet of Lake Superior, of vertical ground motion at the above 8 stations and the standard deviations.

Gauge (Period of Record) **change in range of year analysis*	Rate (mm/year)	Standard Error (mm/year)
Marquette (1931-2015)	-1.03	0.026
**Marquette (1951-2015)*	-0.98	0.035

Ontonagon (1960-2015)	-1.69	0.092
Duluth (1931-2015)	-2.67	0.045
**Duluth (1951-2015)*	-2.82	0.061
Grand Marais (1966-2015)	-0.92	0.079
Thunder Bay (1931-2015)	0.35	0.058
**Thunder Bay (1951-2015)*	0.15	0.082
Rossport (1967-2015)	2.42	0.149
**Rossport (1973-2015)*	1.85	0.121
Michipicoten (1931-2015)	2.25	0.044
**Michipicoten (1951-2015)*	2.01	0.053
Gros Cap (1961-2015)	-0.21	0.176
**Gros Cap (1986-2015)*	0.04	0.076

Table 1. The relative rates to Point Iroquois, which is the closest station to the outlet of Lake Superior, of vertical ground motion at the above 8 stations and the standard deviations. The stations with * in front is the scenarios with data removed. The removed data are described above for each station.

- Pattern

In addition, in order to obtain the general pattern of vertical ground motion of Lake Superior, here compared the vertical ground motion between the eastern and western ends as well as between southern and northern ends of Lake Superior. The plotting of Duluth (western end) minus Gros Cap (eastern end) and the plotting of Marquette (southern end) minus Rossport (northern end) are shown below in Figure 22 and Figure 23 respectively.

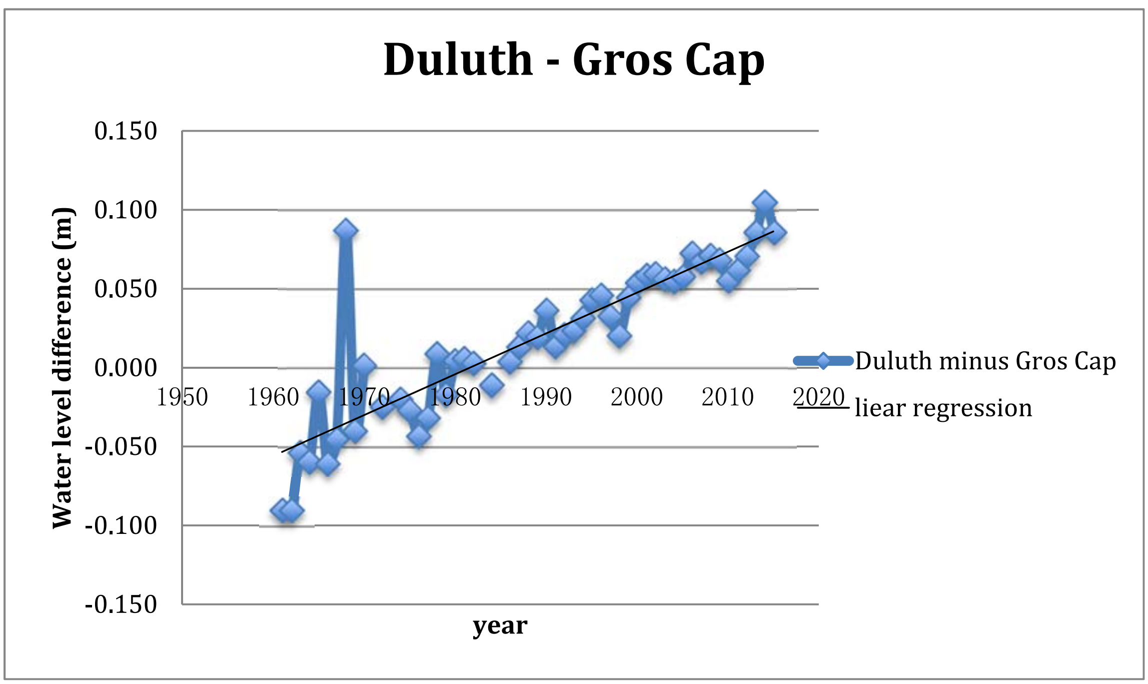

Figure 22. Duluth minus Gros Cap water level difference plot from 1961 to 2015.

Water level data record at Duluth is from 1931 while at Gros Cap is from 1961, so the water level difference between these two stations can be only calculated from 1961. The equation for the linear regression line is y= y = 0.0026x - 5.128 (R^2 = 0.78043) (1961 – 2015). The slope is positive, which indicates that the relative water level at the Duluth station decreased after and including 1961 compared to the Gros Cap station. This decreased rate is 0.0008 m/year (1961 – 2015) between these stations. Therefore, it could be assumed that the ground decreased due to GIA at Duluth compared to that at Gros Cap.

To refine the plot by evaluating data, since it is no need to remove any single outliers, the potential outlier (1968, 0.087) in the middle of the plot can remain. Also, the dataset is continuous without dramatic jump timepoint and high variable period, no data are supposed to be removed.

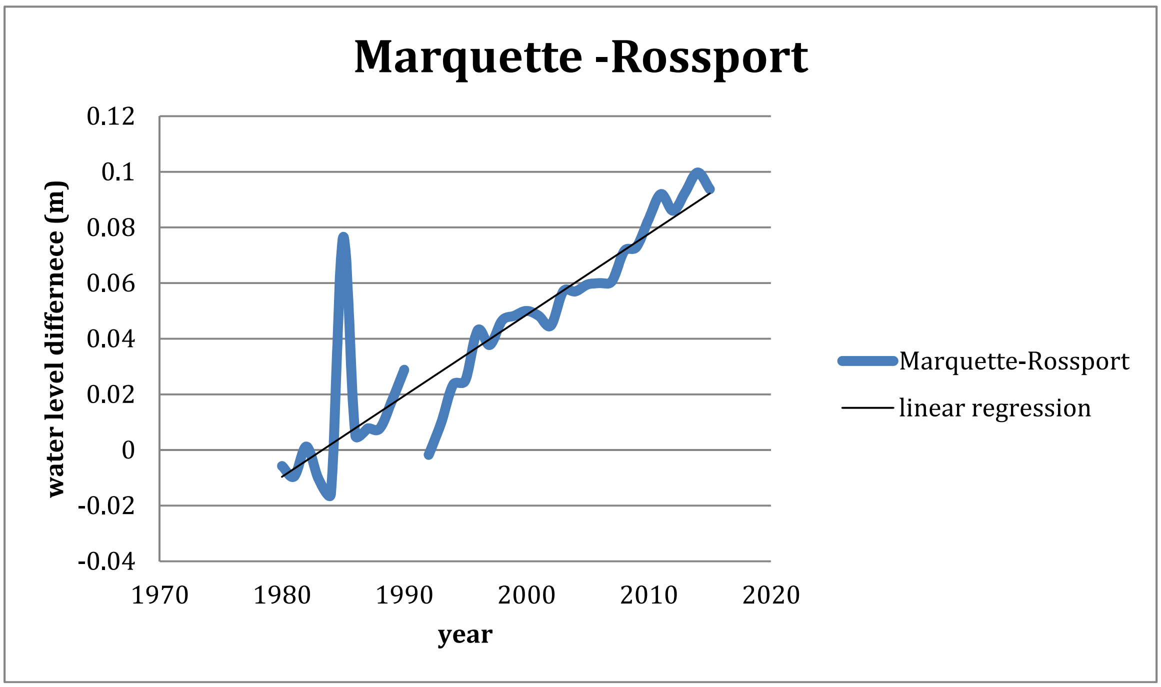

Figure 23. Marquette minus Rossport water level difference plot from 1980 to 2015.

Figure 23 shows the water level difference plot of Marquette minus Rossport from 1980 to 2015. The equation for the linear regression line is y= 0.0029x - 5.772 (R^2 = 0.81159)

(1980 – 2015). The positive slope indicates that the water level at Marquette station decreased after 1980 compared to that at Rossport station. The relative decrease rate is 2.9 mm/year (1980 – 2015).

Considering the significant drop in 1992, the new water level difference plot of Marquette minus Rossport is plotted in Figure 24 by plotting water level difference post 1992. The slope of 0.0032 m/year gives the uplift rate at Rossport relative to Marquette of 3.2 mm/year (1992 – 2015).

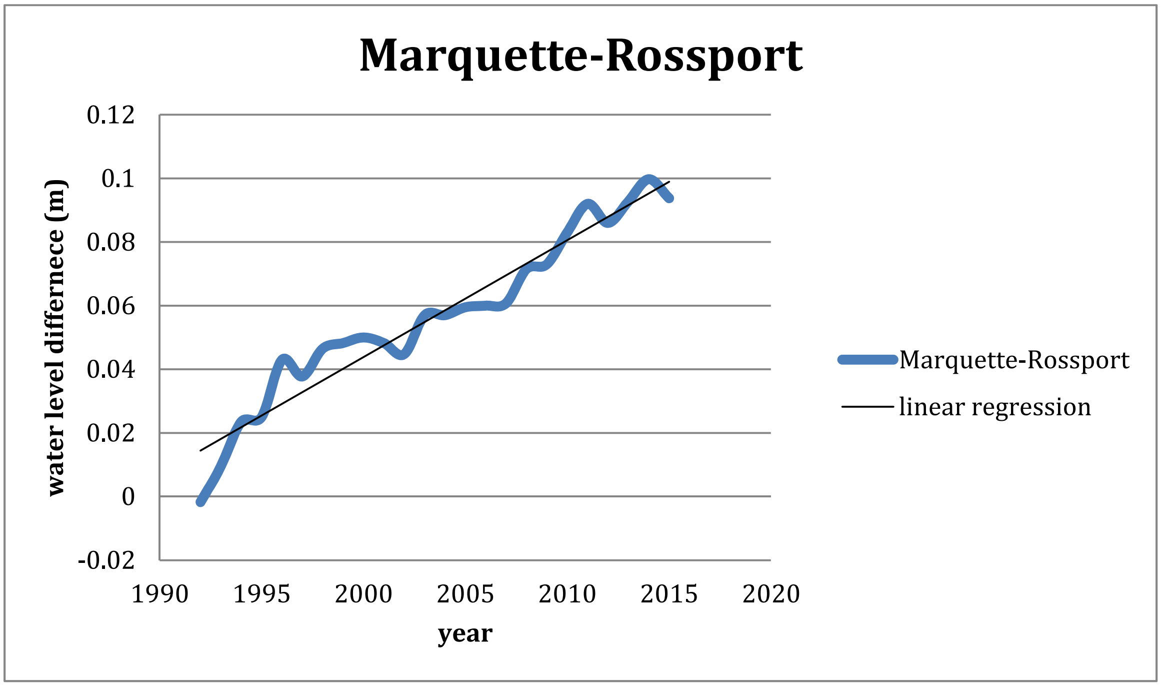

Figure 24. Marquette C.G. minus Rossport water level difference plot from 1992 to 2015.

To summarize the pattern of GIA for Lake Superior obtained from water level gauges data, Figure 25, a map of Lake Superior with the calculated relative rates labeled on the above 8 water level gauge stations, shows the pattern.

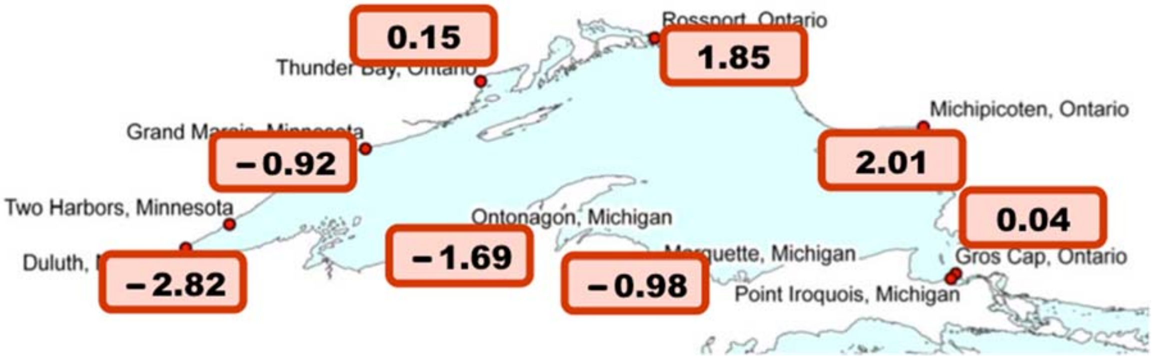

Figure 25. Lake Superior map with relative rate to Point Iroquois labeled for current available water level stations surrounding Lake Superior. All the rate values are reported in mm/year. The rates are obtained from water level difference plots with outliers removed. The range of years of outliers is described above for each station. Map modified from Bruxer and Southam (2008).

As shown in Figure 25, compared to Point Iroquois, the ground is uplifting in the northeastern part of Lake Superior and subsiding in the southwestern part of the lake. The highest rate of rising relative to Point Iroquois is 2.01 mm/year at the northeast point of the lake while the greatest falling rate relative to Point Iroquois is -2.82 mm/year at the southwest corner of the lake. The difference of relative rate of vertical ground motion for the whole lake is 2.01 mm/year - (-2.82 mm/year) = 4.83 mm/year. Combined with the rate pattern analyzed in Figure 12 and 13, the result is that each year the crust vertical difference underneath the lake would change by 4.83 mm with relative subsidence to the southwestern end and relative uplift to the northeastern end. The rate gradient in terms of distance, which is 4.83 mm/year over 412 km of the lake from southwest end to northeast end, gives the value of 0.0117 mm/year/km, or 0.117 cm/century/km.

Discussion

GPS Data

- Rates

According to the results of GPS, after a long time, the ground vertical position would have a significant change. If the rate change is considered nearly as a constant recently and in the future, after a century the places on the isobase of the highest elevation rate would rise up by 36 cm; also, the ground under the places with the lowest rate of vertical ground movement would drop down by 9 cm. Hence, the maximum elevation difference of Lake Superior will probably increase by 45 cm after a century.

- Pattern

Based on the pattern described in the results of GPS, because the rate gradient is 0.02 mm/year per kilometer, passing 100km along the direction that perpendicular to the isobase lines, which is 24.19°SW (i.e. strikes 204.19°N), the rate would decrease fastest, by 2 mm/year. Hence, if over a century, two sites with a distance of 100 km along that normal direction to the isobases would add their crust elevation difference by 20 cm. Error and inaccuracy of this analysis is caused by the intrinsic limitations of this evaluating method for GPS. Firstly, because the GPS data is limited spatially, the isobases of 0.5 mm/year, 0.0 mm/year and -0.5 mm/year can only be obtained by estimating. Secondly, all the points with 0.5n (Again, n = -1, 0, 1, 2, 3, …) mm/year are determined by considering the rate change is linear. It is definitely that the rate change following other nonlinear pattern or a complex form without certain logical pattern. Also, since the Laurentian Ice Sheet has been gone for a long time, assuming an exponential function, the analysis considers that during historical time the rate is close to be a constant over time; however, actually, the rate should decrease over time.

Water Level Gauges Data

- Rates

Comparisons between all eight stations were performed by plotting all the water level difference data after the variable data was removed (Figure 26). In Figure it can be seen that the stations along the southwest boundary of Lake Superior, which are Grand Marais, Duluth, Ontonagon and Marquette, have negative slopes while the stations along the northeastern boundary have positive slopes. Because the slopes represent the relative rates of vertical ground motion relative to Point Iroquois, the distribution of sign of values shows that the northeastern lakeside is uplifting and the southwestern lakeside is subsiding. For the stations with negative slopes, Duluth has the largest subsidence rates relative to Point Iroquois, larger than Ontonagon, following by Marquette, and slowest subsiding station is Grand Marais. For the stations with positive slope values, these stations are uplifting relative to the ground surface at Point Iroquois. From the fastest rate to the slowest rate of relative uplift to Point Iroquois, the stations are Michipicoten, Rossport, Thunder Bay and Gros Cap.

To compare water level gauge data to GPS data the rate of vertical ground motion (relative to a fixed point in the center of Earth) at Point Iroquois was obtained by estimating a value from contoured GPS data or the isobase profile map (Figure 5). This absolute value of 1.2 mm/year for Point Iroquois can then be used to derive an absolute value for each station by using each rate in relative movement. The 8 stations of absolute vertical motion relative to the geo-center is -1.62 mm/year for Duluth, -0.49 mm/year for Ontonagon, 0.22 mm/year for Marquette, 0.28 mm/year for Grand Marais, 1.24 mm/year for Gros Cap, 1.35 mm/year for Thunder Bay, 3.05 mm/year for Rossport and 3.21 mm/year for Michipicoten. According to this group of rates, there are two stations Duluth and Ontonagon where the ground surface is falling, while the ground surface at other stations is rising. Therefore, according to the analysis of water level gauges data after absolute rated are derived, subsidence is occurring in the southwest end of Lake Superior while uplift is occurring in the rest of the lake. This ground movement is associated with glacial unloading and is interpreted to represent the effects of glacial isostatic adjustments or GIA.

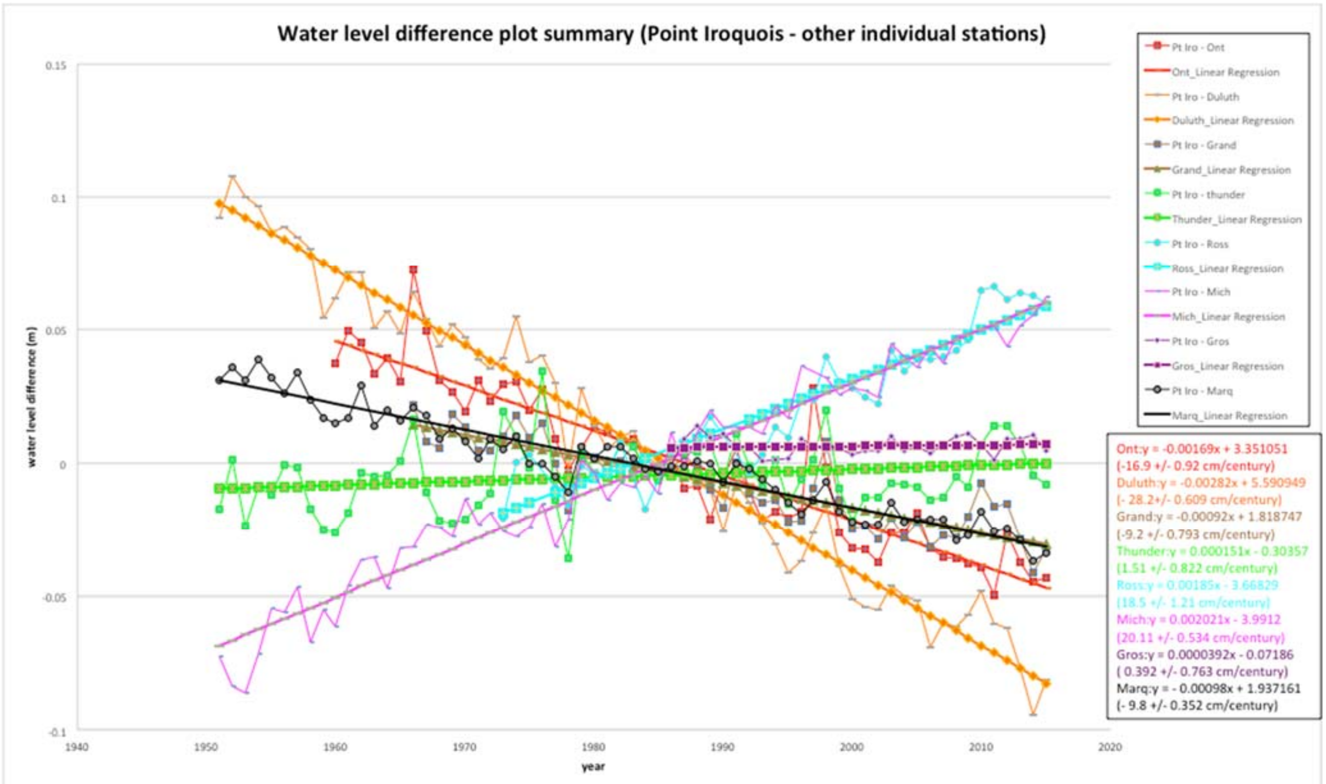

Figure 26. Summary plot of water level difference between Point Iroquois and eight other individual stations around Lake Superior.

1). Removing early variable data

The difference in slopes or relative rate of vertical ground movement between years including variable data and not including variable data are shown in Table 2. Variable data was removed for six stations while all data was used for two stations in the analysis. These two stations where differences in slope were not calculated were Ontonagon and Grand Marais. Removing earlier years of variable data influences slopes of water level difference plots and hence interpretation of GIA.

Water Level Gauge Stations	Rate & Error (mm/year)		Difference (mm/year)
	including variable data	removing variable data	
Marquette C.G.	-1.03 +/- 0.026	-0.98 +/- 0.035	0.05
Ontonagon	-1.69 +/- 0.092		
Duluth	-2.67 +/- 0.045	-2.82 +/- 0.061	0.15
Grand Marais	-0.92 +/- 0.079		
Thunder Bay	0.35 +/- 0.058	0.15 +/- 0.082	-0.2
Rossport	2.42 +/- 0.149	1.85 +/- 0.121	-0.57
Michipicoten	2.25 +/- 0.044	2.01 +/- 0.053	-0.24
Gros Cap	-0.21 +/- 0.176	0.04 +/- 0.076	0.25

Table 2. Comparison of rates by including variable data and not including variable data water level difference plots and difference between rates for current available water level gauge stations surrounding Lake Superior.

To evaluate whether removing the early variable data significantly changed the rate at each gauge station, errors about the slope were investigated. Figure 27 shows a comparison of the error range in rates obtained by plots with including variable data and plots with removing variable data for the six stations Marquette, Duluth, Thunder Bay, Rossport, Michipicoten and Gros Cap. These ranges of rates were obtained by the rate values plus and minus their corresponding error values.

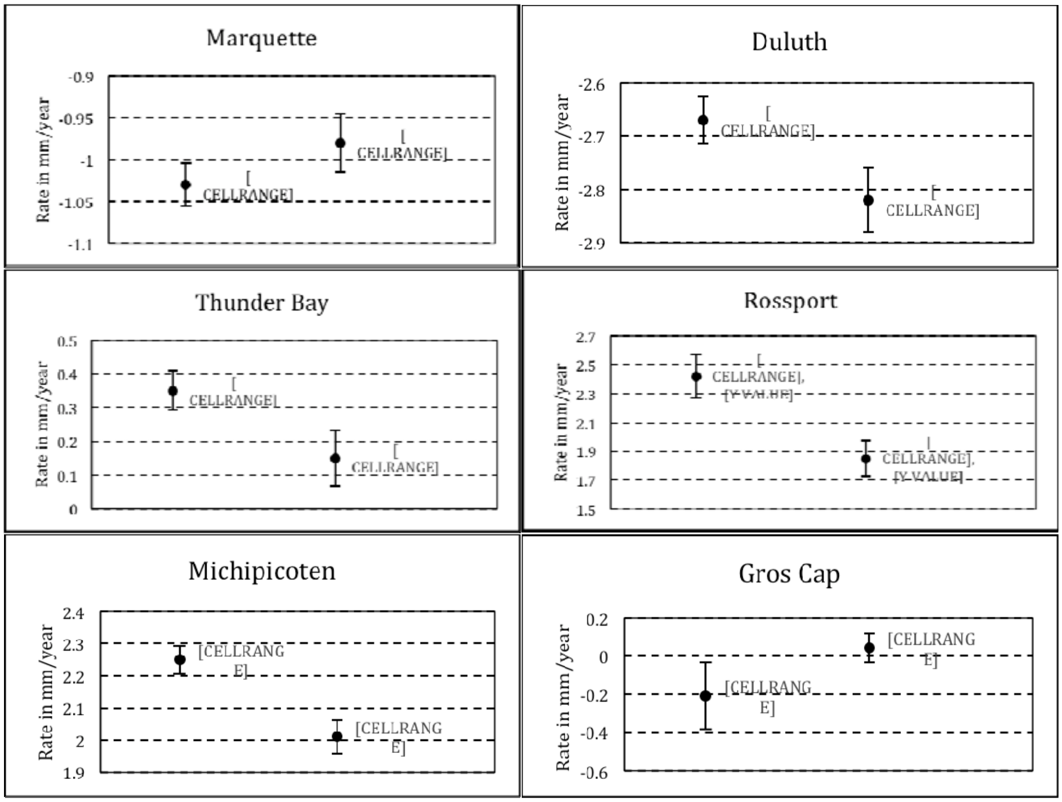

Figure 27. The comparison of the slopes and associated error range including variable data (left) and removing variable data (right) for each of the six water level gauge stations. Please note: for the stations Marquette, Duluth, Thunder Bay, and Michipicoten, the rate by includinging variable data is from 1931 to 2015 while the rate by removing variable data is from 1951 to 2015; for Rossport, the rate by including variable data is from 1967 to 2015 while the rate by removing variable data is from 1973 to 2015; for Gros Cap, the rate by non-removing variable data is from 1967 to 2015 while the rate by removing variable data is from 1973 to 2015.

From Figure 27, we can see that there are two stations, Marquette and Gros Cap where the two error ranges overlap. Hence, the rates at this station by including variable data and removing variable data are statistically similar. Therefore, for two of the six stations, removing variable data does not influence the slope or relative rate of ground movement. For the other four stations, Duluth, Thunder Bay, Rossport, and Michipicoten, the rates from including and removing variable data are not statistically similar. Therefore, for these four stations or the majority of gauge stations studied, removing variable data in water level difference plots influences the slopes or relative rate of ground movement. It is expected that removing the early variable data improvements makes to better estimate long-term rates of glacial isostatic adjustment. And close attention should be made to the quality of the early data collected by gauge stations because it has be shown to greatly influence the interpreted rate of GIA.

2). Updating Datasets

The rates and errors obtained by updating water level data to 2015 appear to be different than the rates and errors reported by Bruxer and Southam (2008). Table 3 shows the rates and error results from water level data updated to 2006 and data updated to 2015. Also, Figure 28 shows a comparison of the acceptable ranges of rates update to 2006 and rates update to 2015 for the all the eight stations.

Gauge (Start year of record) * change in range of year analysis (Start year of record)	Rate and Standard Error (mm/year)		Rate difference (mm/year) between update to 2006 and update to 2015
	Update to 2006	Update to 2015	
Marquette (1931-)	-1.05 +/- 0.032	-1.03 +/- 0.026	0.02
*Marquette (1951-)	-0.978 +/- 0.045	-0.98 +/- 0.035	0.002
Ontonagon (1960-)	-1.732 +/- 0.127	-1.69 +/- 0.092	0.042

Duluth (1931-)	-2.685 +/- 0.053	-2.67 +/- 0.045	0.015
*Duluth (1951-)	-2.900 +/- 0.073	-2.82 +/- 0.061	0.08
Grand Marais (1966-)	-1.026 +/- 0.101	-0.92 +/- 0.079	0.106
Thunder Bay (1931-)	0.384 +/- 0.070	0.35 +/- 0.058	-0.034
*Thunder Bay (1951-)	0.129 +/- 0.106	0.15 +/- 0.082	0.021
Rossport (1967-)	2.455 +/- 0.221	2.42 +/- 0.149	-0.035
*Rossport (1973-)	1.541 +/- 0.164	1.85 +/- 0.121	0.309
Michipicoten (1931-)	2.339 +/- 0.052	2.25 +/- 0.044	-0.089
*Michipicoten (1951-)	2.063 +/- 0.071	2.01 +/- 0.053	-0.053
Gros Cap (1961-)	-0.291 +/- 0.252	-0.21 +/- 0.176	0.081
*Gros Cap (1986-)	-0.111 +/- 0.133	0.04 +/- 0.076	0.151

Table 3. Relative rates to Point Iroquois and standard errors from water level data updated to 2006 (Bruxer and Southam 2008) and data updated to 2015. Please note that the rate difference is the rate update to 2015 minus the rate update to 2006.

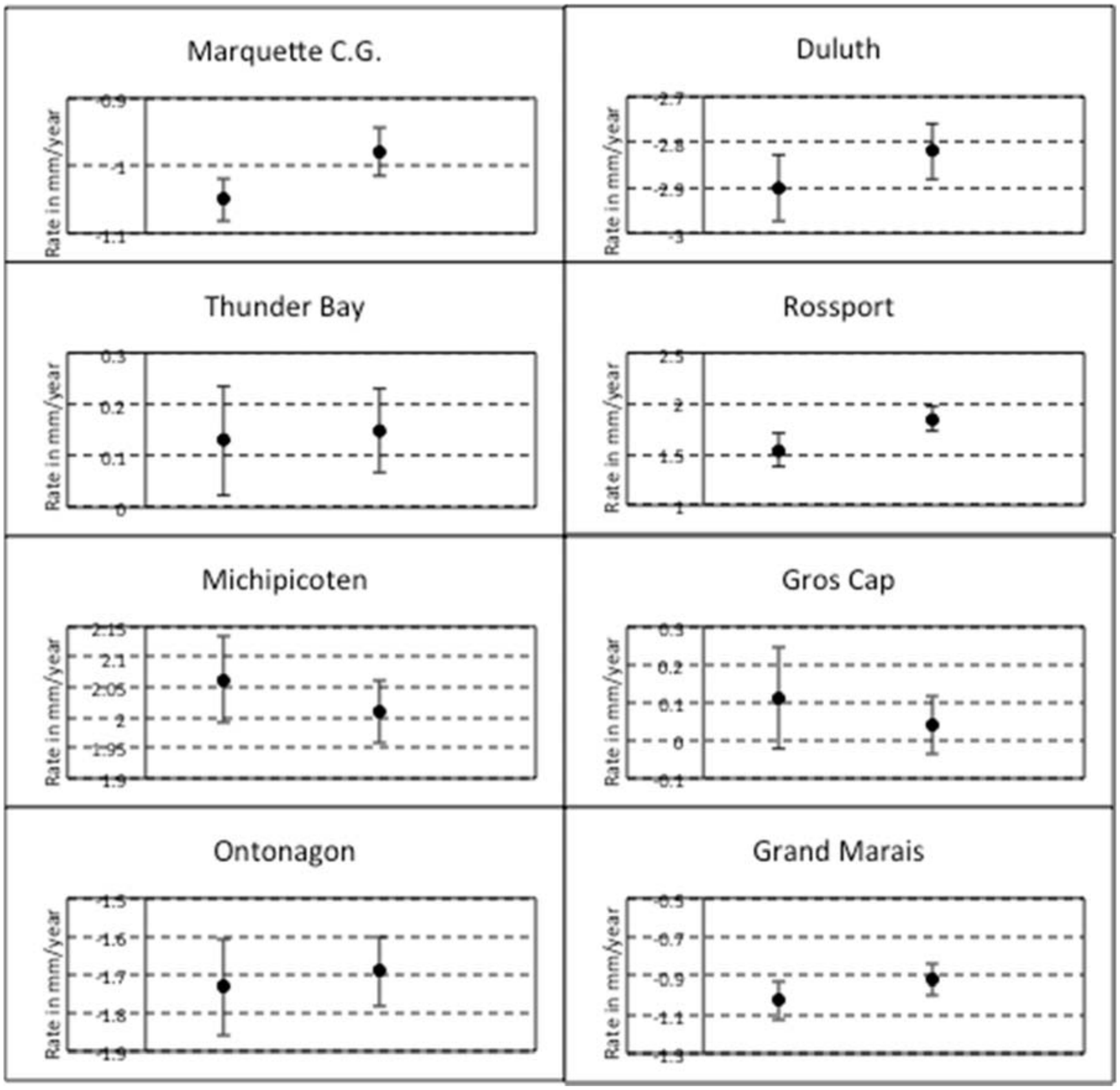

Figure 28. The comparison of the acceptable ranges of rates update to 2006 (left in each plot) and rates update to 2015 (right in each plot) for all of the eight stations. For the stations Marquette, Duluth, Thunder Bay, Rossport, Michipicoten, and Gros Cap, this figure uses the rates obtained from water level difference plots with variable data removed. For the other two stations without variable data, this figure uses the rates obtained from their water level difference plots with all data applied.

From Figure 28, except Marquette and Rossport, the error ranges for the other stations overlap. Hence, for the majority of the stations, the new updating to 2015 is statistically similar as the result updated to 2006. Also, for the two stations without ranges overlapping, the two ranges are relatively close to each other as shown in Figure 28. This may indicate the updating does not change in rate by much.

In addition, the errors of rates decrease for the data updated to 2015 compared with the data updated to 2006 as shown in Table 3. This indicates that the new collected data from 2007 to 2015 have the similar change trends as their pre-collected data. Also, because all stations, after removing the variable data in earlier year, the lengths of recorded data used for analysis are not very long. Before updating, the length of data used for plotting varies from 56 years (Marquette, Duluth, Thunder Bay and Michipicoten) to 21 years (Gros Cap). Taking Gros Cap for example, after removing variable data, the data used for plotting by Bruxer and Southam (2008) is from 1986 to 2006, so there are only 21 years used into plot. For this reason, the new update that adds 9-year (from 2007 to 2015) data into plots would increase the length of data record significantly. Therefore, the decreasing error may be reasonable because there are more data added to the database, which makes the recording period of data longer than before.

As Bruxer and Southam (2008) mentioned, the longer period of water level data record would make the analysis better and more accurate. For this new analysis updated to 2015, the length of period of recorded data used in this analysis is longer than the analysis updated to 2006. Therefore, the results for this updating tend to be more accurate. However, most of the slopes are statistically similar and may not suggest a change in the previously interpreted rate of GIA. But the period of data record is still limited to decades, which is much shorter compared to the length of period that GIA has been occurring (several millennia). But these results obtained by analyzing relatively short period of data are a good estimation of GIA between GPS and geologic or ancient shorelines records.

Besides the length of record, Bruxer and Southam (2008) list some other factors that may influence the interpreted rate and not be related to GIA. These include meteorological factors, calculation process, information missing, and invalidity of a linear regression. Meteorological factors are eliminated by only including data collected in summer months and calculating rates over several decades. Information missing is mainly caused by using data from only June to September. Also, the analysis is based on the water level difference to Point Iroquois; the lengths of period of data record for several other stations are different from the length of period of data record by Point Iroquois, which would lead to information missing for the station with longer period of data record. A linear regression model is applied because it is the simplest model that can be applied consistently to all water level difference plots and best represents the end of a long-term exponential function that describes GIA.

- Pattern

For the pattern obtained by analyzing water level data, we can see the stations with negative relative rates to Point Iroquois are all in the southwestern part of Lake Superior. For the stations with positive relative rates to Point Iroquois, the stations in southwestern lakeside of Lake Superior have the smaller relative rates than the stations in northeastern side of the lake. Also, the maximum negative rate is at Duluth, the southwest end of the lake; the maximum positive rate appears at Michipicoten, the northeast end of the lake.

In order to compare the western end with eastern end of Lake Superior and compare the southern end with the northern end of the lake, two plots of water level difference between Duluth and Gros Cap (Figure 22) and between Marquette and Rossport (Figure 24) were plotted in result.

For the plot of water level difference between Duluth and Gros Cap (Figure 22) in result, since the Gros Cap is on the eastern end of Lake Superior while Duluth is on the western end of the lake, based on the rate, the crust vertical difference caused by GIA underneath the lake would change by 2.6 mm with the western end relative subsidence and the eastern end relative uplift.

For the plot of water level difference between Marquette and Rossport (Figure 24) in result, considering that the Rossport station is at the northern end of Lake Superior while Marquette C.G. is at the southern corner of the lake, according to the rate, the vertical difference of ground underneath the lake would change by 3.2 mm with the southern corner relative falling and the northern corner relative rising after a year.

Also, a rate gradient in terms of distance of 0.0117 mm/year/km is obtained in result. The rate gradient is calculated by the rate difference between the southwest end and the northeast end, which is the maximum rate difference, divided by the distance between these two ends. The value of 0.0117 mm/year/km indicates that if passing 100 km along the direction parallel to the line defined by southwest end and northeast end, the vertical ground movement rate would change 1.17 mm/year. The distance between the southwest end Duluth station and the northeast end Michipicoten is about 412 km. Therefore, it can be assumed that after a century, the ground would tilt down toward the southwest end of Lake Superior relative to the northeast end of the lake by 482.04 mm (= 0.0117 mm/year/km * 412 km * 100 year) or 0.48204 m, nearly half a meter.

Comparison

1. Comparison between analysis results between GPS data and water level gauges data

- Rates

The rates of vertical ground motion obtained from GPS data and water level gauges data have different meanings.

For the rates in isobase profile obtained from GPS data are the absolute rates of vertical ground movement. This set of rates is the rate of vertical ground movement relative to the earth geo-center. However, for the rates obtained from water level gauge data for the 8 water level gauge stations, which are Marquette, Ontonagon, Duluth, Grand Marais, Thunder Bay, Rossport, Michipicoten and Gros Cap, are rates relative to Point Iroquois. For instance, the rate for station Ontonagon is equal to the vertical ground movement at Point Iroquois minus that at Ontonagon.

For this reason, in order to compare the two sets of rates, this research converted the absolute rates obtained by GPS into the relative rates to Point Iroquois.

The first step is plotting the above 8 water level gauge stations and Point Iroquois on to the map of isobase constructed from GPS dataset, as shown by Figure 29.

Then, the rates of vertical ground motion for above 8 stations and Point Iroquois can be estimated from the map or obtained from the spreadsheet by Peltier et al (2015). For the station Thunder Bay, Rossport and Gros Cap, the rates can be obtained from Peltier et al (2015). For the stations, Marquette C.G., Ontonagon, Grand Marais, Michipicoten and Point Iroquois, the rates are obtained by estimating the values in between isobases based on the assumption that rates change linearly through distance. For the station Duluth, there is no nearby isobase around this station. Because it can be seen that the distance between every adjacent isobases is approximately the same, the rate gradient obtained in result can be used to estimate the rate at Duluth. Again, these rates obtained from the map of isobases are the absolute rates of vertical ground movement relative to the earth geo-center. These rates are listed in Table 4.

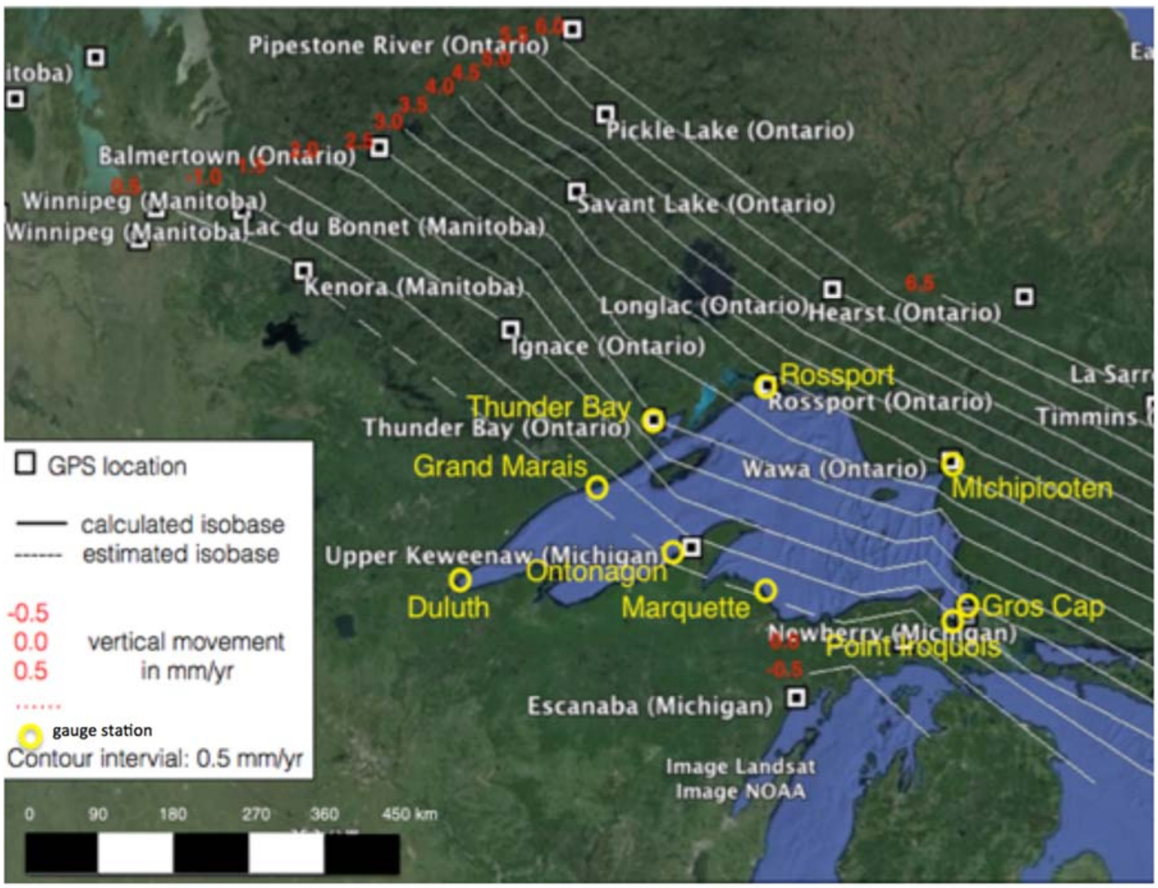

Figure 29. Water level gauge stations plotting on the isobase profile map based on GPS dataset.

Stations	Rate (mm/year) by GPS	
	Rate	Error
Marquette C.G.	(0.4)	
Ontonogan	(0.2)	
Duluth	(-0.9)	
Grand Marais	(0.5)	
Thunder Bay	2.5	±2.1
Rossport	3.3	±2.1
Michipicoten	(3.4)	
Gros Cap	1.3	±2.8
Point Iroquois	(1.2)	

Table 4. Rates of vertical ground motion relative to the earth geo-center at 8 water level gauge stations surrounding Lake Superior estimated by the map of isobases constructed by GPS data. Note that the rates in parentheses are the estimated values from isobase profile map while the ones without parentheses are the values reported by Peltier et al (2015). The vacancies in error list mean that the error values for the rates at the corresponding stations are unknown.

Calculating the rate of absolute vertical motion at each of the above 8 stations by subtracting the rate at Point Iroquois from them could convert these absolute rates for the 8 stations to the relative rates to Point Iroquois.

This series of rates of vertical ground movement calculated by GPS data and the relative rates obtained by water level gauges data are summarized in Table 5.

Stations	Relative rate (mm/year) to Point Iroquois by GPS	Water level differences (mm/year) to Point Iroquois by water level gauges
Marquette C.G.	-0.8	-0.98 +/- 0.0352
Ontonogan	-1.0	-1.69 +/- 0.0920
Duluth	-2.1	-2.82 +/- 0.0609
Grand Marais	-0.7	-0.92 +/- 0.0793
Thunder Bay	1.3 +/- 2.1	0.15 +/- 0.0822
Rossport	2.1 +/- 2.1	1.85 +/- 0.1210
Michipicoten	2.2	2.01 +/- 0.0534
Gros Cap	0.1 +/- 2.8	0.04 +/- 0.0763
Point Iroquois	0	0

Table 5. Relative rates to Point Iroquois by GPS data and water level differences to Point Iroquois by water level gauges data (with errors). Again, the errors of some rates related to GPS are unknown.

Comparison between these two sets of rates listed in Table 5 shows that if taking the errors of water level differences into consideration, there is only station Gros Cap having the consistent values of relative rates by GPS and water level gauges. While, if the errors for GPS data are considered as well, the three stations of Thunder Bay, Rossport and Gros Cap, of which the errors for GPS data are known, show the two values in agreement. Therefore, speculating that if the errors of rates for all the 8 stations are known, the two rate values could be of highly potential to be consistent with each other.

- Pattern

In terms of the pattern of GIA, the results obtained by the two methods are similar. Both of the results show a pattern of subsidence at the southeastern part of Lake Superior and uplift at the northwestern part of the lake. The highest rates of uplift and subsidence obtained by the both two methods are at the northeast end and the southwest end of the lake respectively. The rate gradient with respect to distance is 0.02 mm/year/km calculated by GPS while the gradient by water level gauges is 0.0117 mm/year/km. The two gradient values are in agreement with each other considering the great variability caused by GPS data collection and water level data analysis.

2. The potential reasons for any differences between the results from GPS data and water level gauge data

The two datasets and the analysis methods for the two datasets would lead to significant variability. The main reasons for this variability can be separated into spatial aspect and temporal aspect.

In terms of spatial aspect, for GPS data, there are 24 observed sites in the Lake Superior region, but these stations are all in northern part of the lake. No observation in southwestern end of the lake. Therefore, the rates in southwestern part of the lake could only by estimated and interpreted. Also, the isobase map is created by assuming that the rate changes linear through distance. However, the pattern of rate change in reality is not likely to be linear. For water level gauges data, although the gauge stations are surrounding the whole Lake Superior, there are only 8 stations (not considering the reference station Point Iroquois) available currently. The limitation of station could lead to inaccuracy of result of pattern.

With respect to temporal aspect, the amount of data used for analyzing, the way to choose data and the model to process data would result in error. For GPS data, the length of the period of data record is about 5 year to 20 year, which is very short compared to the long period of GIA. For water level gauges data, the analysis process would cause information missing because only data from summer months are chosen to calculate annual average. Also, the water level data has been recorded for several decades, the length of the period of data record is still short compared to the long historical time period of GIA. In terms of the model for data analysis for the two dataset, by assuming the decreasing or negative exponential function, the rate of GIA is considered to be a constant through time during historical time because the Laurentian Ice Sheet has gone for a long time; however, the rate should decrease gradually.

In addition, in terms of future analysis for shoreline data, the result may be different with the results by GPS data and water level gauges data. Also, the potential reasons include two aspects. Spatially, there are only 4 sites observed, and these observed sites are all in southeast part of Lake Superior. Again, Johnston et al (2012) also used linear regression to evaluate data in regard to GIA. Temporally, unequal decadal time interval is used to analyze the paleohydrographs, which may be not the best way to evaluate the detailed paleohydrographs in regard to GIA. Also, the linear regression over time is also used for obtaining the rates associated with GIA.

Conclusion and Recommendation

This research project is designed to evaluate the rates and pattern of GIA in Lake Superior region. After collecting two datasets of GPS and water level gauges and analyzing them in regards to GIA, two series of rates and pattern are obtained. For GPS data, the rates and pattern are summarized in an isobase profile map. For water level gauges data, the rates are obtained by water level difference plots relative to Point Iroquois, and the pattern is obtained by plotting all the water level stations onto the map of this region. Comparison between the two series of rates and pattern shows relative similarity. Although there is a slight difference between the two results obtained from the two datasets, the results are statistically similar with each other for the majority of observations. For this reason, both of the two datasets and the two results of GIA are considered to be reasonable and reliable.

For prospective work, three main recommendations are as follows.

Firstly, in terms of shoreline data collected from Johnston et al (2012), they only used limited information from the detailed paleohydrographs in regard of GIA. Other methods need to be explored to evaluate the paleohydrographs for GIA analysis. Also, analysis results by shoreline data can be compared with the results obtained from GPS data and water level gauges data.

Secondly, considering there are only nine water level gauge stations surrounding Lake Superior, more stations could be installed to obtain more data for GIA analysis. Also, for GPS data, because of no observation in southwest part of Lake Superior, we can only estimate some isobases during constructing the isobase profile map. Hence, more GPS observation sites are recommended to install in the southwest part of the lake.

Lastly, future research could aim at constructing a suitable model instead of linear regression to understand rate change spatially for GPS data and temporally for water level differences.

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Appendix

Appendix 1. GPS data of site beneath Laurentide Ice Sheet collected from Peltier et al (2015)

Place	Lat.	Lon.	Vertical Up			ICE-6GVM5a	Technique
	°N	°E	mm/yr			mm/yr	site abbreviation, observation time in yr
Inuvik (Northwest Territories)	68.31	−133.53	−1.2	+	2.1	−1.4	G invk 9
Tuktoyaktuk (Northwest Territories)	69.44	−132.99	−1.6	+	2.2	−2.1	G tukt 9
Fort Nelson (British Columbia)	58.84	−122.58	2.8	+	3.0	3.2	C fnel 12
Fort Saint John (British Columbia)	56.25	−120.73	3.4	+	2.7	2.3	C ftsj 12
Grand Prairie (British Columbia)	55.19	−118.54	4.3	+	2.2	1.4	C gdpr 15
Holman (Victoria Island)	70.74	−117.76	2.8	+	1.8	1.5	G holm 11
Grimshaw (Alberta)	56.36	−117.67	4.3	+	1.9	3.8	C grms 15
Fox Creek (Alberta)	54.38	−116.78	2.8	+	2.2	0.6	C fxcr 15
Fort Vermillion (Alberta)	58.52	−116.15	5.6	+	1.9	5.6	C ftvm 15
Kugluktuk (Nunavut)	67.82	−115.13	5.3	+	3.6	2.5	C kugl 11

Slave Lake (Alberta)	55.54	–114.83	2.9	+	2.2	3.5	C slvl 15
Gainford (Alberta)	53.60	–114.72	1.5	+	2.2	0.2	C gnfd 15
Yellowknife (Northwest Territories)	62.48	–114.48	6.1	+	1.1	5.0	V ylow7296 12 G yell 15 yel5 15 D yela 13
Calgary (Alberta)	51.10	–114.37	0.5	+	1.9	–0.8	C cal4 15
Calgary (Alberta)	50.87	–114.29	–0.1	+	2.2	–0.8	G prds 8
Calgary (Alberta)	50.83	–113.92	–1.0	+	2.1	–0.8	C cp32 15
Kathryn (Alberta)	51.21	–113.82	–0.4	+	2.1	–0.8	C katn 15
Bashaw (Alberta)	52.69	–113.25	0.1	+	2.2	–0.1	C bshw 15
Edmonton (Alberta)	53.57	–113.17	1.1	+	2.2	1.0	C edmn 15
Egremont (Alberta)	54.04	–113.16	1.5	+	2.2	1.7	C egmt 15
Lethbridge (Alberta)	49.59	–112.60	–2.8	+	2.1	–1.2	C leth 15
Mundare (Alberta)	53.57	–112.41	0.7	+	2.2	1.4	C mndr 15
Brooks (Alberta)	50.66	–112.12	–2.5	+	2.1	–0.7	C brks 15
Mariana Lake (Alberta)	55.95	–112.03	2.9	+	1.9	4.4	C mrlk 15
Veteran (Alberta)	52.04	–111.12	–1.1	+	2.2	0.5	C vetn 15
Bonnyville (Alberta)	54.56	–110.98	1.3	+	2.2	2.9	C bnyv 15
Lloydminster (Alberta)	53.25	–109.87	0.1	+	2.2	1.5	C ldmn 15
Maple Creek (Saskatchewan)	49.99	–109.47	–3.9	+	2.1	–1.0	C mpck 15
Kindersley (Saskatchewan)	51.50	–109.16	–2.0	+	2.1	0.4	C kndl 15

La Loche (Saskatchewan)	56.90	−108.98	5.2	+	2.1	6.1	C locn 15
Meadow Lake (Saskatchewan)	54.09	−108.48	0.8	+	2.1	2.1	C mdlk 15
North Battleford (Saskatchewan)	52.74	−108.23	−0.8	+	2.1	0.8	C nbtf 15
Swift Current (Saskatchewan)	50.25	−107.77	−3.5	+	2.0	−0.9	C swcr 15
Loreburn (Saskatchewan)	51.23	−106.61	−2.9	+	2.1	−0.1	C lorb 15
Saskatoon (Saskatchewan)	52.20	−106.40	−3.3	+	1.4	0.2	G sask 9 C sak4 15
Assiniboia (Northwest Territories)	49.63	−106.03	−4.1	+	3.1	−1.6	C asbl 9
Prince Albert (Saskatchewan)	53.21	−105.93	−1.4	+	1.9	0.7	C pral 16
La Ronge (Saskatchewan)	55.16	−105.30	2.5	+	2.0	3.3	C lrng 15
Dafoe (Saskatchewan)	51.75	−104.51	−2.4	+	2.1	0.3	C dfoe 16
Regina (Saskatchewan)	49.80	−104.26	−1.8	+	4.1	−1.1	C rg12 9
Regina (Saskatchewan)	50.31	−104.21	−4.0	+	2.0	−0.6	C reg8 16
Wollaston Lake (Saskatchewan)	58.06	−103.80	7.8	+	2.0	8.5	C wolk 15
Regina (Saskatchewan)	50.34	−103.61	−2.0	+	3.9	−0.4	C rg14 9
Stoughton	49.68	−102.98	−3.0	+	1.9	−0.7	C sgtn 16

(Saskatchewan)							
Yorkton (Saskatchewan)	51.22	–102.40	–0.9	+	2.0	0.6	C yrkt 15
Hudson Bay (Saskatchewan)	52.84	–102.38	0.9	+	1.9	1.3	C hdby 15
Flin Flon (Saskatchewan)	54.73	–101.98	2.3	+	1.7	3.4	G flin 11
Swan River (Manitoba)	52.07	–101.28	0.2	+	1.9	1.1	C swnr 15
Lynn Lake (Manitoba)	56.86	–101.07	7.0	+	2.1	7.4	C lnlk 15
Dauphin (Manitoba)	51.08	–100.00	–0.3	+	2.0	1.0	C daup 15
Brandon (Manitoba)	49.89	–99.91	–1.2	+	2.0	0.9	C brdn 15
Grand Rapids (Manitoba)	53.27	–99.33	2.9	+	2.1	2.1	C grap 15
Ponton (Manitoba)	54.70	–99.01	5.1	+	2.1	4.2	C pntn 15
Fairford (Manitoba)	51.62	–98.74	0.6	+	2.0	1.3	C fard 15
Thompson (Manitoba)	55.44	–98.22	6.0	+	2.1	5.7	C tmpg 15
Thompson (Manitoba)	55.85	–98.02	7.0	+	2.1	6.4	C thmp 15
Winnipeg (Manitoba)	49.85	–97.48	0.2	+	2.0	1.6	C wina 15
Winnipeg (Manitoba)	50.18	–97.28	0.3	+	2.8	1.5	C win5 11
Baker Lake (Nunavut)	64.32	–96.00	10.8	+	3.8	10.5	G bake 5
Split Lake (Manitoba)	56.39	–95.90	8.3	+	2.0	7.3	C splk 15
Lac du Bonnet (Manitoba)	50.26	–95.87	0.1	+	1.8	1.6	G dubo 10
Kenora (Manitoba)	49.72	–94.76	0.6	+	1.9	1.5	C knra 15

Gods Lake (Manitoba)	54.55	–94.48	7.0	+	2.9	5.9	C gdlk 10
Churchill (Manitoba)	58.76	–94.09	10.6	+	1.9	8.6	G chur 10
Balmertown (Ontario)	51.01	–93.77	2.5	+	1.9	1.8	C bmtn 15
Ignace (Ontario)	49.29	–91.46	1.4	+	2.2	1.5	C ignc 14
Pipestone River (Ontario)	52.33	–90.78	6.3	+	3.3	5.1	C pipr 9
Savant Lake (Ontario)	50.70	–90.56	3.9	+	2.2	3.1	C svlk 14
Pickle Lake (Ontario)	51.48	–90.16	5.6	+	2.5	4.5	G picl 7
Thunder Bay (Ontario)	48.47	–89.22	2.5	+	2.1	2.1	C tbyg 14
Upper Keweenaw (Michigan)	47.23	–88.62	0.8	+	1.6	1.1	G kew1 12
Rossport (Ontario)	48.83	–87.52	3.3	+	2.1	3.6	G ross 9
Escanaba (Michigan)	45.75	–87.07	–0.9	+	1.8	0.6	G sup2 11
Longlac (Ontario)	49.78	–86.52	5.5	+	2.8	5.2	C lglk 13
Newberry (Michigan)	46.30	–85.51	–0.1	+	1.8	1.8	G sup3 11
Peawanuck (Ontario)	55.01	–85.41	12.0	+	2.5	9.2	C peaw 13
Wawa (Ontario)	48.07	–84.76	3.6	+	2.8	4.3	C wawa 13
Sault Saint Marie (Ontario)	46.53	–84.59	1.3	+	2.8	2.3	C ssmg 13
Hearst (Ontario)	49.67	–83.51	7.3	+	1.7	6.5	G hrst 7 C hrst 12
Igloolik (Nanavut)	69.38	–81.81	10.8	+	4.1	11.3	C iglo 10
Timmins (Ontario)	48.52	–81.54	6.4	+	2.6	5.8	C tims 13
Port Elgin (Ontario)	44.44	–81.40	0.3	+	2.9	0.2	C pteg 13

Sudbury (Ontario)	46.45	–81.19	3.2	+	2.7	3.0	C sdby 13
Moosonee (Ontario)	51.29	–80.61	9.9	+	2.2	9.7	C mosn 13
Parry Sound (Ontario)	45.34	–80.04	1.4	+	1.7	1.8	G pary 9 C pars 13
Toronto (Ontario)	43.73	–79.61	–0.6	+	2.4	–0.7	C tort 13
La Sarre (Quebec)	48.78	–79.16	8.2	+	2.3	6.5	C lsar 15
Temiscaming (Quebec)	46.72	–79.09	3.9	+	2.4	3.5	C tmsc 15
La Grande (Quebec)	53.70	–78.57	13.3	+	2.1	11.8	C lg1g 14
Peterborough (Ontario)	44.31	–78.30	1.2	+	2.6	0.5	C pter 13
Inukjuak (Quebec)	58.46	–78.11	11.0	+	2.9	10.7	C injk 13
Algonquin Park (Ontario)	45.96	–78.07	2.5	+	0.9	2.5	V algopark 19 G algo 17
Bancroft (Ontario)	45.04	–77.89	2.7	+	2.5	1.5	C bcft 13
Kuujjuarapik (Quebec)	55.28	–77.75	14.2	+	2.4	11.8	G kuuj 6 C kuuj 7
Val-d'Or (Quebec)	48.10	–77.56	8.3	+	1.5	5.5	G vald 7 C vald 14
Louise (Quebec)	50.50	–77.43	9.1	+	3.0	9.8	C luse 9
Pembroke (Ontario)	45.84	–77.25	3.4	+	2.8	2.3	C pemb 13
Eastmain (Quebec)	52.11	–77.20	11.7	+	2.0	12.1	C estm 14
Belleville (Ontario)	44.23	–77.19	1.2	+	2.5	0.4	C bel3 13
Gananoque (Ontario)	44.35	–76.17	1.6	+	2.8	0.6	C gang 13

Grand-Remous (Quebec)	46.67	−75.99	4.5	+	2.4	3.2	C gdrm 15
Bossler (Ontario)	45.40	−75.92	3.0	+	2.1	1.7	C bslr 15
Mallorytown (Ontario)	44.47	−75.87	2.1	+	2.5	0.7	C mltn 14
Gatineau (Quebec)	45.59	−75.81	2.5	+	1.7	1.9	G cags 11
Salluit (Quebec)	62.19	−75.67	7.2	+	3.0	7.3	C sall 13
Ottawa (Ontario)	45.45	−75.62	2.9	+	1.2	1.8	G nrc1 16 nrc2 3 D otta 4
Laggan Glenelg Road (Ontario)	45.39	−74.70	3.2	+	1.9	1.6	C hlag 15
Parent (Quebec)	47.92	−74.62	6.4	+	2.8	4.5	C prnt 15
Saint-Jovite (Quebec)	46.11	−74.59	3.3	+	2.4	2.2	C stjv 15
Chibougamau (Quebec)	49.91	−74.39	9.5	+	2.2	8.2	C cmou 15
Chambly (Quebec)	45.41	−73.35	2.7	+	2.2	1.3	C cnmc 15
La Tuque (Quebec)	47.42	−72.79	4.4	+	2.5	2.6	C ltuq 15
Sherbrooke (Quebec)	45.41	−71.99	1.9	+	2.6	0.7	C srbk 15
Laval University (Quebec)	46.78	−71.28	2.7	+	2.5	0.9	C lave 15
Laforge (Quebec)	54.60	−71.27	13.2	+	2.2	13.3	C lfrg 14
Chicoutimi (Quebec)	48.48	−71.20	4.5	+	2.6	2.4	C ccmi 15
Saint-Georges (Quebec)	46.02	−70.74	1.8	+	3.0	0.3	C stgo 15

Charlevoix (Quebec)	47.55	–70.33	3.3	+	2.1	0.5	C crlv 14
La Pocatiere (Quebec)	47.34	–70.01	2.4	+	1.8	0.1	C lpoc 15
Cacouna (Quebec)	47.91	–69.48	2.3	+	2.0	–0.2	C cacu 15
Iqaluit (Nunavut)	63.75	–68.55	3.2	+	3.5	2.2	C iqlu 10
Kuujjuaq (Quebec)	58.11	–68.41	8.6	+	2.8	9.0	C kujq 13
Edmundston (New Brunswick)	47.40	–68.36	1.2	+	2.2	–1.4	C edmd 15
Baie-Comeau (Quebec)	49.19	–68.26	3.0	+	2.1	0.6	G baie 9
Manic-5 (Quebec)	51.25	–68.20	8.2	+	2.7	8.6	C mnc5 13
Baie Comeau (Quebec)	49.27	–68.16	3.8	+	2.4	0.7	C bcom 15
Mont-Joli (Quebec)	48.52	–67.98	1.6	+	2.4	–1.1	C mtjl 15
Schefferville (Quebec)	54.83	–66.83	11.1	+	2.3	11.4	G sch2 8
Port-Cartier (Quebec)	50.05	–66.78	4.1	+	2.6	2.7	C pcrt 15
Sainte-Anne-des-Monts (Quebec)	49.12	–66.54	2.3	+	2.6	–0.9	C stan 15
Bathurst (New Brunswick)	47.62	–65.78	0.4	+	2.0	–2.8	C btht 16
Chandler (Quebec)	48.38	–64.56	1.0	+	2.2	–3.2	C cnda 15
Harvre-Saint-Pierre (Quebec)	50.30	–63.83	3.4	+	2.3	2.0	C hvrp 15
Folly Mountain (Nova Scotia)	45.51	–63.54	–0.6	+	3.1	–1.8	C flmt 9 flm2 3
Nain (Labrador)	56.54	–61.69	4.0	+	1.4	2.0	G nain 9 C

							nain 14
Goose Bay (Labrador)	53.30	–60.54	4.8	+	2.7	7.1	C gsby 13

Appendix 2. Annual averages (Summer months) for water level gauge stations from 1931 to 2015. The values from 2007 to 2015 were updated in this research. The values before 2007 were collected from Bruxer & Southam (2008).

Year	Point Iroquois	Marquette G.C.	Ontonagon	Duluth	Grand Marais	Thunder Bay	Rossport	Michipicoten	Gros Cap
1931	183.375			183.24125		183.415		183.51	
1932	183.54875			183.39825		183.57		183.6725	

1933	183.55875			183.44125		183.5925		183.6875	
1934	183.565			183.441		183.6025		183.695	
1935	183.61275			183.4895		183.6425		183.74	
1936	183.588			183.47075		183.625		183.705	
1937	183.5695			183.44375		183.605		183.6875	
1938	183.721			183.59325		183.7525		183.84	
1939	183.72325			183.60075		183.7425		183.8375	
1940	183.523			183.3965		183.55		183.63	
1941	183.523			183.4075		183.5475		183.6375	
1942	183.62425			183.5055		183.645		183.73	
1943	183.779			183.65775		183.7975		183.8775	
1944	183.68775			183.585		183.72		183.7875	
1945				183.5445		183.6625		183.74	
1946				183.494		183.615		183.6875	
1947				183.63		183.75		183.815	
1948				183.39		183.5025		183.57	
1949				183.475		183.58		183.66	
1950				183.72825		183.8375		183.9025	
1951	183.80275			183.71075		183.82		183.875	
1952	183.779			183.671		183.7775		183.8625	
1953	183.66625			183.5665		183.69		183.7525	
1954	183.58625			183.4895		183.595		183.6575	
1955	183.43075			183.344		183.4425		183.485	
1956	183.43925			183.35025		183.44		183.495	
1957	183.45825			183.37325		183.46		183.505	
1958	183.37275			183.29225		183.39		183.44	
1959	183.5		183.5305	183.4455		183.525		183.555	
1960	183.549		183.5115	183.48725		183.575		183.61	
1961	183.389		183.33925	183.31725		183.4075		183.435	183.4075

1962	183.41625		183.37075	183.34475		183.42		183.4525	183.435
1963	183.41475		183.38125	183.364		183.42		183.45	183.4175
1964	183.49025		183.45075	183.43325		183.495		183.5375	183.4925
1965	183.42325		183.3925	183.37475		183.4225		183.455	183.39
1966	183.51625		183.44375	183.452	183.4945	183.5		183.5475	183.5125
1967	183.50175		183.452	183.4475	183.49375	183.5125	183.57	183.525	183.4925
1968	183.66075		183.62975	183.617	183.655	183.6825	183.7375	183.685	183.53
1969	183.5725		183.546	183.52025	183.55425	183.595	183.6375	183.6	183.56
1970	183.579		183.5595	183.53175	183.5655	183.6	183.6425	183.5925	183.53
1971	183.68425		183.653	183.6455	183.6795	183.7	183.7525	183.7075	183.6733333
1972	183.64375		183.6205	183.608	183.639	183.655	183.695	183.6625	183.6325
1973	183.757		183.7275	183.71775	183.747	183.7375	183.7775	183.7825	183.7766667
1974	183.73775		183.70725	183.68275	183.71975	183.7275	183.7375	183.765	183.7025
1975	183.6635		183.6435	183.62575	183.65375	183.665	183.66	183.6875	183.6525
1976	183.61225		183.58475	183.572	183.59725	183.5775	183.595	183.6275	183.615
1977	183.42875		183.41975	183.3985	183.42875	183.4425	183.4375	183.46	183.43
1978	183.519		183.52175	183.5215	183.5365	183.555	183.535	183.54	183.5125
1979	183.67625		183.67075	183.64825	183.671	183.6725	183.6775	183.675	183.665
1980	183.48375	183.48175	183.47	183.4695	183.4815	183.4875	183.4875	183.4875	183.465
1981	183.4685	183.463	183.45675	183.4635	183.4715	183.4725	183.4725	183.4825	183.4575
1982	183.5175	183.51125	183.50925	183.508	183.51675	183.51	183.51	183.525	183.505
1983	183.62125	183.6195	183.61225	183.60925	183.6145	183.615	183.63	183.63	183.63
1984	183.63025	183.63175	183.62875	183.62675	183.634	183.6325	183.6475	183.635	183.6375
1985	183.76375	183.7665	183.76575	183.76475	183.7675	183.77	183.69	183.775	
1986	183.80675	183.80775	183.80425	183.8115	183.80875	183.8025	183.8025	183.795	183.8075
1987	183.5115	183.51275	183.521	183.51575	183.50875	183.5075	183.505	183.5125	183.5025
1988	183.33925	183.33775	183.3475	183.34725	183.34025	183.335	183.33	183.3275	183.325
1989	183.51475	183.51525	183.53575	183.5245	183.52475	183.5075	183.4975	183.495	183.505
1990	183.3285	183.3355	183.3345	183.354	183.345	183.335	183.3066667	183.315	183.3175

1991	183.43625	183.43625	183.43075	183.44375	183.43575	183.425	#DIV/0!	183.4225	183.43
1992	183.44875	183.45075	183.45925	183.4635	183.46	183.45	183.4525	183.435	183.4425
1993	183.5635	183.5695	183.585	183.58625	183.57825	183.5725	183.56	183.5525	183.5625
1994	183.52875	183.5385	183.54675	183.559	183.5425	183.5275	183.515	183.5075	183.5275
1995	183.3695	183.385	183.39025	183.4105	183.3915	183.385	183.36	183.3525	183.3675
1996	183.7065	183.7255	183.72475	183.7435	183.728	183.7125	183.6825	183.67	183.6975
1997	183.669	183.68275	183.64075	183.69525	183.67825	183.6675	183.645	183.6	183.6625
1998	183.38475	183.3915	183.3865	183.4005	183.3765	183.365	183.345	183.3525	183.38
1999	183.40575	183.42325	183.432	183.4445	183.41975	183.415	183.375	183.38	183.4
2000	183.27825	183.3	183.31	183.329	183.303	183.3	183.25	183.25	183.275
2001	183.34975	183.37325	183.38225	183.4035	183.3735	183.3625	183.325	183.3225	183.345
2002	183.35975	183.38225	183.397	183.4145	183.388	183.3725	183.3375	183.335	183.355
2003	183.26	183.2745	183.286	183.30625	183.2805	183.2675	183.2175	183.215	183.25
2004	183.39975	183.422	183.42575	183.44975	183.4275	183.4075	183.365	183.36	183.395
2005	183.37625	183.397	183.395	183.42775	183.3985	183.385	183.3375	183.34	183.37
2006	183.26625	183.2875	183.298	183.335	183.2975	183.28	183.2275	183.2225	183.2625
2007	182.98225	183.00325	183.01775	183.042	183.00925	182.995	182.9425	182.945	182.975
2008	183.3625	183.3915	183.3985	183.42375	183.39025	183.3675	183.32	183.315	183.3525
2009	183.35125	183.378	183.389	183.40825	183.3715	183.36	183.305	183.3025	183.34
2010	183.18225	183.2005	183.22125	183.23025	183.1895	183.175	183.1175	183.1325	183.175
2011	183.2215	183.247	183.271	183.28175	183.23775	183.2075	183.155	183.17	183.22
2012	183.2365	183.261	183.26275	183.29825	183.252	183.2225	183.175	183.1925	183.2275
2013	183.379	183.40775	183.41625	183.45575	183.40725	183.3725	183.315	183.3275	183.37
2014	183.6405	183.67725	183.68525	183.735	183.68175	183.645	183.5775	183.585	183.63
2015	183.65975	183.69375	183.70275	183.74075	183.692	183.6675	183.6	183.5975	183.655

Appendix 3. Water level differences relative to Point Iroquois for the 8 stations, which are Marquette, Ontonagon, Duluth, Grand Marais, Thunder Bay, Rossport, Michipicoten, and Gros Cap.

Point Iroquois - Marquette		Point Iroquois - Ontonagon		Point Iroquois - Duluth		Point Iroquois - Grand Marais		Point Iroquois - Thunder Bay		Point Iroquois - Rossport		Point Iroquois - Michipicoten		Point Iroquois - Gros Cap	
Year	Jun-Sep Avg	Year	Jun-Sep Avg	Year	Jun-Sep Avg	Year	Jun-Sep Avg	Year	Jun-Sep Avg	Year	Jun-Sep Avg	Year	Jun-Sep Avg	Year	Jun-Sep Avg
1931	0.053	1960	0.0375	1931	0.13375	1966	0.02175	1931	-0.04	1967	-0.06825	1931	-0.135	1961	-0.0185

1932	0.066	1961	0.04975	1932	0.1505	1967	0.008	1932	-0.02125	1968	-0.07675	1932	-0.12375	1962	-0.01875
1933	0.051	1962	0.0455	1933	0.1175	1968	0.00575	1933	-0.03375	1969	-0.065	1933	-0.12875	1963	-0.00275
1934	0.052	1963	0.0335	1934	0.124	1969	0.01825	1934	-0.0375	1970	-0.0635	1934	-0.13	1964	-0.00225
1935	0.057	1964	0.0395	1935	0.12325	1970	0.0135	1935	-0.02975	1971	-0.06825	1935	-0.12725	1965	0.03325
1936	0.057	1965	0.03075	1936	0.11725	1971	0.00475	1936	-0.037	1972	-0.05125	1936	-0.117	1966	0.00375
1937	0.053	1966	0.0725	1937	0.12575	1972	0.00475	1937	-0.0355	1973	-0.0205	1937	-0.118	1967	0.00925
1938	0.047	1967	0.04975	1938	0.12775	1973	0.01	1938	-0.0315	1974	0.00025	1938	-0.119	1968	0.13075
1939	0.049	1968	0.031	1939	0.1225	1974	0.018	1939	-0.01925	1975	0.0035	1939	-0.11425	1969	0.0125
1940	0.044	1969	0.0265	1940	0.1265	1975	0.00975	1940	-0.027	1977	-0.00875	1940	-0.107	1970	0.049
1941	0.049	1970	0.0195	1941	0.1155	1976	0.015	1941	-0.0245	1978	-0.016	1941	-0.1145	1972	0.01125
1942	0.046	1971	0.03125	1942	0.11875	1977	0	1942	-0.02075	1979	-0.00125	1942	-0.10575	1974	0.03525
1943	0.034	1972	0.02325	1943	0.12125	1978	-0.0175	1943	-0.0185	1980	-0.00375	1943	-0.0985	1975	0.011
1944	0.027	1973	0.0295	1944	0.10275	1979	0.00525	1944	-0.03225	1981	-0.004	1944	-0.09975	1976	-0.00275
1951	0.031	1974	0.0305	1951	0.092	1980	0.00225	1951	-0.01725	1982	0.0075	1951	-0.07225	1977	-0.00125
1952	0.036	1975	0.02	1952	0.108	1981	-0.003	1952	0.0015	1984	-0.01725	1952	-0.0835	1978	0.0065
1953	0.031	1976	0.0275	1953	0.09975	1982	0.00075	1953	-0.02375	1986	0.00425	1953	-0.08625	1979	0.01125
1954	0.039	1977	0.009	1954	0.09675	1983	0.00675	1954	-0.00875	1987	0.0065	1954	-0.07125	1980	0.01875
1955	0.032	1978	-0.00275	1955	0.08675	1984	-0.00375	1955	-0.01175	1988	0.00925	1955	-0.05425	1981	0.011
1956	0.026	1979	0.0055	1956	0.089	1985	-0.00375	1956	-0.00075	1989	0.01725	1956	-0.05575	1982	0.0125
1957	0.034	1980	0.01375	1957	0.085	1986	-0.002	1957	-0.00175	1992	-0.00375	1957	-0.04675	1984	-0.00725
1958	0.024	1981	0.01175	1958	0.0805	1987	0.00275	1958	-0.01725	1993	0.0035	1958	-0.06725	1986	-0.00075
1959	0.017	1982	0.00825	1959	0.0545	1988	-0.001	1959	-0.025	1994	0.01375	1959	-0.055	1987	0.009
1960	0.015	1983	0.009	1960	0.06175	1989	-0.01	1960	-0.026	1995	0.0095	1960	-0.061	1988	0.01425
1961	0.017	1984	0.0015	1961	0.07175	1990	-0.0165	1961	-0.0185	1996	0.024	1961	-0.046	1989	0.00975
1962	0.029	1985	-0.002	1962	0.0715	1991	0.0005	1962	-0.00375	1997	0.024	1962	-0.03625	1990	0.011
1963	0.014	1986	0.0025	1963	0.05075	1992	-0.01125	1963	-0.00525	1998	0.03975	1963	-0.03525	1991	0.00625
1964	0.02	1987	-0.0095	1964	0.057	1993	-0.01475	1964	-0.00475	1999	0.03075	1964	-0.04725	1992	0.00625
1965	0.016	1988	-0.00825	1965	0.0485	1994	-0.01375	1965	0.00075	2000	0.02825	1965	-0.03175	1993	0.001
1966	0.021	1989	-0.021	1966	0.06425	1995	-0.022	1966	0.01625	2001	0.02475	1966	-0.03125	1994	0.00125

1967	0.018	1990	-0.006	1967	0.05425	1996	-0.0215	1967	-0.01075	2002	0.02225	1967	-0.02325	1995	0.002
1968	0.009	1991	0.0055	1968	0.04375	1997	-0.00925	1968	-0.02175	2003	0.0425	1968	-0.02425	1996	0.009
1969	0.013	1992	-0.0105	1969	0.05225	1998	0.00825	1969	-0.0225	2004	0.03475	1969	-0.0275	1997	0.0065
1970	0.008	1993	-0.0215	1970	0.04725	1999	-0.014	1970	-0.021	2005	0.03875	1970	-0.0135	1998	0.00475
1971	0.002	1994	-0.018	1971	0.03875	2000	-0.02475	1971	-0.01575	2006	0.03875	1971	-0.02325	1999	0.00575
1972	0.009	1995	-0.02075	1972	0.03575	2001	-0.02375	1972	-0.01125	2007	0.03975	1972	-0.01875	2000	0.00325
1973	0.005	1996	-0.01825	1973	0.03925	2002	-0.02825	1973	0.0195	2008	0.0425	1973	-0.0255	2001	0.00475
1974	0.01	1997	0.02825	1974	0.055	2003	-0.0205	1974	0.01025	2009	0.04625	1974	-0.02725	2002	0.00475
1975	0	1998	-0.00175	1975	0.03775	2004	-0.02775	1975	-0.0015	2010	0.06475	1975	-0.024	2003	0.01
1976	0	1999	-0.02625	1976	0.04025	2005	-0.02225	1976	0.03475	2011	0.0665	1976	-0.01525	2004	0.00475
1977	-0.005	2000	-0.03175	1977	0.03025	2006	-0.03125	1977	-0.01375	2012	0.0615	1977	-0.03125	2005	0.00625
1978	-0.011	2001	-0.0325	1978	-0.0025	2007	-0.027	1978	-0.036	2013	0.064	1978	-0.021	2006	0.00375
1979	0.006	2002	-0.03725	1979	0.028	2008	-0.02775	1979	0.00375	2014	0.063	1979	0.00125	2007	0.00725
1980	0.002	2003	-0.026	1980	0.01425	2009	-0.02025	1980	-0.00375	2015	0.05975	1980	-0.00375	2008	0.01
1981	0.006	2004	-0.026	1981	0.005	2010	-0.00725	1981	-0.004			1981	-0.014	2009	0.01125
1982	0.006	2005	-0.01875	1982	0.0095	2011	-0.01625	1982	0.0075			1982	-0.0075	2010	0.00725
1983	0.002	2006	-0.03175	1983	0.012	2012	-0.0155	1983	0.00625			1983	-0.00875	2011	0.0015
1984	-0.002	2007	-0.0355	1984	0.0035	2013	-0.02825	1984	-0.00225			1984	-0.00475	2012	0.009
1985	-0.003	2008	-0.036	1985	-0.001	2014	-0.04125	1985	-0.00625			1985	-0.01125	2013	0.009
1986	-0.001	2009	-0.03775	1986	-0.00475	2015	-0.03225	1986	0.00425			1986	0.01175	2014	0.0105
1987	-0.001	2010	-0.039	1987	-0.00425			1987	0.004			1987	-0.001	2015	0.00475
1988	0.001	2011	-0.0495	1988	-0.008			1988	0.00425			1988	0.01175		
1989	0	2012	-0.02625	1989	-0.00975			1989	0.00725			1989	0.01975		
1990	-0.007	2013	-0.03725	1990	-0.0255			1990	-0.0065			1990	0.0135		
1991	0	2014	-0.04475	1991	-0.0075			1991	0.01125			1991	0.01375		
1992	-0.002	2015	-0.043	1992	-0.01475			1992	-0.00125			1992	0.01375		
1993	-0.006			1993	-0.02275			1993	-0.009			1993	0.011		
1994	-0.01			1994	-0.03025			1994	0.00125			1994	0.02125		
1995	-0.015			1995	-0.041			1995	-0.0155			1995	0.017		

1996	-0.019			1996	-0.037			1996	-0.006			1996	0.0365		
1997	-0.014			1997	-0.02625			1997	0.0015			1998	0.03225		
1998	-0.007			1998	-0.01575			1998	0.01975			1999	0.02575		
1999	-0.018			1999	-0.03875			1999	-0.00925			2000	0.02825		
2000	-0.022			2000	-0.05075			2000	-0.02175			2001	0.02725		
2001	-0.023			2001	-0.05375			2001	-0.01275			2002	0.02475		
2002	-0.023			2002	-0.05475			2002	-0.01275			2003	0.045		
2003	-0.015			2003	-0.04625			2003	-0.0075			2004	0.03975		
2004	-0.022			2004	-0.05			2004	-0.00775			2005	0.03625		
2005	-0.021			2005	-0.0515			2005	-0.00875			2006	0.04375		
2006	-0.021			2006	-0.06875			2006	-0.01375			2007	0.03725		
2007	-0.021			2007	-0.05975			2007	-0.01275			2008	0.0475		
2008	-0.029			2008	-0.06125			2008	-0.005			2009	0.04875		
2009	-0.02675			2009	-0.057			2009	-0.00875			2010	0.04975		
2010	-0.01825			2010	-0.048			2010	0.00725			2011	0.0515		
2011	-0.0255			2011	-0.06025			2011	0.014			2012	0.044		
2012	-0.0245			2012	-0.06175			2012	0.014			2013	0.0515		
2013	-0.02875			2013	-0.07675			2013	0.0065			2014	0.0555		
2014	-0.03675			2014	-0.0945			2014	-0.0045			2015	0.06225		
2015	-0.034			2015	-0.081			2015	-0.00775						