NOAA Technical Report NOS CO-OPS 0074

Gap Analysis of the Great Lakes Component of the National Water Level Observation Network (NWLON)

Silver Spring, Maryland

September 2014

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

Center for Operational Oceanographic Products and Services

National Ocean Service
National Oceanic and Atmospheric Administration
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Stephen K. Gill

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EXECUTIVE SUMMARY

This gap analysis for the Great Lakes component of the National Oceanic and Atmospheric Administration (NOAA) National Water Level Observation Network (NWLON) is a companion to an earlier NOAA gap analysis of the tide station network prepared in 2008 and updated in 2014 (*A Network Gaps Analysis for the National Water Level Observation Network, NOAA Technical Memorandum NOS CO-OPS 0048*). Each report looks at the fundamental requirements for networks of long-term continuous water level stations and assesses the present day network configuration and how well it meets requirements. For the Great Lakes NWLON, the requirements are inherently bi-national in nature, as water level monitoring and regulation is a dual responsibility of both Canada and the United States. The international agreements and coordinating bodies all have specific needs for water level measurement, and they are briefly discussed in this document to provide a sense of the complexity of the Great Lakes hydrological system. The NOAA NWLON covers the U.S. shoreline and a similar Canadian network covers the Canadian shoreline.

The gap analysis presented here looks at data from both networks in a comprehensive and an integrated manner. The lake-by-lake assessments draw upon previous studies, reports, and analyses as well as a statistical comparative analysis of a recent seven-year period of data (2005-2011). The impact of differences in the rates of vertical land movement across the Great Lakes emerges as one of the most important parameters in defining the water level station network configuration requirements. The present network of 53 NWLON stations has very little redundancy in spatial coverage, and several areas with weaknesses in coverage are shown. Three (3) specific locations have been identified as NWLON gaps; two in Lake Michigan and one in Lake St. Clair. This report will provide input into program planning for the upcoming update of the International Great Lakes Datum from IGLD 1985 to IGLD 2020.

Gap Analysis of the Great Lakes Component of the NWLON

1.0 PURPOSE

A network gap analysis for the National Water Level Observation Network (NWLON) was completed in 2008 (Gill and Fisher, 2008). However, the Great Lakes component of the NWLON was not included in that analysis because an entirely different evaluation methodology needed to be developed for the Great Lakes. The purpose of this document is to provide a gap analysis for the Great Lakes component of the NWLON. This assessment is necessary to ensure that observing system goals are being met by the operational networks, the current and projected resources are aligned to meet existing and future requirements, the data meet the needs of other federal agencies who rely upon NOAA data to meet their missions, and the future and emerging requirements can contribute to NOAA/Center for Operational Oceanographic Products and Services (CO-OPS) strategic planning. The NWLON is a managed network of permanent stations established to obtain sustained long-term high quality water level measurements.

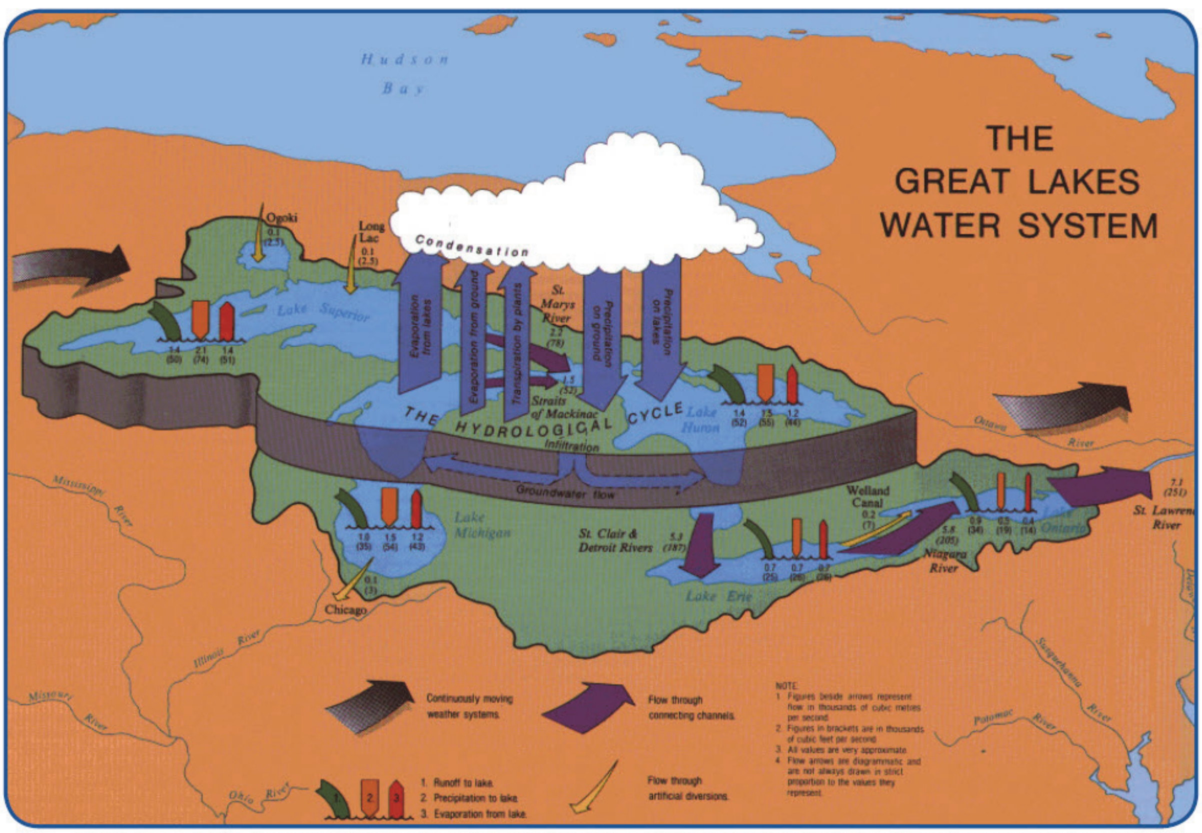
This report primarily also draws upon information compiled for a series of Great Lakes Water Level, Hydraulic Corrector, and Geodetic Datum Assessment reports that are presently being completed by CO-OPS for each lake (CO-OPS 2013). One of the primary purposes of these individual reports is to define the requirements for the seasonal gauge program effort associated with the 2020 update to the International Great Lakes Datum (IGLD). This report reviews the NWLON station requirements to assess the network against international and national requirements for datum control and continuous monitoring for a variety of applications.

By design, this report contains a substantial background section that has two main purposes: first, to provide those with little knowledge of the Great Lakes a basic understanding of Great Lakes hydrology, lake level variations, and the human interaction with management and regulation; and second, to provide background information on lake level variations such that the reader can better appreciate the approach to identifying gaps and how filling those gaps would improve the water level network.

While focusing on the U.S. network perspective, it is understood that ultimately the goal for observing systems in the Great Lakes is bi-national, requiring close collaboration and coordination with observing system agency counterparts in both countries. It is hoped that this report can be used as constructive input into future coordinated assessments for the entire Great Lakes observing system.

2.0 BACKGROUND

The Great Lakes-St. Lawrence River System is a large, complex natural hydrologic system of lakes and rivers that has been altered over time by dredging, locks, dams, hydroelectric power facilities, canals, and diversions. The Great Lakes Basin is approximately 295,000 square miles in size, covering both Canadian and U.S. territory, and includes eight U.S. states and two Canadian provinces. The nature of the complexity in the system is illustrated in Figure 1. The complexity of natural and human-influenced variability of the lake levels and inter-connecting flows in this system presents a continual challenge for the bi-lateral interests of both countries. The water balance of the system includes inflow components to each lake in the following forms: over-lake precipitation, runoff, ground water seepage, diversions into a particular lake, and flow from the connecting channels. Outflow from any particular lake includes components from evaporation, flow into a connecting channel, diversions away from a particular lake, and consumptive use (Neff and Nicholas, 2005). The foundational requirement for the Great Lakes NWLON is vertical control for safe navigation and for water resource management in the lakes. Two of the most important drivers for international management of the water levels are safe and efficient navigation for the port facilities and maintaining adequate flows for the hydroelectric power plants. Other needs include water management, flood damage reduction, water supply, and recreation.



USEPA and Environment Canada, The Great Lakes: An Environmental Atlas and Resource Book. http://www.epa.gov/glnpo/atlas/glat-ch2.html. Accessed May 23, 2012.

Figure 1. Schematic drawing of the Great Lakes Hydrologic Water System.

Gronewold *et al.* (2013) note the increased emphasis on the inclusion of climate change and adaptive management by the Great Lakes management community, which further justifies the requirement for a robust monitoring infrastructure and strong research program.

2.1 Regulation and Water Management

The International Joint Commission (IJC) and their Boards of Control provide for the international regulatory framework for the Great Lakes. The outflows from Lakes Superior and Ontario are regulated under the auspices of the IJC. A separate bi-national Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, which is not under the auspices of the IJC, performs applicable hydrologic and hydraulic studies, coordinates data collection activities, coordinates data for use by both countries, sets protocols, performs studies, and establishes the vertical reference control datum.

Lake Superior

The Long Lac and Ogoki diversions re-direct water from Canadian rivers into Lake Superior (approximately 5,580ft ^{3}/s). Outflows into Lakes Michigan and Huron from the St. Marys River are affected by hydroelectric power plants, the Soo Navigation Locks, the International Compensating Works dam, and municipal and industrial uses. The IJC's International Lake Superior Board of Control established the basic objectives for and limits to the regulation of Lake Superior's outflow and established the Lake Superior Board of Control to determine outflows and oversee operation of the various control works. The regulation plan acknowledges the needs of various interests on Lake Superior, the St. Marys River, and Lake Michigan-Huron, including navigation, hydropower, fishery, and riparian rights. The main objective of the present regulation plan is to determine a flow that will bring the levels of Lakes Superior, Huron, and Michigan to the same relative position within their respective ranges of historic seasonal averages. Average monthly outflows are 75,000 ft^3/s (Neff and Nicholas, 2005).

Lake Michigan and Lake Huron

The Straits of Mackinac allow Lakes Michigan and Huron to be considered one lake for hydraulic flow and lake level applications. The net flow of this system is from Lake Michigan into Lake Huron; however, there is evidence of a strong oscillatory flow pattern (Anderson and Schwab, 2013). The Lake Michigan Diversion at Chicago accounts for an average outflow of 3,200 ft^3/s to the Chicago Sanitary and Ship Canal System. Natural outflow occurs through the St. Clair River, Lake St. Clair, Detroit River connecting waterway, and into Lake Erie. The connecting waterway has no man-made water level maintenance mechanism or diversion; it does have a navigation channel which is maintained by the U. S. Army Corps of Engineers (USACE) Detroit District office and the Canadian Coast Guard. This waterway accounts for a monthly average outflow of 188,000 ft^3/s from Lakes Huron and Michigan (Neff and Nicholas, 2005). Historically, deepening the navigation channel was found to have a significant effect in the levels of Lakes Michigan and Huron. The flows in this waterway have been the subject of recent intense investigation given the recent low lake levels (IUGLSB, 2009).

Lake Erie

Lake Erie is particularly susceptible to high frequency seiche events in which significant differentials in water level elevation (greater than 1 meter) can occur between the western and eastern ends of the lake. When high lake levels occur on the western end of the lake, the inflow from the Detroit River can be impeded and, on rare occasion, temporarily reversed. In the other direction (west to east) during significant wind events, the western end of Lake Erie can drop significantly, leaving commercial ships transiting into Lake Erie from the Detroit River without adequate draft to do so. The Niagara River and the Welland Canal are the main conduits of outflow from Lake Erie into Lake Ontario.

The amount a power company can divert from the Niagara River is defined by the required flow over Niagara Falls as specified in the 1950 Treaty between Canada and the United States of America concerning uses of the water of the Niagara River. The average monthly outflow into Lake Ontario from Lake Erie is approximately 210,000 ft^3/s (Neff and Nicholas, 2005).

Lake Ontario – St. Lawrence River

One requirement of the IJC's International St. Lawrence River Board of Control is to regulate Lake Ontario within a monthly-mean target range from 74.2 to 75.4 meters (243.3 to 247.3 feet) above sea level (presently defined by IGLD 1985). The International St. Lawrence River Board of Control was established by IJC in a 1952 order to ensure outflows from Lake Ontario meet the requirements of the Commission's Order of Approval. The Board implements the current regulation plans and conducts studies as requested by the Commission in order to improve its regulatory practices. Water flows from Lake Ontario into the St. Lawrence River are regulated by several power entity control structures, dams, and locks. The average monthly outflow from Lake Ontario into the St. Lawrence River is 246,000 ft^3/s (Neff and Nicholas, 2005).

2.2 Crustal Movement

Current crustal movement in the Great Lakes basin is the result of the natural rebound of the Earth's crust following the removal of the weight of the glaciers that covered the region thousands of years ago. The force pushing down on the Earth's crust was much less near the edges of the glacial shield. The Earth's crust north of the Great Lakes in Canada was pressed down by as much as 3 km of ice in some areas during the last glacial era. When the ice began melting some 10,000 years ago, the crust started rebounding. This phenomenon is historically known as Post-Glacial Rebound (PGR) and is the key reason why the Great Lakes vertical control datum requires updating approximately every thirty years. The term PGR is gradually being replaced by the term Glacial Isostatic Adjustment (GIA). This is in recognition that the response of the Earth to glacial loading and unloading is not limited to the upward rebound movement but also involves downward land movement, horizontal crustal motion, changes in global sea levels, the Earth's gravity field, induced earthquakes, and changes in the rotational motion.

As a result of GIA, there are significant differences in rates of vertical movement of the earth's crust across the Great Lakes-St. Lawrence River System (Mainville and Craymer, 2005; Lee and Southam, 1994). In general, the land north of the Great Lakes is rising and the land south of the Great Lakes, never covered by the glaciers, is subsiding (see Figure 2). As seen in Figure 2, the "0" axis from positive to negative vertical land movement transects the lakes, and regional movement is on the order of several centimeters per century. The long-term time series of monthly mean water levels from the U.S. and Canadian networks were used to construct the model for vertical land motion.

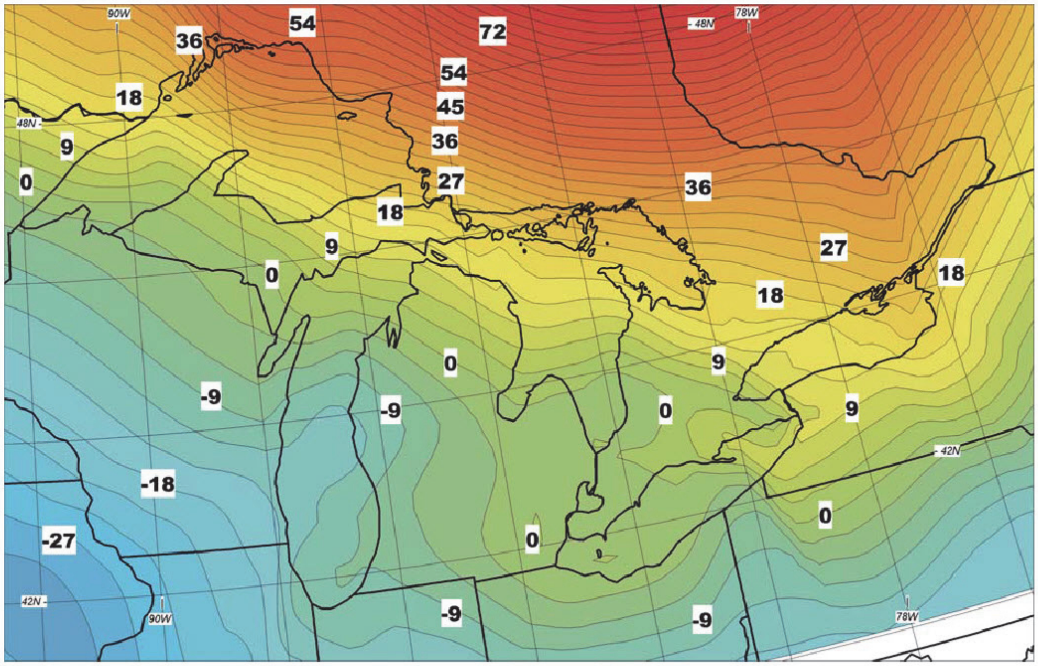


Figure 2. Contoured rates of vertical velocities (in cm/century) derived from water level gauges surrounded by ICE-3G-model-derived velocities in the Great Lakes region (Mainville and Craymer 2005).

This GIA impact on datum control is somewhat analogous to the requirement in the U.S. to periodically update the National Tidal Datum Reference System to new 19-year periods due to relative sea-level change (CO-OPS, 2001; Zervas*, et al.*, 2013).The crustal movement has a significant effect on the vertical datum planes used to reference water levels and also changes the hydraulic flow characteristics of the connecting channels. To be meaningful, water level datum elevations relative to the land must be updated over time.

The effects of GIA have recently been studied further as part of the International Upper Great Lakes Study (Bruxer and Southam, 2008; IUGLS, 2009). The study reports that the physical and apparent effects of GIA result from the relative differences in the movement of the earth's crust and the impact this has on water levels observed at different locations around each of the lakes (i.e., the apparent observed surface elevation at any given time and location relative to the lake-wide mean levele). The study found that the apparent effect of GIA accounts for about 4 to 5 cm (1.6 to 2 in) of the approximately 23 cm (9 in) decline in the head difference between Lake Michigan-Huron and Lake Erie between 1963 and 2006, which was determined based on water levels recorded at Harbor Beach, Michigan on Lake Huron and Cleveland, Ohio on Lake Erie.

For this gap analysis, the differential rates of vertical movement relative to each lake's outlet is most relevant, as these rates have significant impact on apparent water levels observed at different locations around each lake over time (Bruxer and Southam, 2008). As shown in

Figure 3, the relative vertical velocities can be determined relative to the stations closest to the outlet for each lake (Mainville and Craymer, 2005).

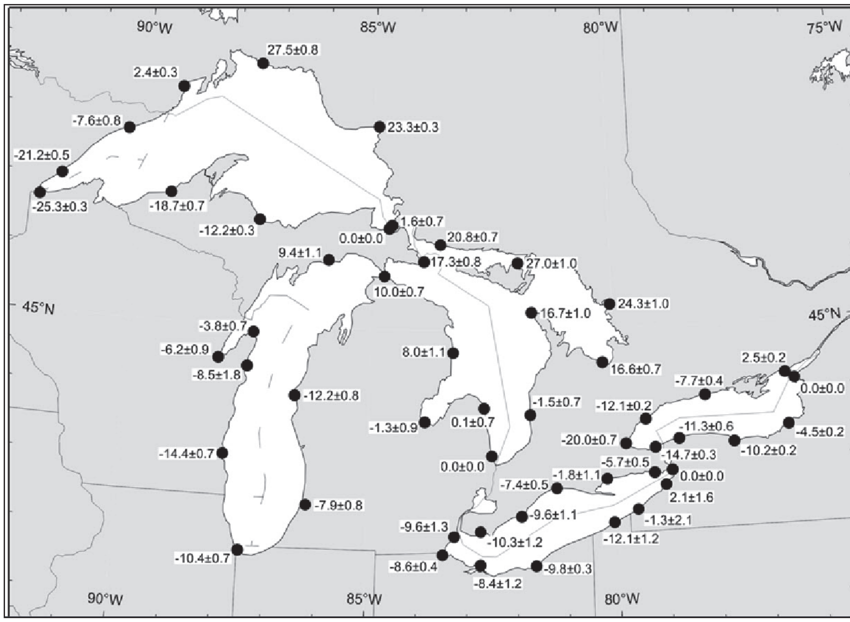


Figure 3. Vertical velocity and standard error relative to each outlet: Cape Vincent for Lake Ontario, Buffalo for Lake Erie, Lakeport for Lakes Michigan-Huron, Point Iroquois for Lake Superior, in centimeters per century.

Figure 3. Relative vertical velocities for each Great Lake (Mainville and Craymer, 2005).

The individual station site biases (Figure 4) determined from the trend analyses are values analogous to the hydraulic corrector values (discussed later in the Section 2.8) and demonstrate the actual variability of the lake surface from lake-wide mean values.

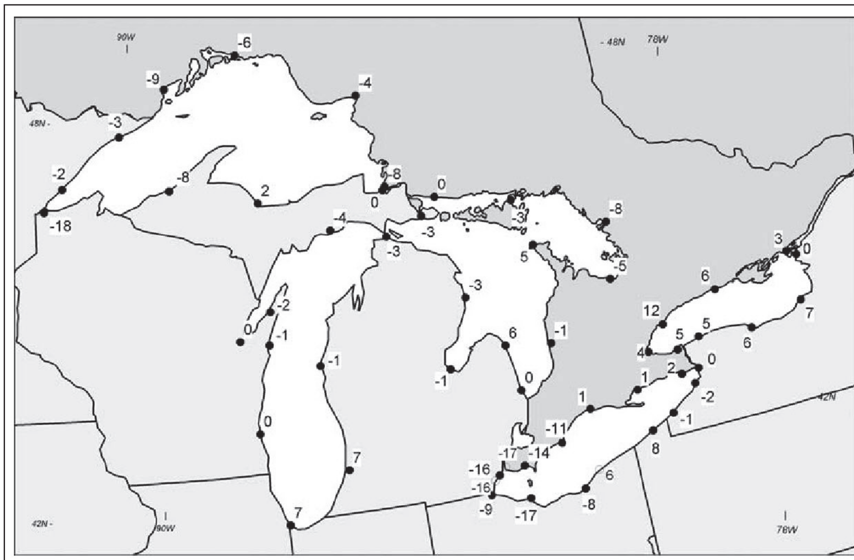


Figure 4. Site biases (in millimeters) relative to reference gauge near each lake outlet.

Figure 4. Individual station biases computed from trends analyses.(Mainville and Craymer, 2005).

The geospatially varying rates have implications on the need to maintain a properly configured network of stations with repeat GPS surveys or co-located Continually Operating Reference Stations (CORS) for both monitoring the changes in hydraulic characteristics of the lake basins and the ongoing need to update the reference datum within the system. More precise estimates of the vertical land movement should be possible through continued establishment of CORS. Over time, precise independent estimates of vertical land motion will be possible. Snay *et al.* (2007) estimate that generally at least twelve years of data will be required before the standard errors of the vertical velocity estimates will be sufficiently small for the velocities to be used with confidence.

2.3 Long-term Average Water Levels

Using subsets of Canadian and U.S. station networks, annual and monthly average water levels have been carefully compiled from observations back as far as 1860 allowing for assessments of the long-term changes in water levels in each lake (GLERL, 2014). For overall context on long-period variability, Figure 5 illustrates the use of multiple water level stations to compile lake-wide averaging to produce a hydrograph for each lake, showing the monthly and annual time series since 1860.The graphic puts the lake level variations into long-term context with sea level variations over the same time period at the Battery, New York City. The historical maximum/minimum range of lake levels over this time period are a little over 1.0 m for Lake Superior, 1.5 m for Lakes Michigan, Huron and Erie, and 1.6 m for Lake Ontario. The relatively lower lake levels since 2000 for the Lakes Superior, Michigan, and Huron and the regulation of Lake Superior (since 1916) and Lake Ontario (since 1960) are particularly noticeable in Figure 5. Gronewold *et al.* (2013) describes the long-term variability of Great Lakes water levels with the perspective of long-term drivers. Major drivers include over-lake precipitation, over-lake evaporation, and land surface runoff. Regional climate changes propagate changes to the water budget and the water levels. Updated hydrographs and water level dashboard products can be obtained at: http://www.glerl.noaa.gov/data/now/wlevels/levels.html.

The stations used in lake level calculations have changed over time based on station operation and data availability, and the official international coordinated period of record presently used is 1918-2012. This official period is after the implementation of regulation of Lake Superior and includes documented adjustments for GIA.

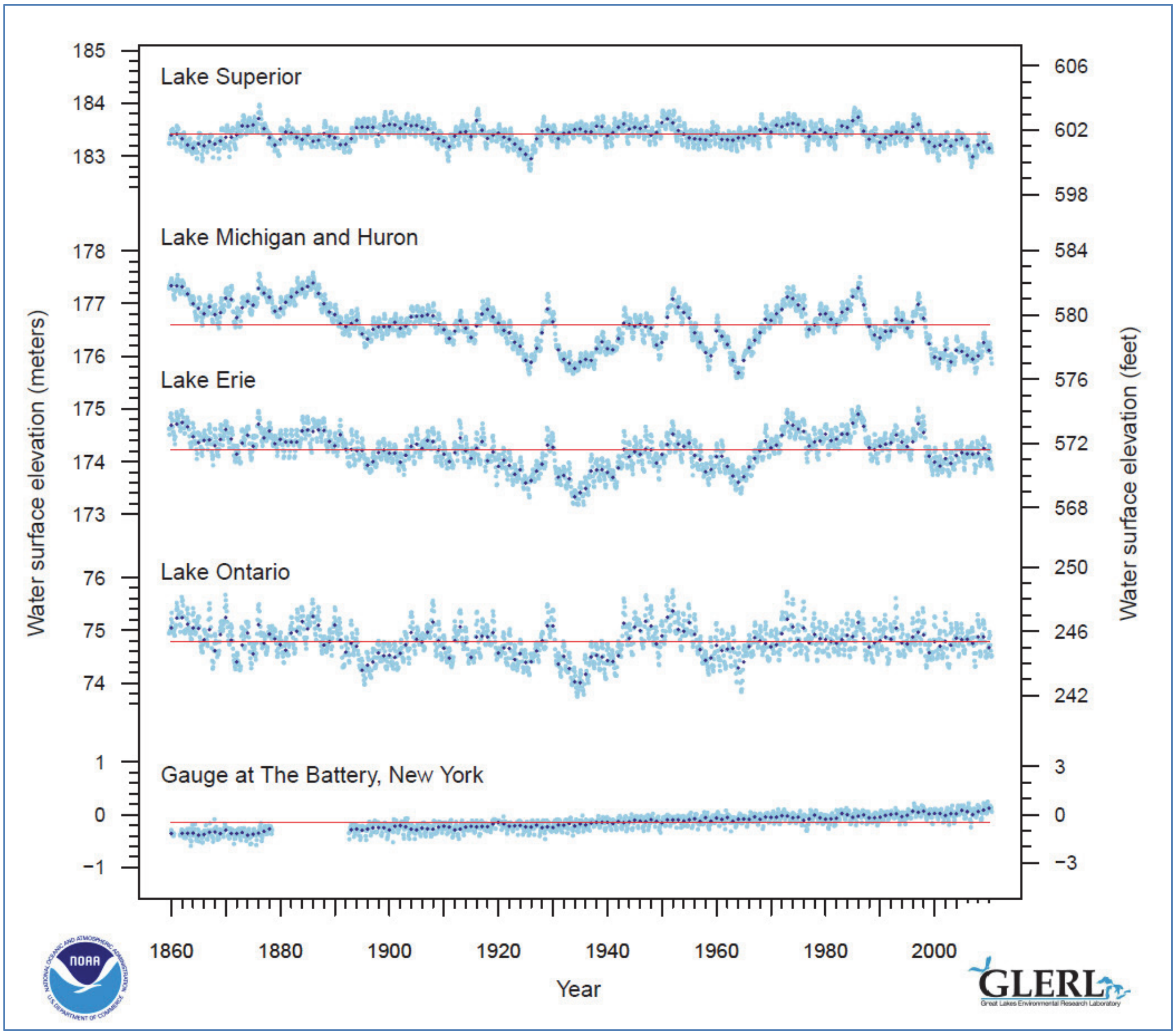


Figure 5. Comparison of long-term hydrographs of each Great Lake with long-term sea level variations at New York City (from GLERL, 2013).

2.4 Monthly Mean Water Levels

Both the U.S. and Canadian water level networks contribute to important operational data products and forecasts. Monthly mean values for each station are compiled, and a coordinated subset of Canadian and U.S. gauges is used to calculate the lake-wide average monthly water levels for each month. These values are put into historical perspective in a *Monthly Bulletin of Lake Levels* product compiled and disseminated by the United States Army Corps of Engineers (USACE, 2014) and Canada. The station locations used to compute the lake-wide means were selected based on their data quality, period of record, and geography.

Figures 6a-e are example USACE bulletin graphics for each lake showing the recent monthly means, the historical long-term average monthly means, the historic maxima and minima monthly means, and the 6-month forecast, all relative to Low Water Datum (LWD). Bulletins are available at:

http://www.lre.usace.army.mil/Missions/GreatLakesInformation/GreatLakesWaterLevels/WaterLevelForecast/MonthlyBulletinofGreatLakesWaterLevels.aspx The Canadian Hydrographic Service puts out a similar bulletin using the same set of stations (http://www.waterlevels.gc.ca/C&A/bulletin.pdf).

The coordinated network of stations presently used by agencies in both countries to calculate the monthly mean lake levels are as follows:

Lake Superior

Duluth, Minn.; Marquette and Point Iroquois, Mich.; Michipicoten and Thunder Bay, Ontario

Lake Michigan-Huron

Harbor Beach, Mackinaw City and Ludington, Mich.; Milwaukee, Wis.; Thessalon and Tobermory, Ontario

Lake St. Clair

St. Clair Shores, Mich. and Belle River, Ontario

Lake Erie

Toledo and Fairport, Ohio (Note: replaced by Cleveland, Ohio in 2009); Port Stanley and Port Colborne, Ontario

Lake Ontario

Rochester and Oswego, N.Y.; Port Weller, Toronto, Cobourg and Kingston, Ontario

Monthly mean water levels in the Great Lakes have a very strong annual variation. The annual range in lake levels is approximately 0.30 m for Lake Superior, 0.30 m for Lakes Michigan-Huron, 0.40 m for Lake St. Clair, 0.35 m for Lake Erie, and 0.50 m for Lake Ontario. Maximum and minimum monthly means do not all occur during the same months for each lake. Figures 6a-e show the uniqueness of the variations for each lake. Typically, the maxima/minima for Lake Superior occur August/March; Lakes Michigan-Huron occur July/February; Lake St. Clair occur July/February; Lake Erie occur June/December; and Lake Ontario occur June/December.

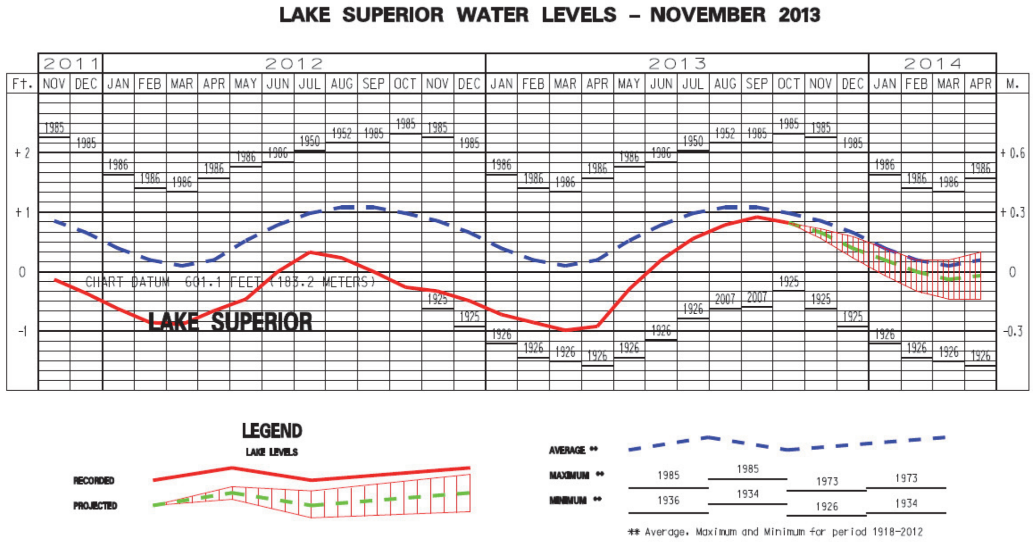


Figure 6a. USACE water level bulletin for Lake Superior for November 2013. Legend depicted is common to all following bulletin plots.

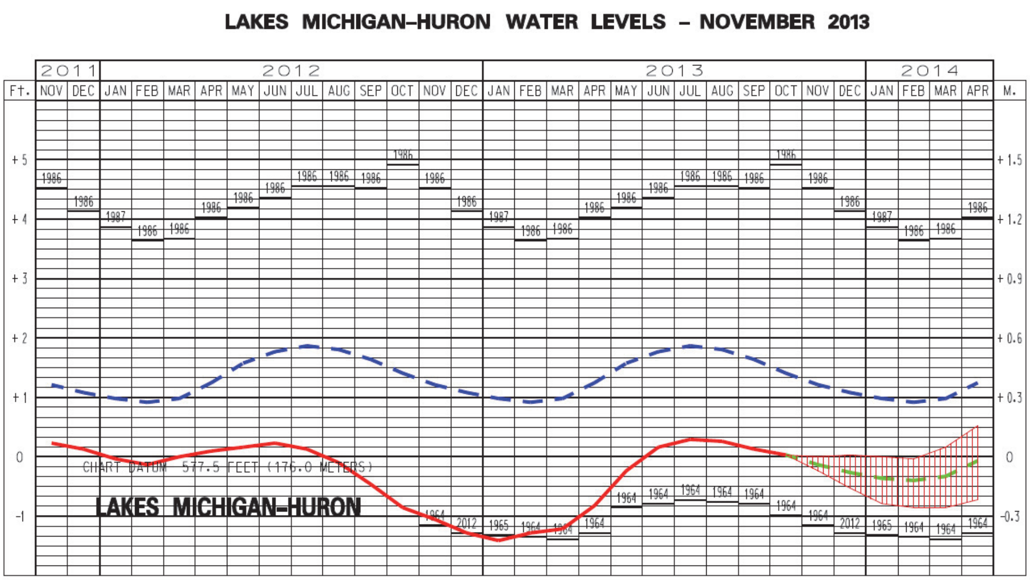


Figure 6b. USACE water level bulletin for Lakes Michigan-Huron for November 2013.

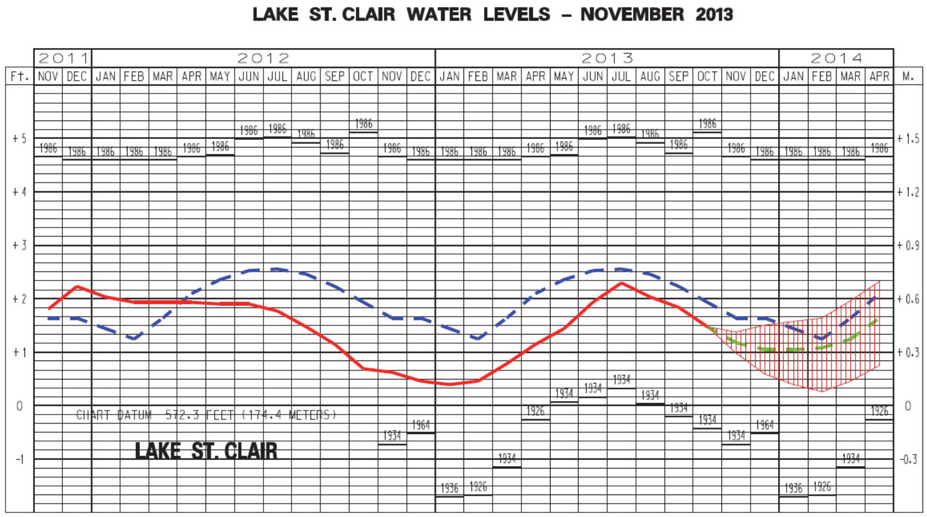


Figure 6c. USACE water level bulletin for Lake St Clair for November 2013.

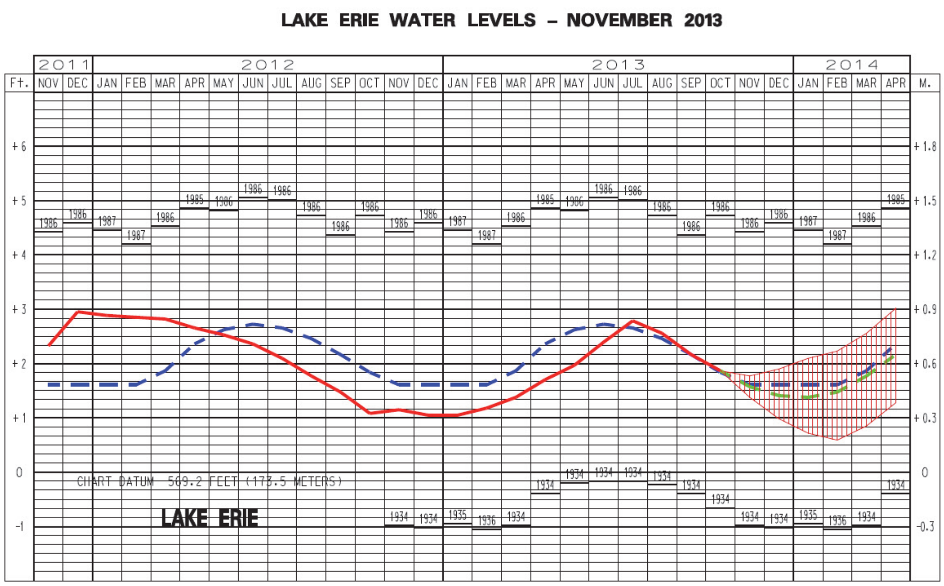


Figure 6d. USACE water level bulletin for Lake Erie for November 2013.

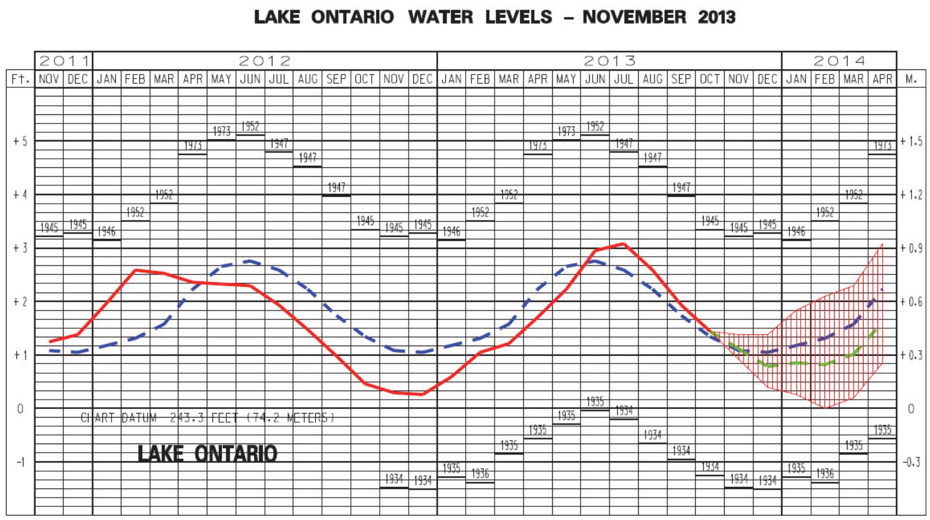


Figure 6e. USACE water level bulletin for Lake Ontario for November 2013.

The figures above show that lake levels in Lake Superior and Lake Michigan/Huron have recently been near or below their respective Chart Datum (LWD) elevations for large stretches of time. These low water stages have been of increasing concern to the coastal communities. Data from the existing gauge networks will provide the basis for any needed update of LWD elevations if the low lake levels do persist.

2.5 Daily Mean Water Levels

Using the same set of stations to establish the lake-wide values for the monthly bulletin described above, agencies in both countries compile and disseminate individual station daily means and lake-wide daily means (for example, from the USACE, see: http://w3.lre.usace.army.mil/hh/GreatLakesWaterLevels/GLWL-1MonthAgo-Meters.pdf).

The daily mean values are used to monitor Great Lakes conditions for various purposes. This includes the determination of net basin supplies, which can be estimated as a residual of inflows, outflows, and change in storage (water level) of the lake over time. The variations in the daily means are also used to study lake dynamics and response to short-to-medium-term weather patterns. Lake surfaces are not uniformly level above a reference datum at all places at all times due to short-period variability in response to meteorological conditions. The effect of wind and differences in barometric pressure over the lake surface create imbalances in water level at various locations or various time scales.

2.6 International Great Lakes Datum (IGLD) Control

The vertical elevation datum for the Great Lakes, known as the International Great Lakes Datum (IGLD), first established in 1955 and last updated in 1985, needs to be updated every 25 to 30 years to reflect continuous and differential changes in land surface elevations across the region. Earlier U.S. datum systems were established in 1903 and 1935.

The general adjustment of the North American Vertical Datum of 1988 (NAVD 88), a minimum-constraint adjustment of Canadian-Mexican-U.S. leveling observations, was performed holding fixed the height of the primary tidal bench mark, referenced to the new International Great Lakes Datum of 1985 (IGLD 85) local mean sea level height value at Father Point/Rimouski, Quebec, Canada. Father Point/Rimouski is an IGLD water-level station located at the mouth of the St. Lawrence River and is the reference station used for IGLD 85. The only difference between IGLD 85 and NAVD 88 is that IGLD 85 bench mark values are given in dynamic height units, and NAVD 88 values are given in Helmert orthometric height units. The geopotential numbers of bench marks are the same in both systems (Zilkoski *et al.,* 1992). The use of dynamic heights provides an accurate measurement of potential hydraulic head, a requirement for the water management of the Great Lakes.

IGLD 85 development involved a comprehensive re-leveling of bench mark networks around each lake. Leveling is no longer viable logistically or financially. A new method of updating dynamic heights, without re-leveling, must be implemented for development IGLD 2020 and is under discussion in the Coordinating Committee. In the U.S., the national vertical datum (NAVD 88) is also being updated, also without re-leveling the country. Canada adopted a new vertical datum (CGVD 2013) in November 2013. Access to the future vertical datum will be through the determination of an ellipsoid height (via the Global Navigation Satellite System or GNSS) minus a geoid undulation (from gravity data, including a new, nationwide airborne gravity campaign called GRAV-D) to determine orthometric heights.

For IGLD, it is proposed that the determination of a dynamic height will begin with a GPS-derived ellipsoid height at a location using a geoid model to obtain an orthometric height. From there, surface and airborne gravity will be used to determine a geopotential number. Normal gravity will then be used to determine dynamic heights. It is noted that the 1985 update from 1955 did not include all stations where IGLD 55 was established. For instance, the seasonal gauging program was not part of that update. This has presented ongoing problems in being able to update datums for IGLD 2020 and in properly interpolating between stations. NOAA has been assessing these requirements for each in lake in a series of lake-by-lake assessment reports (CO-OPS 2013), and those recommendations will be included in planning for IGLD 2020.

2.7 Hydraulic Correctors

The mean water surfaces of the Great Lakes are considered to be geopotentially equal within each lake basin. Therefore, on any particular lake, at the time a new vertical datum is established, all Mean Water Level (MWL) values for gauging stations around a particular lake should coincide. The difference between NAVD 88 Dynamic Heights used to reference IGLD 85 is the application of a Hydraulic Corrector (HC) derived during the measurement period, 1982-1988, at each subordinate lake station. Only within each lake are Hydraulic Correctors used and applied at each of the lakes subordinate water level gauges to reference the base elevation, Low Water Datum/Chart Datum. In the sloping surfaces, rivers and channels, Dynamic Heights equal IGLD 85 and HCs are not applied.

For present definition, the MWL is the average water surface elevation for the summer months (June-September) for the years 1982-1988 referenced to each gauging station's Primary Bench Mark (PBM) Dynamic Height. The MWL at each gauging station was then treated as a bench mark in the network adjustment. Following the adjustment it was found that the MWL at each gauging station on a particular lake was slightly different from the expected value if the lake is a geopotential surface. The differences were due to cumulative differences in the leveling adjustments, steric effects, and dynamic effects. The Coordinating Committee (1995) decided to apply the Hydraulic Corrector to each subordinate gauge station on each lake so that each station has the same dynamic elevation as the Master Station for that lake. This is accomplished by holding the Master Station as the controlling value and comparing all other gauging stations to it. The Master Lake Stations were:

- Lake Ontario: Oswego, New York
- Lake Erie: Fairport, Ohio
- Lake St. Clair: St. Clair Shores, Michigan
- Lake Huron: Harbor Beach, Michigan
- Lake Michigan: Harbor Beach, Michigan
- Lake Superior: Marquette, Michigan

Note that since this calculation, the station at Fairport has been determined to be vertically unstable due to nearby mining operations and will most likely be replaced by Cleveland. Each HC was obtained by subtracting the MWL at the Master Station (MWL_{Master}) from the MWL at the subordinate gauging station in question (MWL_{Sub}). The answer retains the arithmetic sign. The HC may be positive or negative and is subtracted algebraically. Figure 7 shows the HC values for each station. The geographic variations in HC provide information on lake level dynamics and lake surface mean differences. These HCs will need to be calculated during the next IGLD update period; for instance over the reference period 2017 through 2023 for an IGLD 2020 update that is currently being proposed by NOAA.

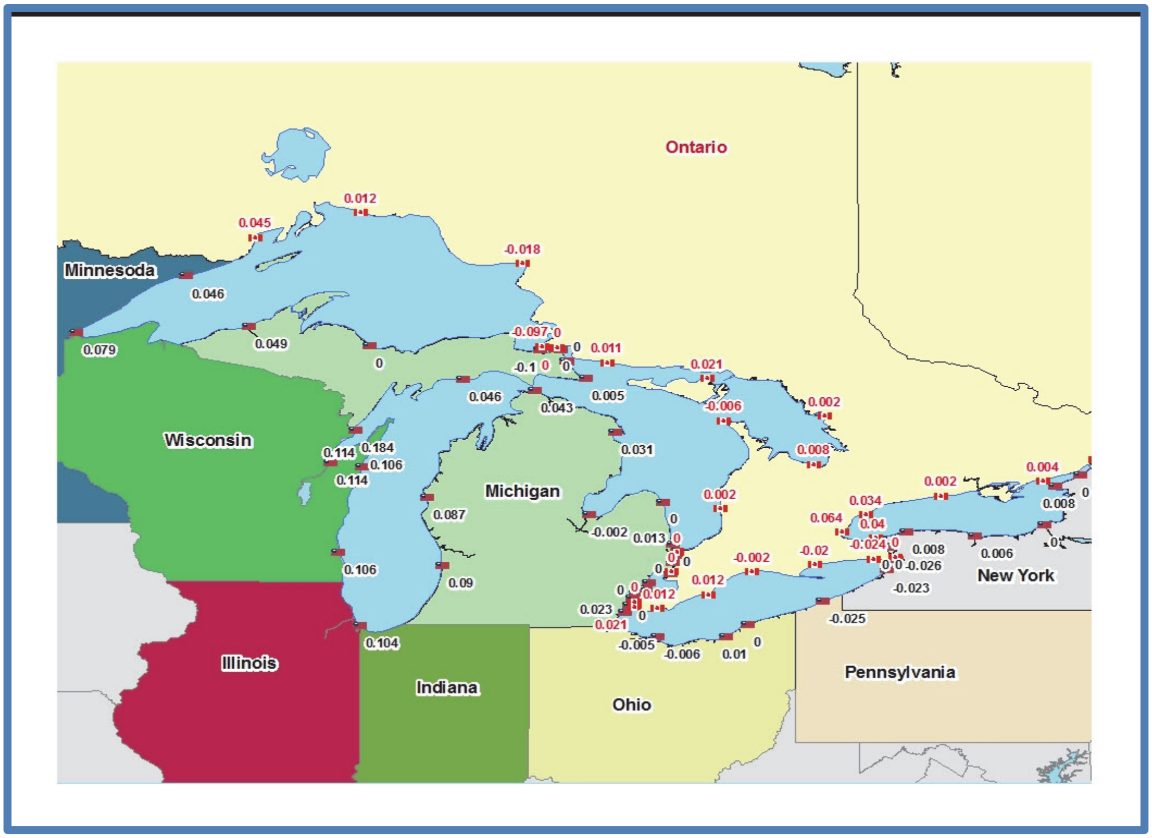


Figure 7. Map of values of the Hydraulic Correctors (meters) for U.S. and Canadian water level stations.

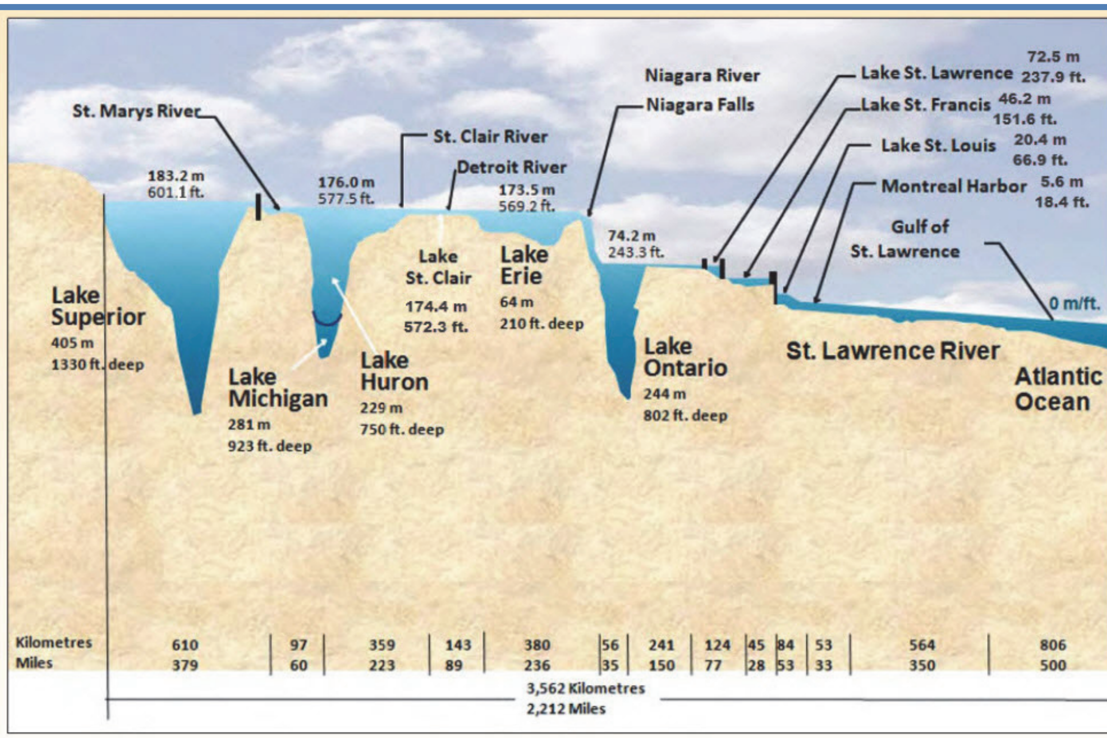
2.8 HC Interpolation Model

A gap in information since implementation of IGLD 85 has been the lack of HC information between existing stations. The seasonal gauging program was not activated as part of IGLD 85 but would have provided much needed information in between the long-term stations. Because of their complex character and geospatial variability, HC estimates at locations other than the long-term operating stations have used interpolated HCs compiled using modeled data grids for potential use prior to future seasonal gauging programs. The NAVD 88/IGLD 85 datum transformation model developed by the National Geodetic Survey spatially interpolates the HC for each location desired. The interpolation-based compilation for HCs; using the existing stations has also been incorporated into the NOAA VDatum product suite (see http://vdatum.noaa.gov/).

The fitting process for the data grids was chosen to honor the Master Station and U.S. and Canadian HC values determined from water level station observations over a seven-year summer-month period, 1982-1988. A post-fit test that re-interpolated the HCs at the Master Stations was shown to agree, with less than 2-mm error. Instrumental error and spatial variation of the HCs will prevent the complete transformation from being more accurate than a few centimeters. The present interpolation model's performance at locations apart from the existing station networks has not been evaluated and the proposed NOS seasonal gauging program is designed to provide actual measured intermediate data points for an improved interpolation model than presently exists. One of the major outcomes of the IGLD update and NOAA's seasonal gauging program will be to evaluate the model performance using an increased number of observational points.

2.9 Low Water Datum (LWD) – Chart Datum

Each of the Great Lakes and Lake St. Clair have individual fixed Low Water Datum (LWD) reference elevation, also used as Chart Datum. The LWD/Chart Datum are chosen as conservative datums for navigation purposes such that during the navigation (ice-free) season the actual water levels in each lake are above the Chart Datum most of the time. LWD is defined by analysis of historical water levels during the summer months June through September at the Master Water Level Stations on the Great Lakes. The heights of LWD are presently computed relative to IGLD 85 and are shown in Figure 8 for the entire Great Lakes-St. Lawrence River System. All subordinate lake stations are hydraulically corrected, adjusted to reference the (Dynamic Height) mean water level of each lake's corresponding Master Station.



(Source: modified from Great Lakes Commission and U.S. Army Corps of Engineers, 1999)
Note: Water surface elevations are at chart datum on IGLD (1985).

Figure 8. IGLD 85 Heights (m) of LWD for the Great Lakes – St. Lawrence River System.

NOAA is transitioning into performing Ellipsoidally Referenced Hydrographic Surveys (ERS) for nautical charts and ellipsoidally referenced Lidar surveys for shoreline delineation. For these types of surveys in the Great Lakes, elevation differences between the elevation of Chart Datum (LWD) and the ellipsoid (NAD83) must be precisely known everywhere in the survey area. NAD83 is an expression of the mathematically-defined ellipsoidal reference surface, which has slopes and variations relative to the Earth's surface. The relationship of LWD to the ellipsoid has been estimated using static GPS surveys on bench marks at most NWLON stations; however, additional repeat surveys are needed to evaluate the GPS data for consistency, both geographically and over time.

3.0 GAP ANALYSIS APPROACH

Continued operations and monitoring in the Great Lakes described in the previous sections require accurate water level measurements and derived products relative to an accurately established vertical reference datum. The necessary measurements require a network of stations to provide spatial and temporal coverage of the water level variations that meet a variety of needs including the following: real-time water levels for safe navigation; data products of daily, monthly and annual means for regulation and monitoring; determination of long-term decadal trends; and long-term data series to monitor crustal movement. The stations are also used operationally, providing real-time data and derived data products for storm surge warnings, restoration projects, and many other coastal zone management applications. The stations located in the connecting channels have very specific location-based requirements for monitoring flows, vertical control for dredging operations and hydrographic surveys, and for safe and efficient navigation.

As of 2014, NOAA's National Ocean Service operates 53 long-term water level monitoring stations in the Great Lakes as part of the larger NWLON operating along all U.S. coasts. Since water levels in the Great Lakes are largely driven by meteorological factors, a robust network of meteorological sensors is required to fully understand lake level dynamics. After a recent ten-year effort, installation of meteorological sensors (winds, barometric pressure, relative humidity, and air/water temperature) has been made at 24 of the 53 U.S. water level stations. The presence of the GIA signal across the region requires accurate monitoring and determination of rates of vertical land motion. One important system to enable this is a network of CORS. Thirteen (13) U.S. stations now have co-located CORS. The Canadian network includes 34 long-term stations, nine of which have CORS. USACE operates several long-term and short-term stations as well depending upon their projects.

The GIS analysis approach used by Gill and Fisher (2008) for the NWLON gaps analysis report is not applicable to a similar analysis for the Great Lakes. That approach was possible due to the existence of error budget equations and existing overlays of co-tidal lines that produced estimated polygons of coverage whose sizes were driven by threshold errors for tidal datum determination. In this report, the approach is taken to separately assess the water level network needs for operational determination of lake-wide averages, for datum elevation variability and hydraulic correctors, for determination of rates of vertical land velocities, and for determination of LWD reference elevations relative to the ellipsoid. These assessments are looked at in the context of each lake to make recommendations and findings for the network.

This report is a preliminary step by NOAA to assess the Great Lakes water level station network. Gaps in network coverage are assessed by determining if the present station location provides the information required to understand the lake wide variations and provide the datum and data products necessary for management of the Great Lakes system. It is hoped that this report can inform any other observing system analyses underway or in planning.

3.1 Assessment of Lake Averages

In a status assessment of Great Lakes-St. Lawrence River Water Resources (Great Lakes Commission, 2003), it was noted that daily and monthly lake-wide averages are reported to the nearest centimeter and determined through professional judgment that the uncertainty in Great Lakes levels may range from 0.003 m to 0.006 m. NOAA (CO-OPS 2013) considers that individual six-minute measurements from the water level gauges relative to IGLD datum have uncertainties of +/-0.006 m and monthly mean water levels have uncertainties of +/-0.003 m.

Neff and Nicholas (2005) estimate that the uncertainty in the normalized daily mean lake-wide average data is likely to be in the range of 0.002 m. These uncertainty estimates are likely underestimates, as they are based primarily on the uncertainty of water level gauge instruments and measurements at individual stations and did not take into consideration the uncertainty resulting from temporal and spatial variability of water levels on each lake, which is very important in determining uncertainty in lake-wide averages (Bruxer, 2010). The uncertainty in change-in-storage calculations depends on the accurate measurement of the change in lake stage and surface area of each lake. Thermal expansion and contraction of water also contributes to uncertainty in estimates of change in storage.

Beginning-of-month (BOM) lake levels are used to determine monthly rates of storage change for operational purposes such as navigation, hydro-electric power, and lake regulation. BOM levels are computed using the daily mean water levels for the first and last days of the month for each network of water level stations on a given lake. Computation of lake-stage data can be complicated primarily by wind set-up and seiche and secondarily by GIA effects. Wind set-up and seiche can cause great variability in lake stage at different parts of a lake; wind set-up is greatest in the fall and winter, when wind tends to be strongest and more prevalent (Croley, 1987). Due to these effects, a straight average of water levels from all of the stations on each lake is not used. One method used to correct for these factors is to measure lake stage at selected locations and average the values in a weighted fashion to determine an average lake stage (Croley, 1987a, 1987b).

Quinn *et al.* (1974-1976) recommended using mean water levels for the two days—the first day of each month and the last day of the previous month—and employing a weighting function strategy with a Thiessen polygon procedure. To support this weighting function strategy, Quinn and Todd (1974) performed initial error analyses for the dependency of network size on the determination of BOM water levels. Through a series of similar analyses for each lake, it was found that placement (geographical distribution) of the gauges is a key factor in successful computation of BOM water levels. In a series of reports analyzing network size requirements of BOM lake levels, Quinn *et al.* (five reports: 1974 through 1976) found that the optimum number of gauges (both U.S. and Canadian) would be:

Nine (9) gauges for Lake Superior
Five (5) gauges for Lake Michigan
Ten (10) gauges for Lake Huron
Four (4) gauges for Lake St. Clair
Nine (9) gauges for Lake Erie
Nine (9) gauges for Lake Ontario

Croley (1987) evaluated optimum network sizes using a spatial-optimization estimating technique for Lakes Superior and Erie and evaluated his results against the Thiessen polygon method developed by Quinn *et al*. Croley determined that, for lake level estimation purposes, to obtain a maximum tolerable error of 0.006 m, an eight -gauge network would be sufficient for

Lake Erie and a network of seven gauges is sufficient for Lake Superior. Croley suggests that the spatial-optimum estimator is superior to the Thiessen polygon method because it eliminates long-term wind set-up errors more effectively.

Zervas (1997) performed an accuracy study of Great Lakes mean water levels for various network configurations using an empirical orthogonal function (EOF) approach. Results were obtained for mean lake levels using two-day averages. Findings include that only small error reductions are obtained for networks greater than eight (8) gauges on each lake. Small errors in mean lake level were classified as those with less than 0.01 m standard error and maximum errors less than 0.10 m. Using hourly data, Zervas also found that lake level differences determined by any of the spatial optimum, Thiessen, or EOF methodologies were similar (within 0.02 m standard error and 0.15 m maximum error). Lake Erie errors are larger than the other lakes because the differential effects of wind stress on Lake Erie are much larger than the other lakes.

Appendix 1 contains hourly water level plots and hourly lake averages for each lake for the year 2005 to provide a sense of the lake-wide variability over a full year. These plots provide a visual sense of the variability of water levels for a given calendar year with the swath of simultaneous data plotted for each lake. November and December were particularly “noisy” due to a series of weather events. The hourly average plots are constructed by averaging the simultaneous hourly water levels for all Canadian and U.S. stations in each lake and computing the standard deviation of the averages for each hour. Lake Ontario is the “quietest” lake with very small standard deviation. Lake Erie is the “noisiest” and Lakes Michigan and Huron are very similar. The interesting feature for Lake Superior is the lake-wide jump in water levels in October 2005, when levels rose 12 cm in three days from the third to the sixth days of the month due to heavy precipitation.

3.2 Assessment of Daily Means

Lake levels are very dynamic surfaces and respond to daily weather patterns, comparisons of simultaneous daily mean water levels are also instructive in understanding the varying slopes of the lake surfaces relative to IGLD. In the assessment sections that follow, example plots of simultaneous daily mean values from individual stations for each lake are compared to the official composite daily means calculated by USACE and Environment Canada from a subset of stations in each lake for a one-month period (June 2013). The nature of the differences in daily variability among stations is examined in these plots. Figure 9 shows a monthly comparison of daily means for Lake Superior for June 1985 and the present (June 2013). All station values plot closer to the lake-wide mean in 1985 than in 2013. The elevations were adjusted to be close together with the application of HCs and 1985 was the center year of the seven-year IGLD 1985 update period. Seasonal and monthly meteorologically driven biases in lake levels among stations and lake dynamics account for some differences; however, the larger separation biases between the same stations in 2013 are also related to the ongoing effects of differential rates of vertical land movement among the stations. The elevation differences among the stations shown over a one-month period in Figure 9 are consistent with longer period statistical comparisons (see following section). These differences are found in similar plots in the following sections for each individual lake. At shorter time steps, the daily variations are often negatively correlated (oscillations out-of-phase) across the lake due to local meteorological effects as seen in both time periods.

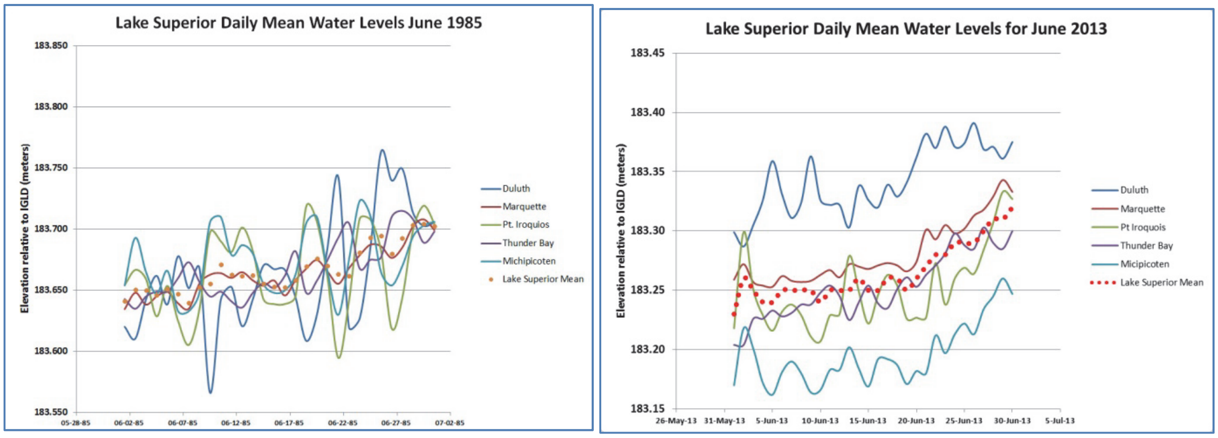


Figure 9. Comparison of daily mean water levels for June 1985 and June 2013 in Lake Superior.

3.3 Assessment of Station Pair Comparisons

One of the statistical analysis procedures used in this report is performed by using hourly heights because they are used to compute subsequent data products such as daily and monthly mean lake levels. Hourly heights are used rather than higher rate data such as six-minute interval data for ease in analysis and because the hourly and six-minute data have the same statistical distributions. In addition, it is the hourly data that are used to derive many subsequent products. For this statistical analysis the seven-year period from 2005 through 2011 was selected. A seven-year period was selected because it is the length of time currently used for the determination of lake-wide datums, mean values, and Hydraulic Correctors. For many applications, only the data from the seasonal low water level months are used over seven-year period (i.e., 1982-1988 for IGLD 1985 Hydraulic Correctors and for LWD); however, statistical comparisons of hourly heights over twelve months for each year of a seven-year period were performed here as a measure of the total water level variability among various U.S. station-pairs on each lake and the connecting waterways. A full year of data is used also to be compatible with the Zervas (1997) and Mainville and Craymer (2005) analyses, which also used full years of data.

Station pairs were generally determined by comparing neighboring stations, but also by pairing stations from each end of the lake to obtain a sense of maximum variability. By analyzing the mean differences, standard deviations, maxima and minima, and correlation coefficients from each comparison, a relative sense of insufficient and/or overlapping control can be obtained. For an initial assessment, only small mean differences would be expected because the data from the stations are all adjusted prior to dissemination by applying each station's HC that was developed in 1985 to reference everything to IGLD. However, this assumption does not hold true due to the relative differences in vertical land movement between station pairs as discussed for each lake in following sections. Comparisons with Canadian stations and Canadian shore station pairs are also included for lake-wide context. It is noted that Lakes Michigan and Huron are connected via hydraulic strait and are considered as one basin for purposes of hydraulic correctors and lake-wide averages. Here we separate the discussion for each lake basin in order to focus the characterization of each lake.

A functional observing system network provides for an appropriate amount of overlap in coverage such that if one station was temporarily lost, another could substitute if certain statistically valid adjustments could be made. For station statistical comparisons, it was generally found that good overlap could be defined as when in seven-year hourly height comparisons, station pairs have mean differences of less than 0.010 m (after accounting for vertical velocity differences), standard deviations of less than 0.020 m, maximum and minimum differences of less than 0.500 m, and linear regression coefficients of 0.99 and higher. Although it depends upon the individual lake, in general, network weaknesses and gaps are identified by station pairs having weaker statistics with mean differences of greater than 0.030 m, standard deviations of greater than 0.060 m, maxima and minima greater than +/-1.000 m and correlation coefficients less than 0.900.

The linear regression coefficients from the recent seven-year period are then compared to the correlation analyses performed by Zervas (1997) to help pinpoint areas of overlap and weakness in network coverage for purposes of establishing datum control and mean lake levels. Zervas used a one-year period of hourly heights from 1990 for his analysis. The following (figures 10 and 11) is an example of a nearby station pair with relatively high statistical correlation:

Point Iroquois and Gros Cap, Lake Superior

7- year Mean Difference: 0.006 m
Standard Deviation: 0.001 m
Least Squares Linear Regression Coefficient: 0.996
Zervas Correlation Coefficient: 0.99

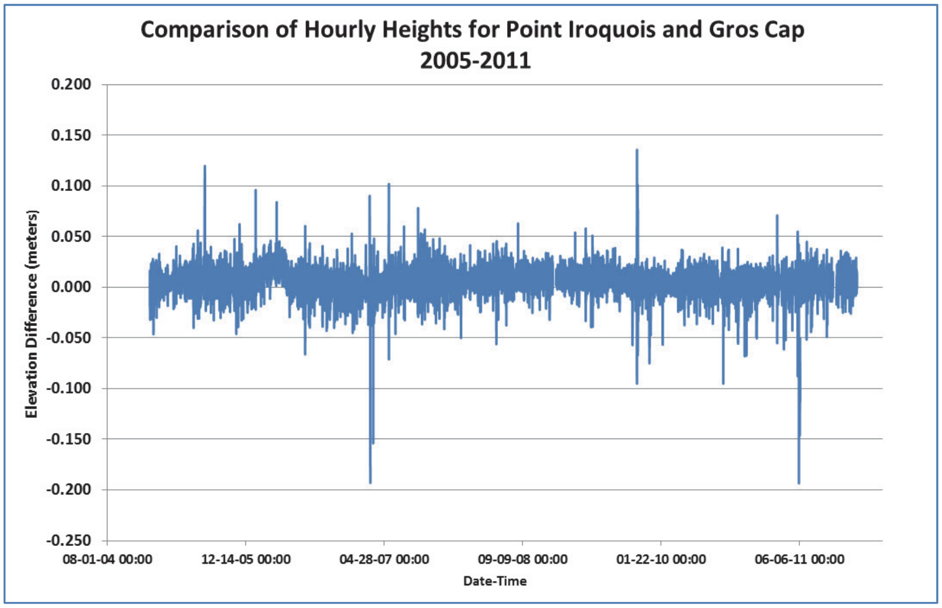


Figure 10. Hourly height differences between Point Iroquois and Gros Cap, 2005-2011.

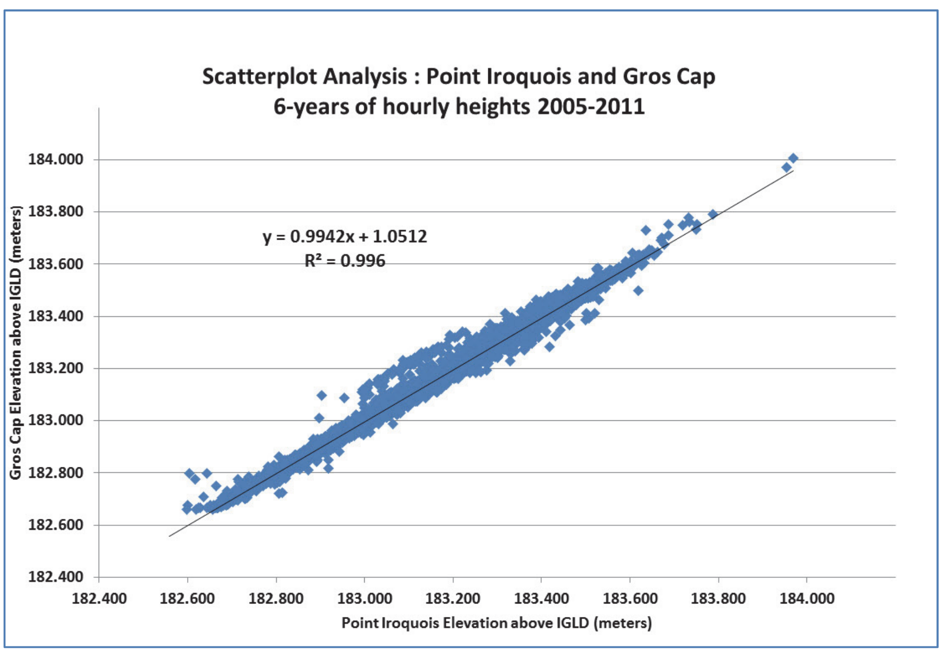


Figure 11. X-Y plot scatterplot comparison of hourly heights for Gros Cap and Point Iroquois.

The following (figures 12 and 13) is an example of a nearby station pair with relatively poor statistical correlation. Note the non-linear feature in the upper right hand corner of the graphic and is most likely due to the unique water level variations in Saginaw Bay (see section 4.3).

Harbor Beach and Essexville, Lake Huron

Mean Difference: -0.021 m
Standard Deviation: 0.095 m
Least Squares Linear Regression Coefficient: 0.780
Zervas Correlation Coefficient: <0.90

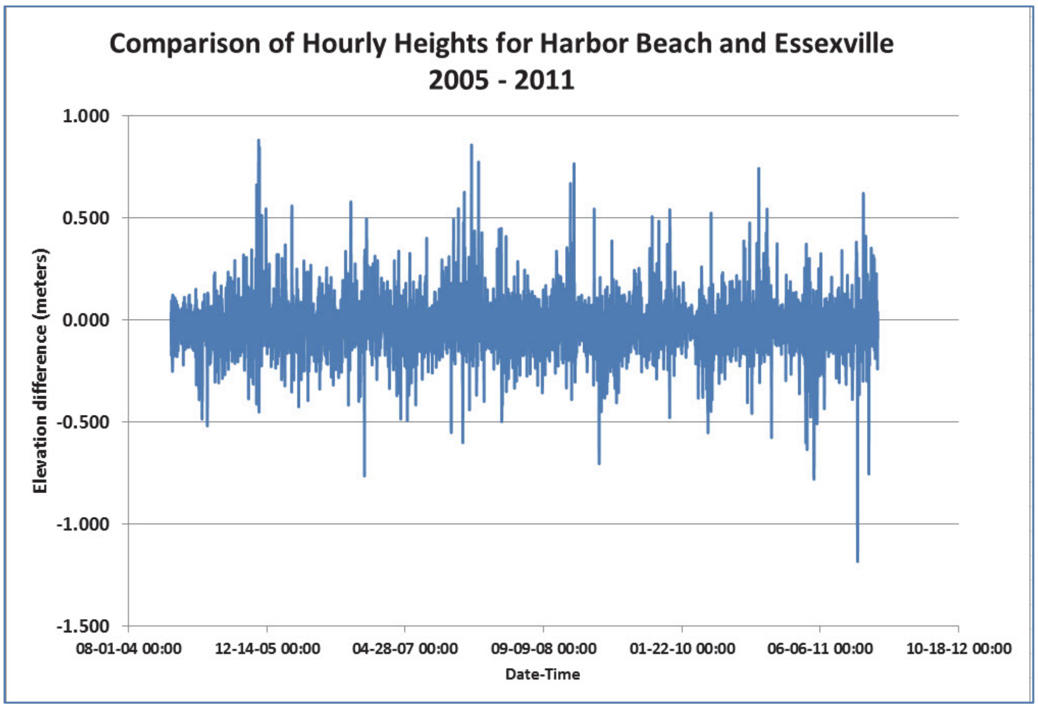


Figure 12. Hourly height differences between Harbor Beach and Essexville, 2005-2011.

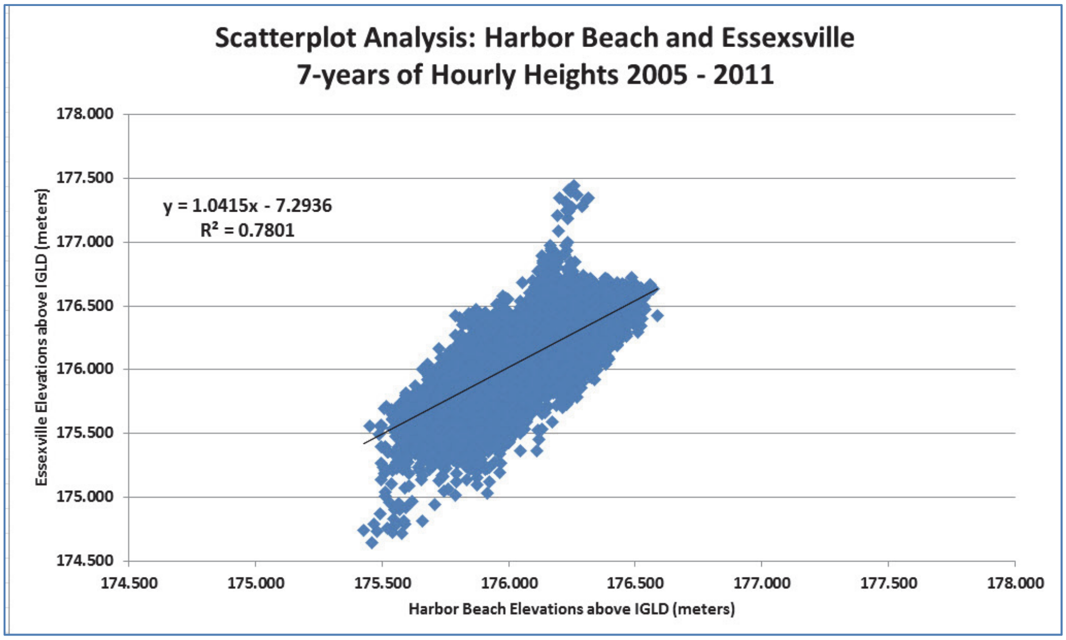


Figure 13. X–Y scatterplot comparison of hourly heights at Harbor Beach and Essexville, 2006-2010.

The mean differences calculated found in tables in the next section for each station pair can largely be accounted for by the relative difference in vertical movement rates between station pairs. This assumption is based on the vertical velocity values in Figure 3 for each station; projected mean elevation change for each station can be estimated by multiplying the vertical velocity rates by 0.23 century (the portion of a century between 1985 and 2008, the central year of the 2005-2011 period) and then differencing the projected elevation between stations.

For example ,(see table 1):
Iroquois-Duluth: Duluth is falling at about 23.5 cm/century relative to Iroquois.

$$(0.23)x\ (-\ 23.5) = -5.8\ \text{cm}$$

Therefore, the land at Duluth has fallen about 5.8 cm relative to Iroquois since 1985. As a result, the water levels being recorded there now are about 5.8 cm higher than at Iroquois. Therefore, the mean difference is projected to be Iroquois – Duluth = -0.058 m. The calculated mean difference from the 2005-2011 hourly data sets is -0.051 m (Table 1).

Projected values using this procedure were obtained for each station pair, and they are listed in italics next to the calculated mean difference in each of the tables of statistics for each lake. In general, the projected and calculated values agree within expected uncertainties given the uncertainties in the procedure used and due to actual dynamical differences in mean lake level between the station pairs.

3.4 Assessment of Hydraulic Correctors

The distribution of the observed and modeled HCs for each lake is examined for adequate network distribution for datum determination and transfer. Contour maps of the HC distributions are presented for each lake in the following sections and assessed for their spatial variations, anomalies, and for areas in which HCs are not well-understood. The values of the hydraulic correctors used for interpolation were those published by the Coordinating Committee (1995). Interpolation of HCs to specific project locations for which directly calculated values from a water level gauge are not available is an ongoing requirement for datum control. Lack of observation points from a distributed network throughout a given lake will negatively affect being able to interpolate the HC variations with any accuracy.

3.5 Assessment of Variations of Crustal Movement

As discussed earlier, GIA is an ongoing, significant differential vertical land motion phenomenon that has the northwest-southeast axis running though the lakes, about which uplift is occurring northeast of the axis and subsidence southwest of the axis. The impact of GIA on the apparent water levels is recorded at each station and over time, the differential rates of vertical land motion affect the hydraulic flow characteristics of the Great Lakes system and drive decisions for updating vertical reference datum systems.

The distribution of the water level network stations are examined for adequacy in determining and monitoring the geospatial variability of the GIA. It is envisioned that as the CORS network co-located at the water level stations expands and accrues longer time series, the measured vertical velocities from CORS will have the accuracy required to better define this geospatial variability than using long-term water level variations. Among other reasons, the present density of Great Lakes stations should still be maintained in order to monitor the vertical land motion and the effects on Great Lakes flows and hydrology. In this study, each lake is examined for any redundancy in the rates of overlap between the stations on that lake. Continued monitoring will enable a more precise GIA model and will enable precise comparisons between using lake level data and CORS data to refine actual gradients in vertical land motion. However, the use of a GIA model is not envisioned to replace requirements of actual long-term water level measurements for the purpose of estimating vertical land motion even if to the present uncertainties in the models is improved. The water levels themselves are best at describing the land-water relationship around each lake, and levels feed into and can help validate other GIA models as well as the CORS data. The water level measurements also capture the impacts of more than just GIA (e.g., the water levels recorded at Fairport helped identify the subsidence issues there). Use of CORS data to independently measure vertical land motion requires installation of CORS at many more water level stations and awaits longer time periods of measurement to obtain precise estimates.

Vertical velocities at each station relative to their respective lake outlets are assessed by referring to the values and graphics from Mainville and Craymer (2005). Bruxer and Southam (2008) also obtained similar estimates using water level data only from the four seasonal low-water months (June-September). The variations in vertical velocities among adjacent station pairs are examined and compared to the computed mean differences found over a recent seven-year period of hourly heights.

3.6 Assessment of Ellipsoidal Height Relationships to Low Water Datum

Using GPS surveys at each of the NWLON stations, graphs of the LWD elevation relationships to the ellipsoid are constructed for each lake for the U.S. gauges. There are significant and varying slopes in the elevation differences across the lake and amongst station pairs; however this information is based on limited numbers of GPS surveys. These slopes and variations could be due to limitations of the GPS surveys or could be actual variation in the two surfaces across the lake shore. Additional GPS surveys are required at these stations to get a more accurate assessment of these apparent slopes and differences. The addition of more co-located CORS and water stations will also assist this effort. The seasonal gauging program planned as part of the IGLD update will assist in this determination by providing intermediate data in between existing NWLON stations.

4.0 INDIVIDUAL LAKE ASSESSMENTS

4.1 Lake Superior

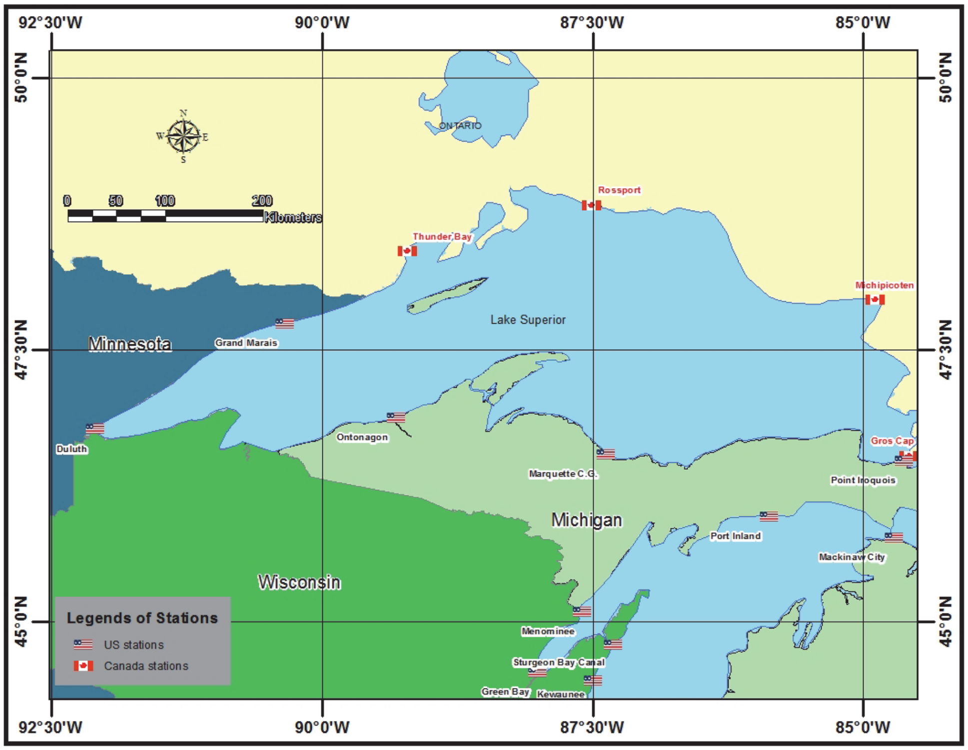


Figure 14. U.S. and Canadian Water level Station locations for Lake Superior.

Figure 14 (above) shows the locations of the U.S. and Canadian water level station networks for Lake Superior. Figure 15 is an example plot of the daily mean water levels from the subset of stations used on Lake Superior to compute lake-wide means for various applications. For the time period plotted for June 2013, three of the five stations track the lake-wide average within a few centimeters, however the two stations at opposite ends of the lake are several centimeters above and below the lake-wide average. This systematic difference is due to the impact of GIA on the land-to-water relationship around Lake Superior over time (See Figure 18). Duluth is subsiding at about 25 cm/century relative to the lake outlet (and its five-gauge lake-wide average level). As a result the water levels recorded there are rising at the same rate over time. The opposite is true at Michipicoten. The differences in Figure 15 for Point Iroquois, Marquette and Thunder Bay are consistent with the changes seen relative to the lake's outlet and its five-station average.

The differences in phase of the daily water level fluctuations recorded at different locations, (e.g., Thunder Bay water levels go up when Point Iroquois water levels go down, and vice versa) are indicative of the short-term seiche effects that are meteorological in origin. The slopes of the lake surface are constantly changing.

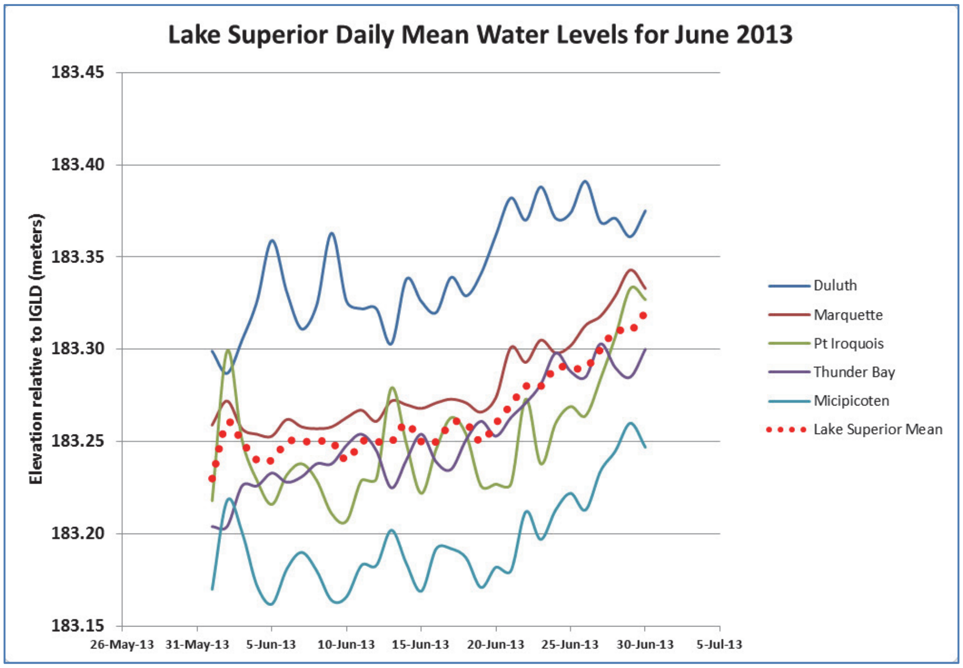


Figure 15. Daily mean water levels for Lake Superior for June 2013.

Except for the pairing of the two stations at the extreme ends of the lake, the station pair statistical differences (Table 1 and Figure 16) between neighboring pairs are 0.03 m or less with linear regression coefficients near or above 0.90 for long-term hourly height comparisons. Correlation coefficients found by Zervas (1997) are very similar using only one year of hourly data from 1990. The station pair of Point Iroquois (U.S.) and Gros Cap (Canada) are located close to each other and show a high degree of correlation (>0.99) and very small statistical differences over the seven-year period. A cross-lake pair is also included here (Ontonagon-Grand Marais) to assess a cross-lake difference over a relatively short distance. Projected mean differences using the differences in vertical velocities between station pairs are listed in italics next to each calculated difference over the seven-year period.

Table 1. Comparison statistics for Lake Superior station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from U.S. and Canadian databases relative to IGLD 1985 (HC applied). Projected mean differences are in italics.

Lake Superior					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Max. Difference (m)**	**Min. Difference (m)**	**Regression Coefficient**
Point Iroquois-Duluth	-0.051 (*-0.058)*	0.110	0.893	-0.707	0.612
Point Iroquois-Marquette	-0.022 (*-0.028)*	0.053	0.542	-0.538	0.900
Marquette-Ontonagon	-0.013 (*-0.015)*	0.042	0.274	-0.468	0.928
Ontonagon-Duluth	-0.016 (*-0.015)*	0.055	0.350	-0.358	0.890
Duluth-Grand Marais	0.031 (*0.041)*	0.042	0.350	-0.244	0.937
Ontonago-Grand Marais	0.015 (*0.026)*	0.034	0.283	-0.219	0.955
Grand Marais-Thunder Bay	0.023 (*0.023)*	0.031	0.313	-0.269	0.961
Thunder Bay-Rossport	0.05 (*0.06)*	0.04	0.49	-0.25	0.942
Rossport-Michipicoten	-0.01 (*-0.01)*	0.04	0.33	-0.59	0.920
Michipicoten-Gros Cap	-0.04 (*-0.05)*	0.05	0.44	-0.46	0.925
Gros Cap-Point Iroquois	-0.01 (*0.0)*	0.01	0.19	-0.14	0.996

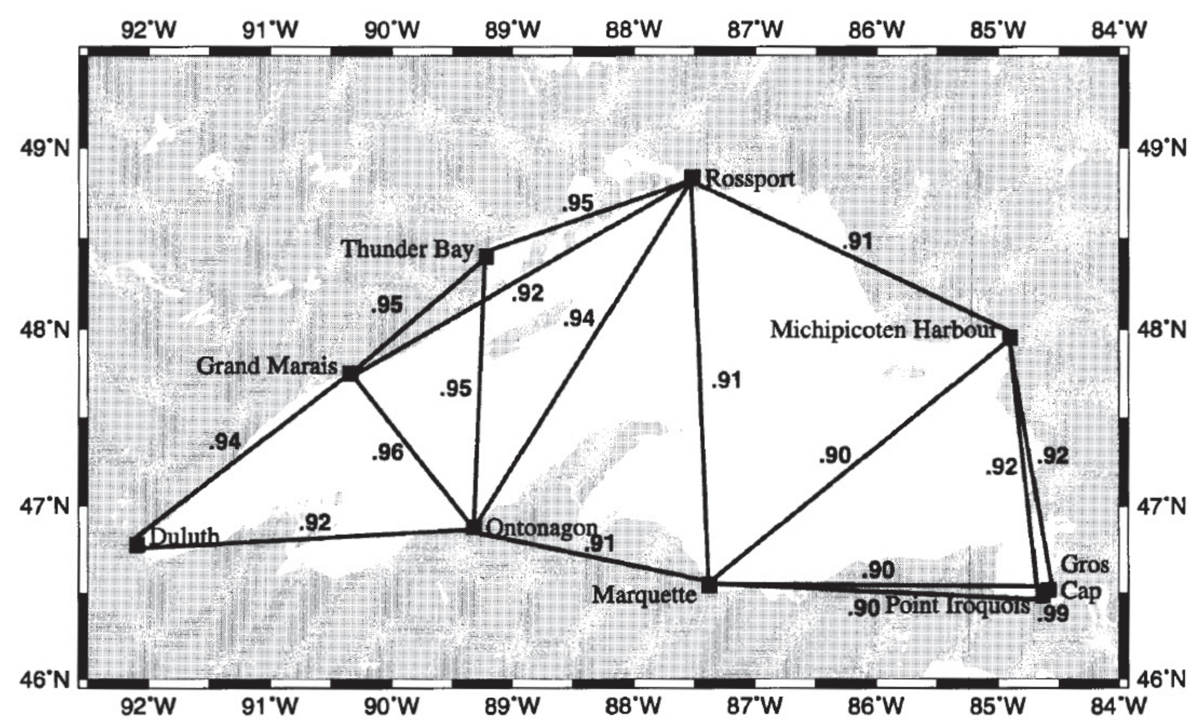


Figure 16. Lake Superior correlation coefficients from Zervas (1997).

The Master Station for determination of HCs in Lake Superior is Marquette, Mich. (Coordinating Committee, 1995). Interpolated HC contours (see Figure 17) are oriented in a general longitudinal direction with maximum values (≥0.10 m) at each end of the lake. Despite the large amplitudes, there do not appear to be any areas with complex HC contour patterns that are seen in other lakes.

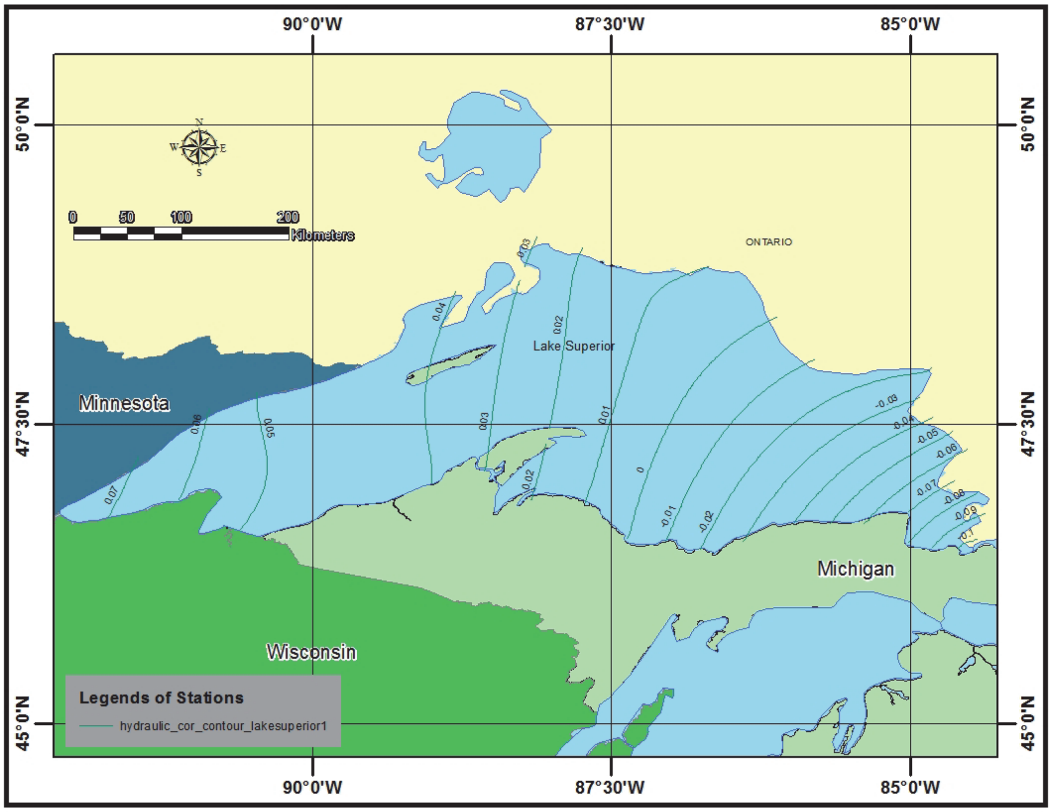


Figure 17. Interpolated HCs for Lake Superior.

The vertical land motion velocities in Lake Superior relative to the lake outlet into the St. Marys River are shown in Figure 18. The values range from highly negative rates (-25 cm/century) in the western end at Duluth to +27 cm/century in the northern end (Rossport). This is due to the fact that the land is rising faster as one moves to the north and east. The 0 cm/century line (which passes through the lake's outlet [Figure 2]) is simply a result of this differential movement and the orientation of the lake itself (since the outlet is at the far eastern end of Lake Superior). There are very large changes in the vertical velocities over relatively small distances. CORS have been established at U.S. stations Marquette (in 2004), Grand Marais (in 2002) and Point Iroquois (in 2003) and at the Canadian stations at Rossport (in 2002) and Michipicoten (in 2009); however, the data series are not yet long enough to accurately estimate vertical velocities for comparison with those from the GIA model and from the water level records.

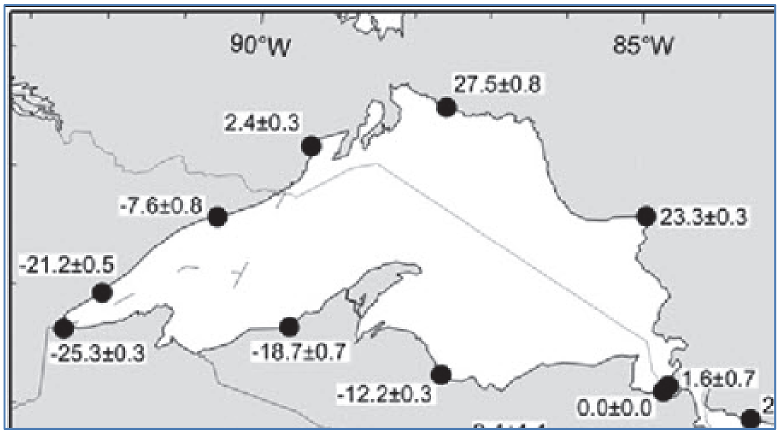


Figure 18. Relative vertical velocities (in cm/century) for Lake Superior (Mainville and Craymer [2005]) relative to the lake outlet.

Differences in the ellipsoidally based elevation surface of NAD 83 relative to LWD shown in Figure 19 are approximately 8.0 m from the western to eastern ends of Lake Superior. These preliminary values are based on static GPS surveys to individual bench marks at each station. This elevation difference between the surfaces could be better refined with more GPS surveys between Ontonagon and Marquette. The amplitudes of the unknown variation in the elevation differences are significant for hydrographic surveying and would need to be known prior to successful surveying on the ellipsoid on Lake Superior.

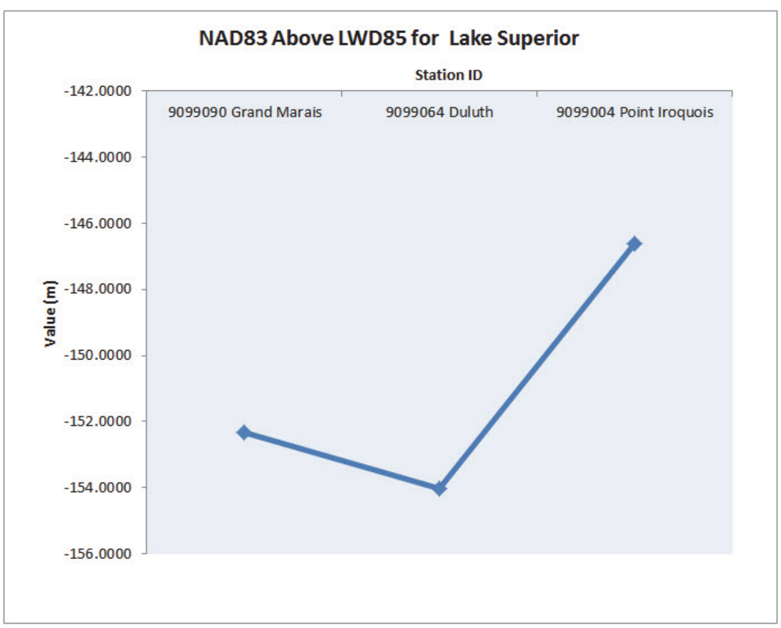


Figure 19. Relationship of LWD and NAD 83 for Lake Superior.

4.2 Lake Michigan

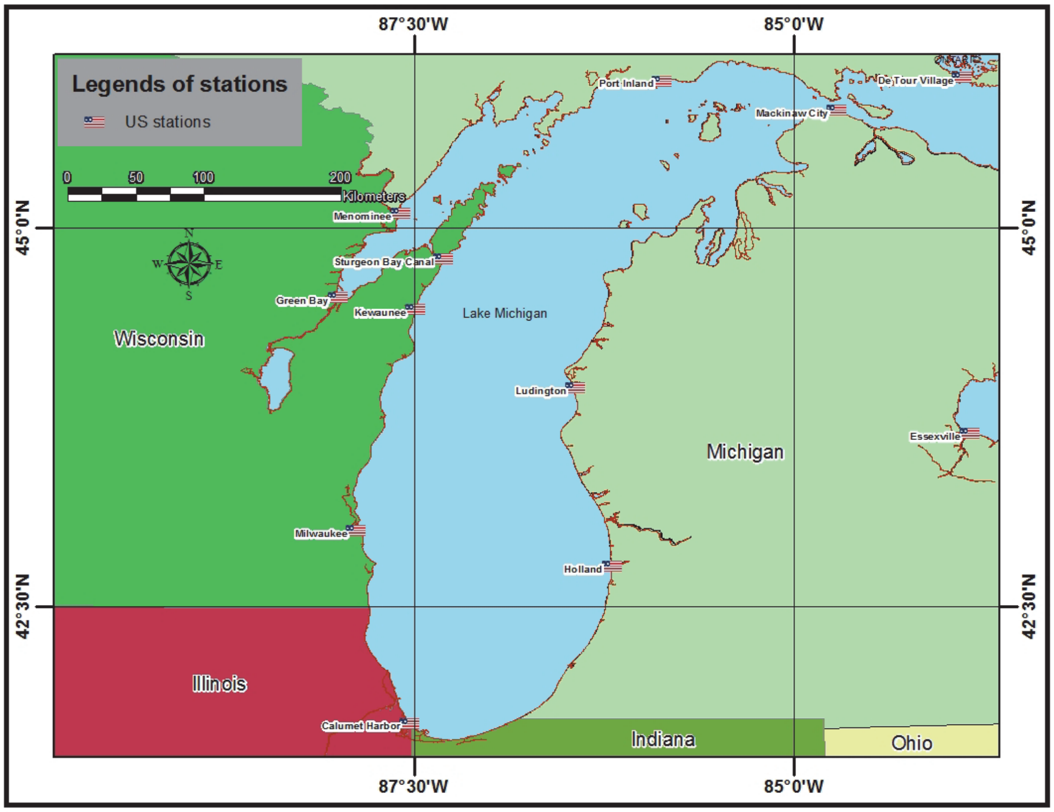


Figure 20. U.S. water level station locations for Lake Michigan and vicinity.

Lakes Michigan and Huron are hydraulically connected and are treated together for most lake level and hydraulic corrector purposes. They are considered separately here for purposes of focusing in on each lake basin. Figure 20 (above) shows the locations of the U.S. water level stations on Lake Michigan. The statistical analyses in Table 2 show that the station pairs Milwaukee-Calumet and Calumet–Holland both have correlation coefficients below 0.90 and have relatively high standard deviations in their mean differences. In Figure 21, the convention of Zervas (1997) is to show lines between stations only if the correlation is greater than or equal to 0.90. The lack of lines depicted between those same two station pairs is because the correlations are less than 0.90, which is consistent with the results from Table 2. Lines are not shown between Green Bay and any other station, or between Ludington and Mackinaw City. This is consistent with the large differences and standard devations and relatively small regression coefficients in Table 2. The calculated mean differences are presented in Table 2 along with the projected mean differences based on the relative differences in vertical velocities of land motion of the station pairs. Vertical velocities are not available for Menominee, as it is a relatively new station. Projected mean differences using the differences in vertical velocities between station pairs are listed in italics next to each calculated difference over the seven-year period. The mean difference is relatively high and the correlation coefficient is relatively low for the Ludington-Mackinaw City station pair.

Table 2. Comparison statistics for Lake Michigan station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from U.S. and Canadian databases relative to IGLD 1985 (HCs applied). Projected mean differences are in italics.

Lake Michigan					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Mackinaw City-Calumet	-0.073 (*-0.047)*	0.120	0.815	-1.162	0.613
Mackinaw City-Port Inland	-0.017 *(-0.001*)	0.051	0.314	-0.458	0.923
Port Inland-Menominee	-0.015 (*n/a)*	0.067	0.711	-0.505	0.888
Menominee-Green Bay	-0.019 (*n/a)*	0.081	0.744	-1.096	0.859
Port Inland-Sturgeon Bay	-0.027 (*-0.030)*	0.054	0.595	-0.377	0.917
Menominee-Sturgeon Bay	-0.012 (*n/a)*	0.044	0.354	-0.333	0.950
Sturgeon Bay-Kewaunee	0.000 (*-0.010)*	0.034	0.340	-0.362	0.962
Kewaunee-Milwaukee	-0.020 (*-0.014)*	0.050	0.533	-0.510	0.919
Milwaukee-Calumet	-0.008 *(+0.009*)	0.064	0.599	-0.616	0.888
Calumet-Holland	0.007 (*0.006)*	0.068	0.564	-0.609	0.873
Holland-Ludington	0.003 (*-0.010)*	0.044	0.571	-0.359	0.938
Ludington-Mackinaw City	0.062 (*0.051)*	0.063	0.326	-0.335	0.869

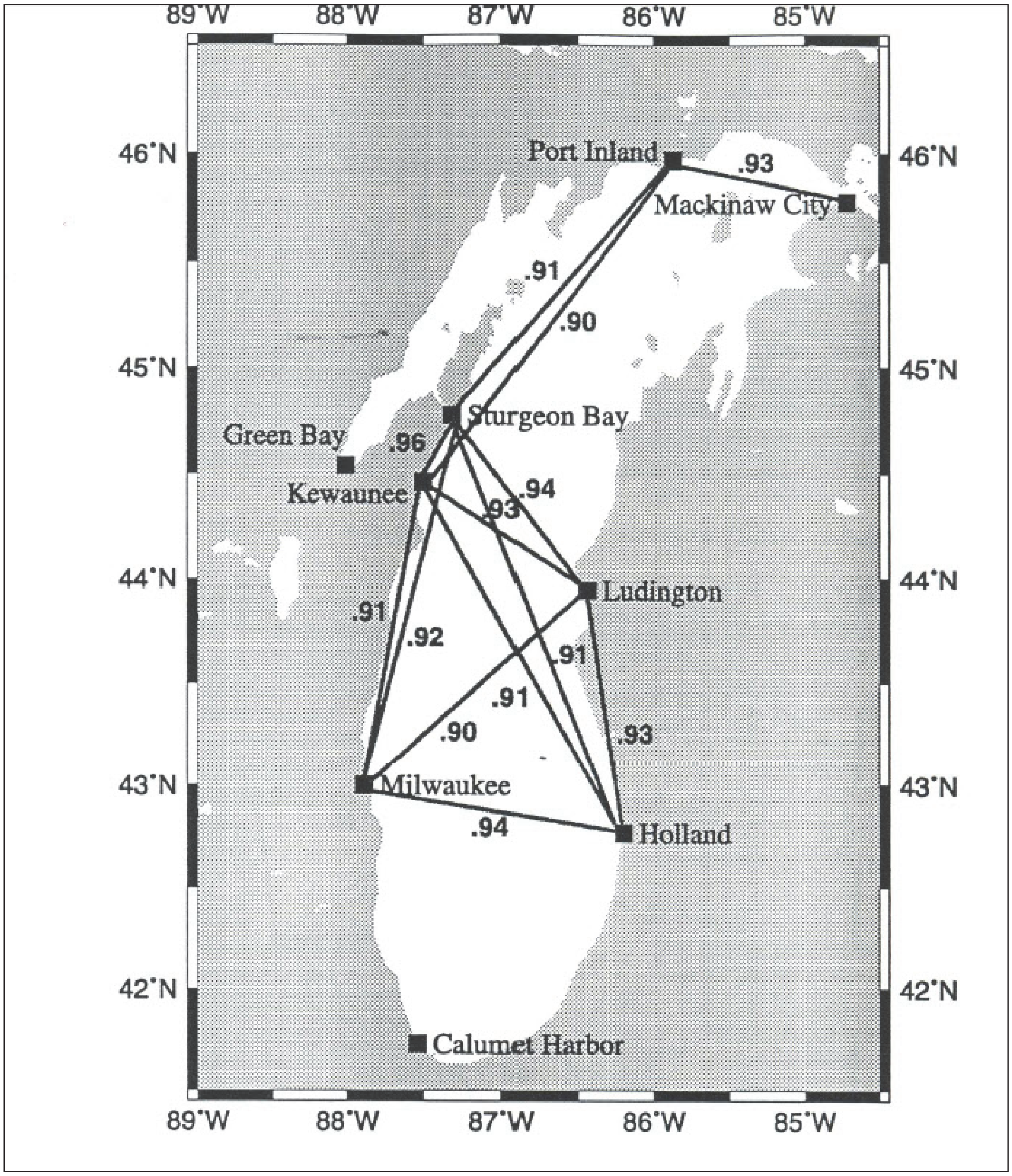


Figure 21. Lake Michigan correlation coefficients from Zervas (1997).

Network coverage in Green Bay is complicated by the active high frequency oscillation in that bay. Zervas (1997) found from EOF analyses that Green Bay variations dominated the second modes, indicating that it has a large water level signal unique to that location. Figure 22 further illustrates the nature of the anomlaous water levels in Green Bay relative to the rest of Lake Michigan using an example simultaneous plot of data from May and June 2013. With Sturgeon Bay representing the outside lake, the plots of Menominee and Green Bay show a regular high frequency oscillation (10 to12 hour period) that increases in amplitude going up into Green Bay. This is symptomatic of a resonance or amplification of the normal lake sieche by the bay configuration. The bathymetric contour map (Figure 23) shows how Green Bay is isolated from the rest of the lake by shallower water at the entrance. Quinn (1975) also considered this anomalous area for purposes of computing lake-wide means by assigning a weight of only 0.037 for a limited geographic Thiessen polygon. The relatively recent establishment of the station at Menominee (not inlcuded in the Zervas (1997) work) has bolstered the network in that region.

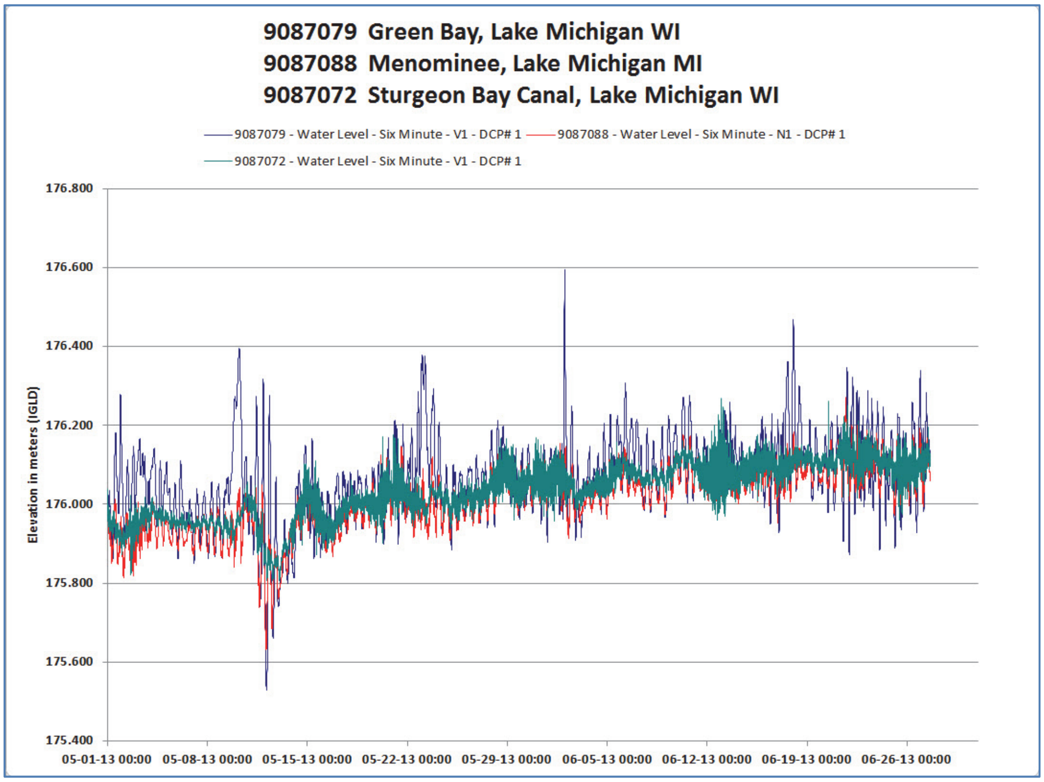


Figure 22. Simultaneous plot of data from Green Bay, Menominee and Sturgeon Bay for May and June 2013.

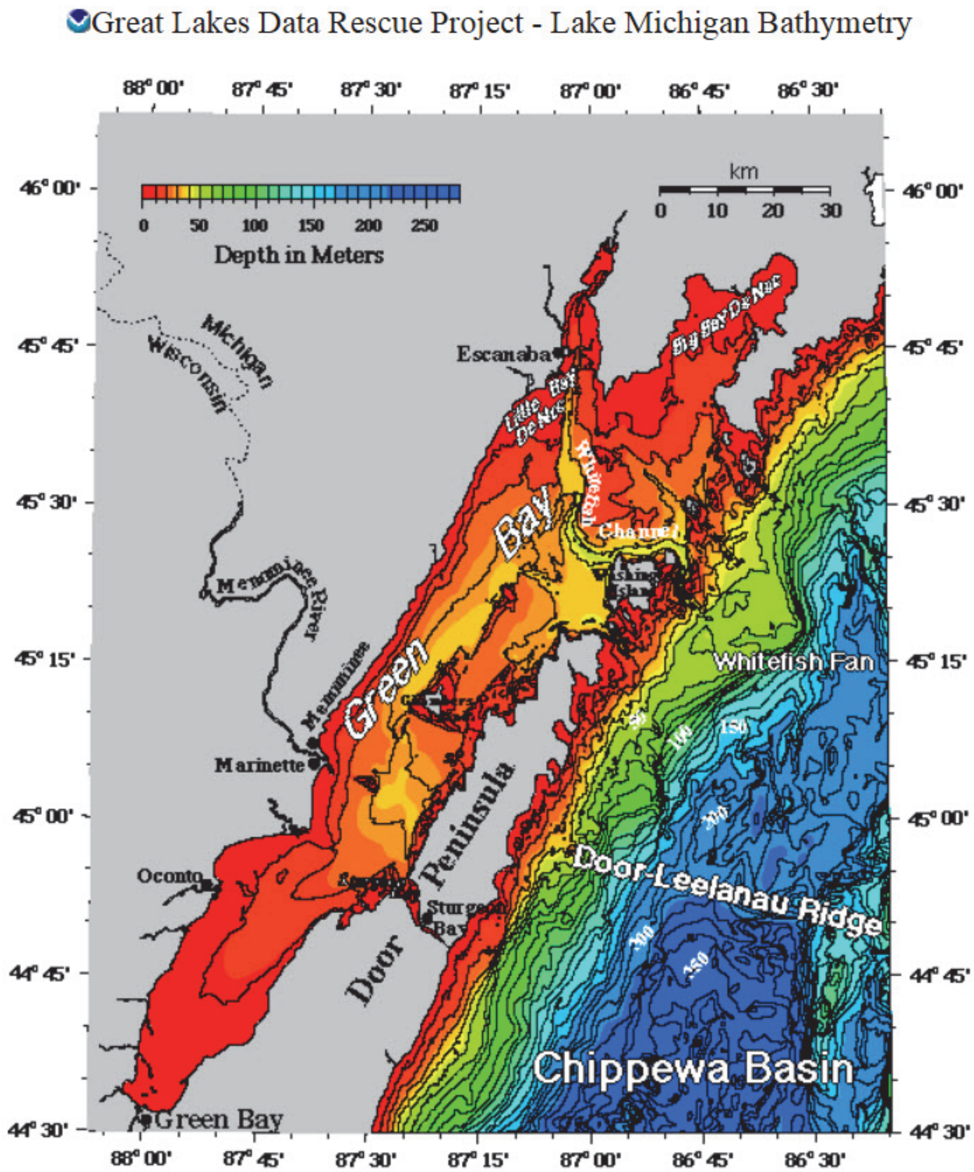


Figure 23. Bathymetric contours for Green Bay, Lake Michigan (from: http://www.ngdc.noaa.gov/mgg/greatlakes/lakemich_cdrom/html/area1.htm).

The orientation of the interpolated HCs is in a longitudinal direction, increasing in value from east to west (see Figure 24). The Master Station from which the HCs are determined is located at Harbor Beach in Lake Huron. The actual location of these HC contours is not well known along the northeastern shore of Lake Michigan due to lack of measurement points between Ludington and Mackinaw City, Lake Huron.

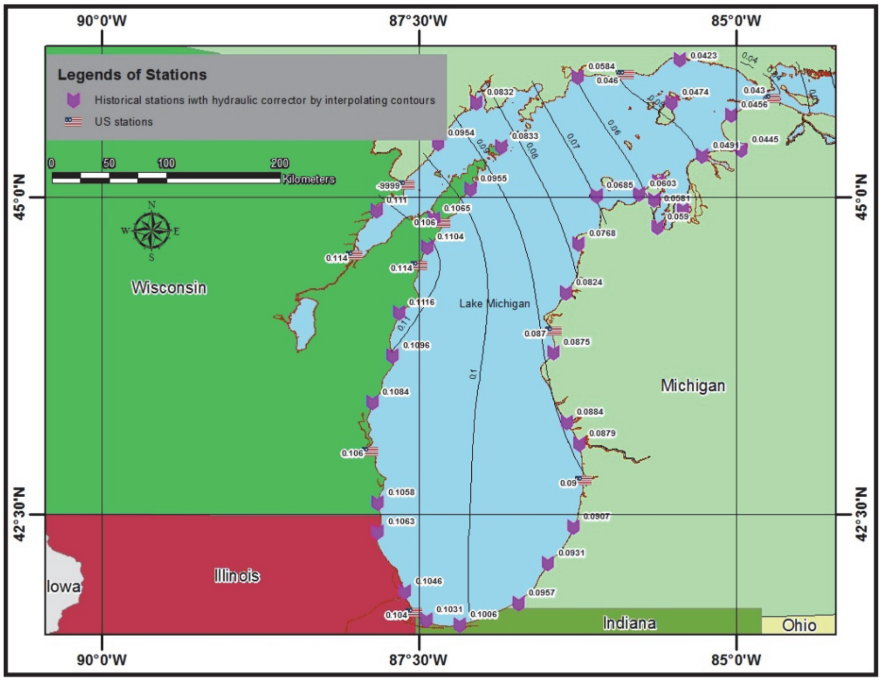


Figure 24. Interpolated Hydraulic Correctors (in meters) for Lake Michigan.

The main feature in the distribution of vertical land velocities in Lake Michigan relative to the Lake Huron outlet is their change from negative velocities (0–14 cm/century) in the southern portion to positive velocities (0-10 cm/century) in the northern portion (see Figure 25). This pattern is caused by the varying differences in velocities of vertical land movement. The GIA tilting axis for the Great Lakes region (see Figure 2) also transects the lake. As mentioned, these velocities are relative to the lake outlet from Lake Huron because the two lakes are considered hydraulically connected through the Straits of Mackinac.

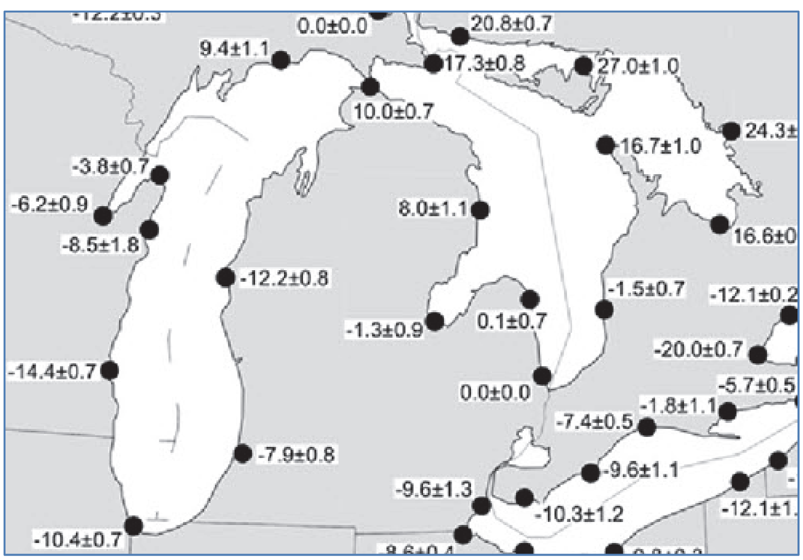


Figure 25. Relative vertical velocities (in cm/century) for Lake Michigan and Lake Huron (Mainville and Craymer [2005]) relative to the lake outlet.

CORS have been established at U.S. water level stations at Calumet (in 2002), Ludington (in 2004), and Mackinaw City (in 2009) and do not yet have a sufficiently long data series to determine accurate vertical velocities. Near-term planning includes potential installation of new CORS at Holland and Menominee.

Differences in the ellipsoidally based elevation surface of NAD 83 relative to LWD shown in Figure 26 vary by approximately 4.0 m from the southern to northern ends of Lake Michigan. Additional information about the differences will be added when GPS survey information becomes available at Holland. The value for Calumet Harbor is an apparent anomaly; however, it may be a true estimate as that is the southernmost station on the lake. The amplitudes of the unknown variation in the elevation differences are significant for hydrographic surveying and must be known prior to successful surveying on the ellipsoid on Lake Michigan. The values presented are based on static GPS surveys to one bench mark at each station.

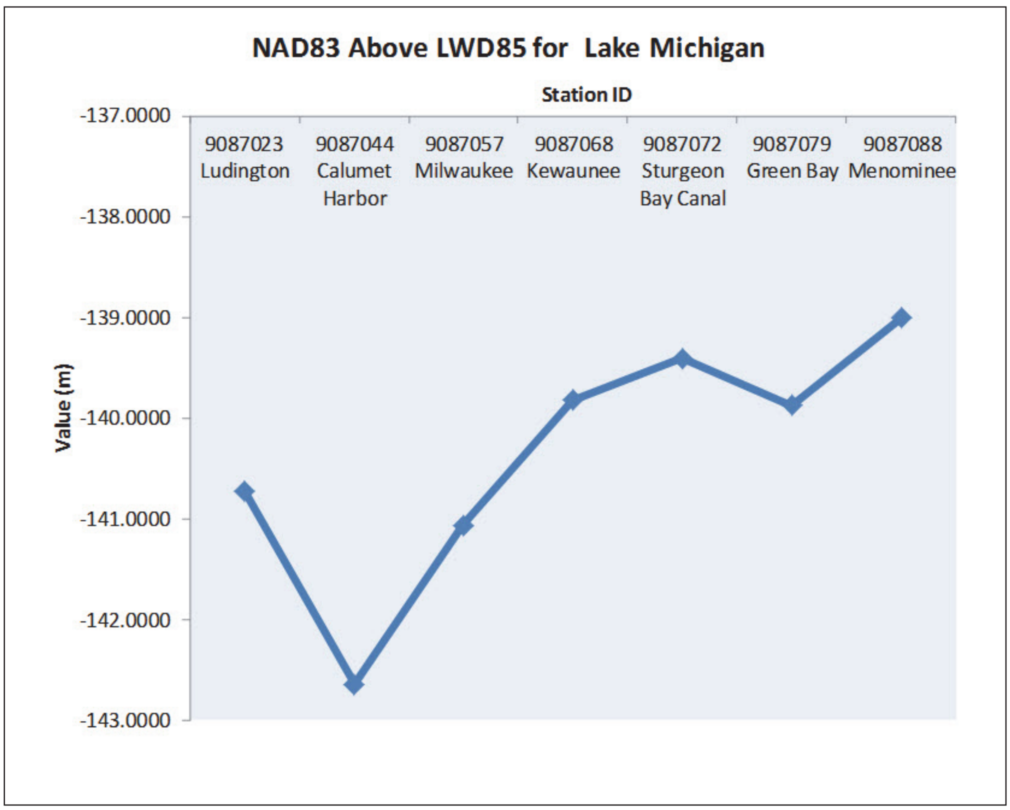


Figure 26. Relationship of LWD to NAD83 for Lake Michigan.

4.3 Lake Huron

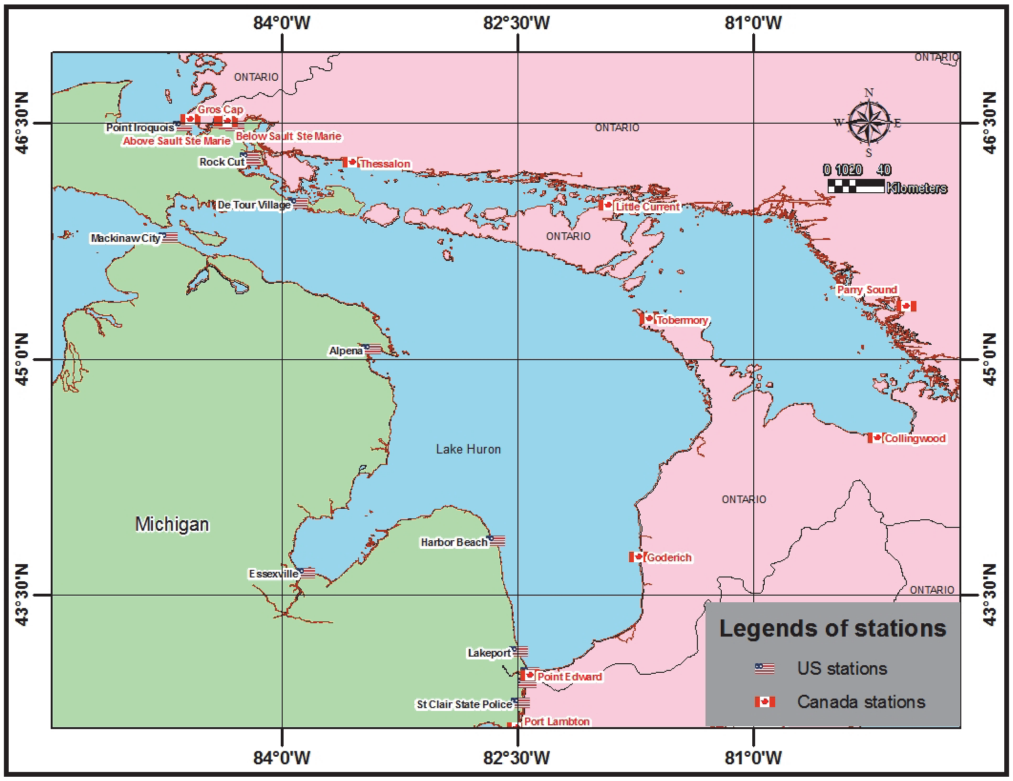


Figure 27. U.S. and Canadian water level station locations for Lake Huron and vicinity.

Figure 27 (above) shows the locations of the U.S. and Canadian water level station networks for Lake Huron. From the plots of daily mean water levels for June 2013 from Lake Huron/Michigan (Figure 28), it can be seen that Harbor Beach water levels track the lake-wide mean closely (Harbor Beach is located geographically close to the lake outlet and has very similar vertical land movement velocities to the outlet). The daily means for northern Lake Huron track below the lake-wide mean by approximately 5 cm during this period. The daily means for the stations in Lake Michigan track above the lake-wide mean by approximately 5 cm. These differences are due to the impact of differential vertical land movement in the lake basins.

In general, differences and standard deviations are higher and regression coefficients lower for the Canadian station pairs, reflective of the two sub-basins in northern Lake Huron. Projected mean differences using the differences in vertical velocities between station pairs are listed in italics next to each calculated difference over the seven-year period.

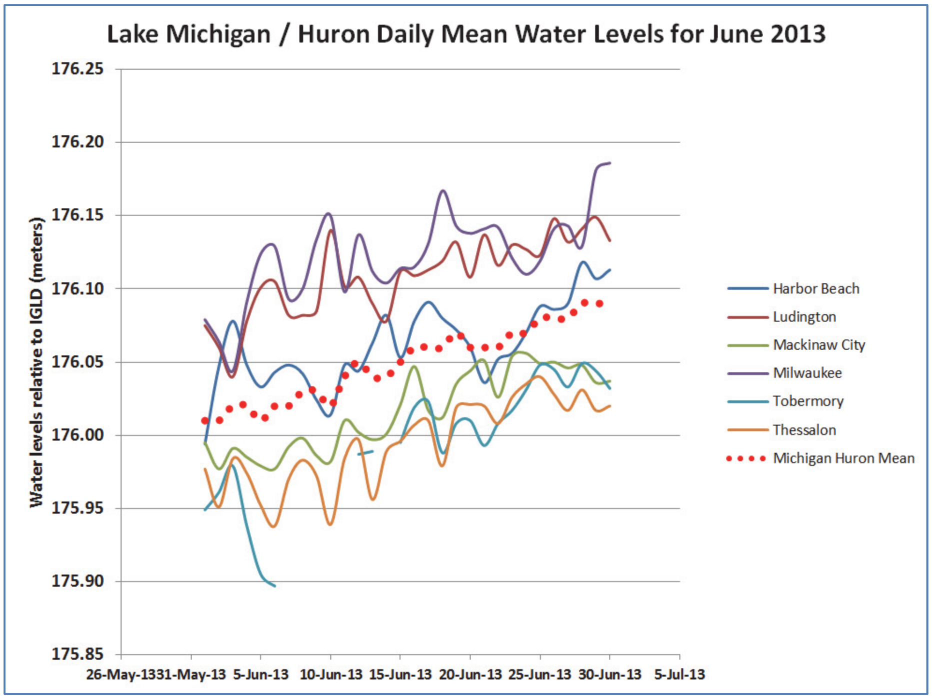


Figure 28. Lake Michigan/Lake Huron Daily Mean Water Levels June 2013.

Table 3. Comparison statistics for Lake Huron station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from U.S. and Canadian databases relative to IGLD 1985 (HCs applied). Projected mean differences are in italics.

Lake Huron					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Lakeport-Mackinaw	0.041 *(0.023)*	0.100	0.899	-0.707	0.702
Lakeport-Harbor Beach	0.006 (*0.000*)	0.041	0.539	-0.477	0.949
Harbor Beach-Essexville	-0.021 (*-0.003)*	0.095	0.881	-1.182	0.780
Essexville-Alpena	0.080 *(n/a)*	0.120	1.455	-0.955	0.677
Alpena-Mackinaw City	-0.022 *(n/a*)	0.050	0.320	-0.573	0.922
Mackinaw City-De Tour Village	0.009 (*0.017*)	0.032	0.298	-0.158	0.965
De Tour Village-Thessalon	0.01 (*0.01)*	0.02	0.18	-0.20	0.989
Thessalon- Little Current	0.00 (*0.01)*	0.05	0.38	-0.55	0.922
Little Current-Parry Sound	0.00 (*-0.01)*	0.06	0.47	-0.64	0.898
Parry Sound-Collingwood	-0.04 (*-0.02)*	0.04	0.37	-0.50	0.959
Collingwood-Tobermory	0.02 *(0.0*)	0.04	0.43	-0.43	0.938
Tobermory-Goderich	-0.06 *(-0.04*)	0.05	0.35	-0.54	0.905
Goderich-Lakeport	0.02 (*0.00*)	0.05	0.62	-0.50	0.918

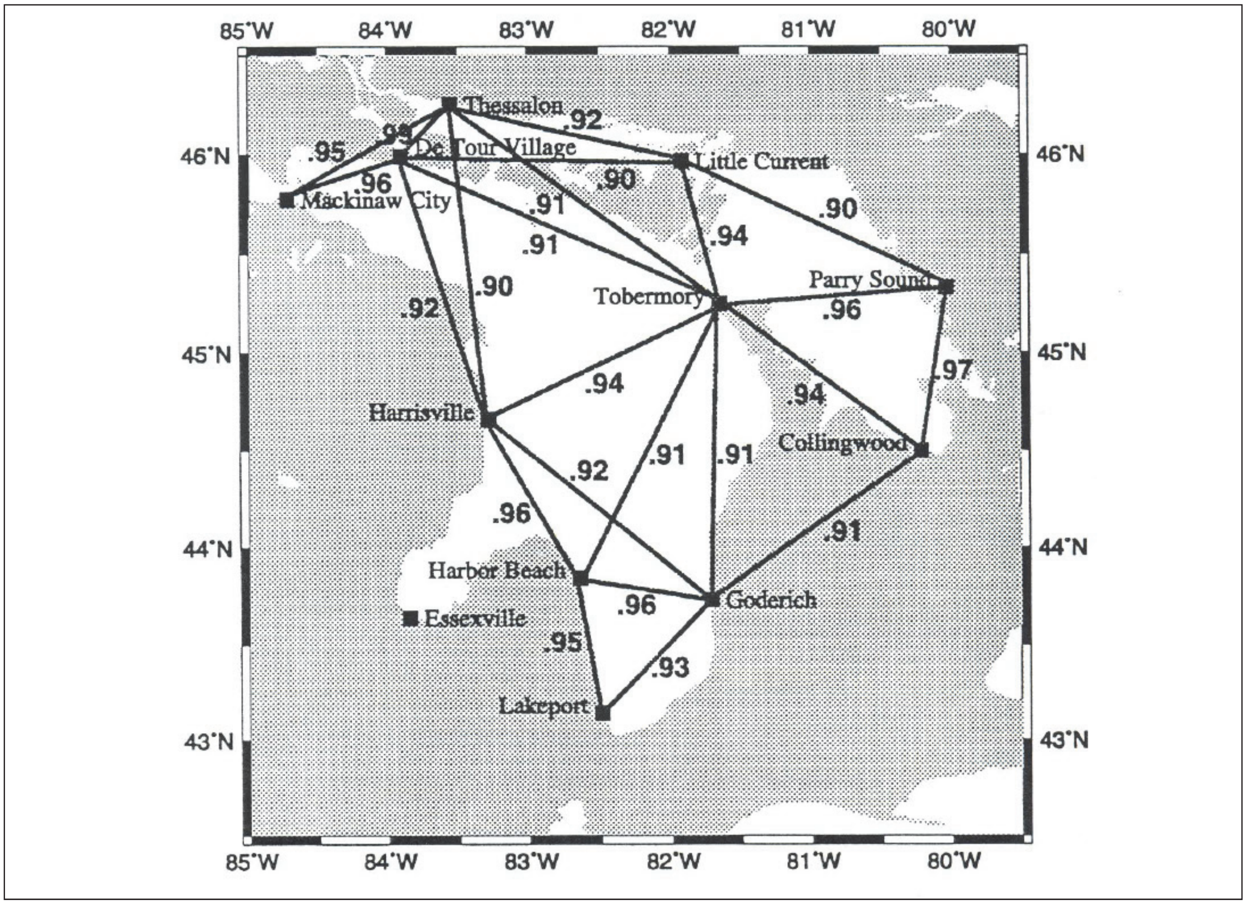


Figure 29. Lake Huron correlation coefficients from Zervas (1997). The new U.S. station at Alpena has replaced Harrisville subsequent to his study.

Both Table 3 statistics and figures 29 and 30 show the anomalous nature of Saginaw Bay water level variations as represented by Essexville. Essexville comparisons show low correlations with both Alpena to the north and Harbor Beach to the east. Zervas (1997) found through an EOF analysis that Essexville data dominates the second modes for Lake Huron, indicating that there is a large signal that is unique to that location. Figure 30 provides insight as to the anomalous nature of the water level variations in Saginaw Bay relative to the rest of Lake Huron. The time series plots over two months illustrate the oscillatory nature of the high water events. The primary modes of oscillation have much longer periods than the outside lake and appear to be due to localized wind set-up and bay configuration. Quinn (1975) found this as well, assigning a weighting factor of 0.035 for a very limited Thiessen polygon for Essexville. The bathymetry of Saginaw Bay (Figure 31) with depths much shallower than the rest of the lake also enhances the effects of wind on the water levels.

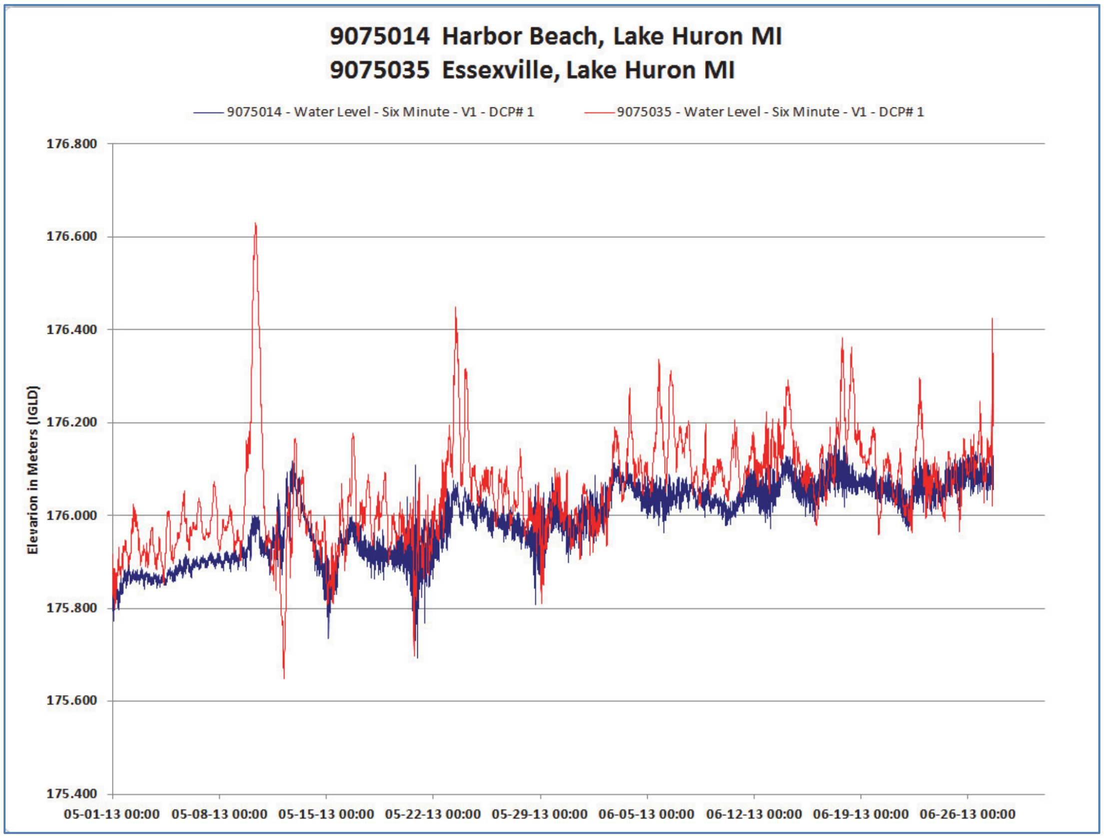


Figure 30. Water level variations for a sample period of May and June 2013 for Essexville and Harbor Beach.

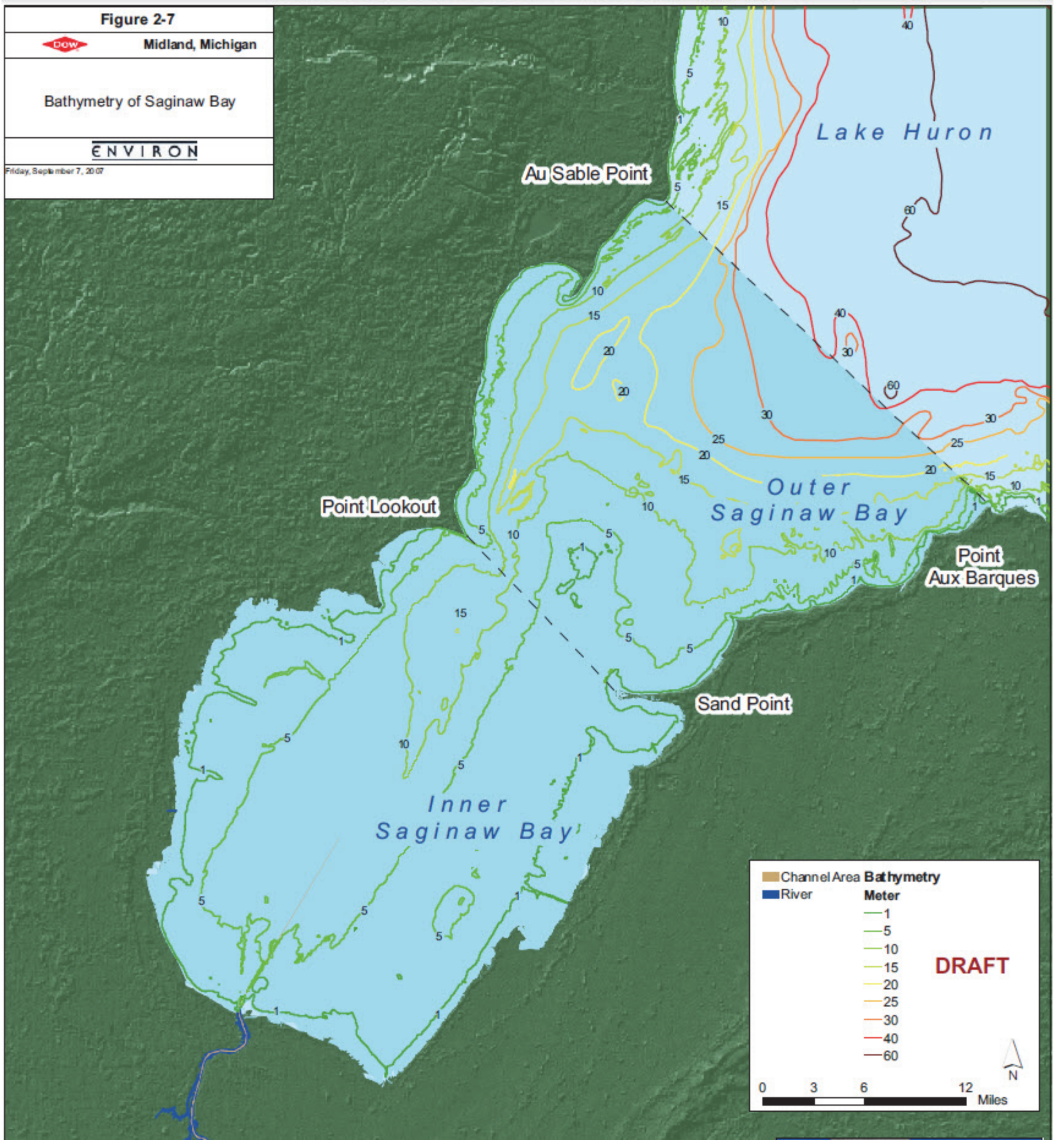


Figure 31. Bathymetric contour plots for Saginaw Bay, Lake Huron (from http://www.michigan.gov/documents/deq/deq-whm-hwp-dow-9-2007-Draft-CCR-SRB-Fig-2-7_210883_7.pdf).

As shown in Figure 32, there are only relatively small variations (< 0.01 m) in the HC on most of the lake, with the largest values up near the Straits of Mackinac. HC values are calculated relative to the Master Station at Harbor Beach.

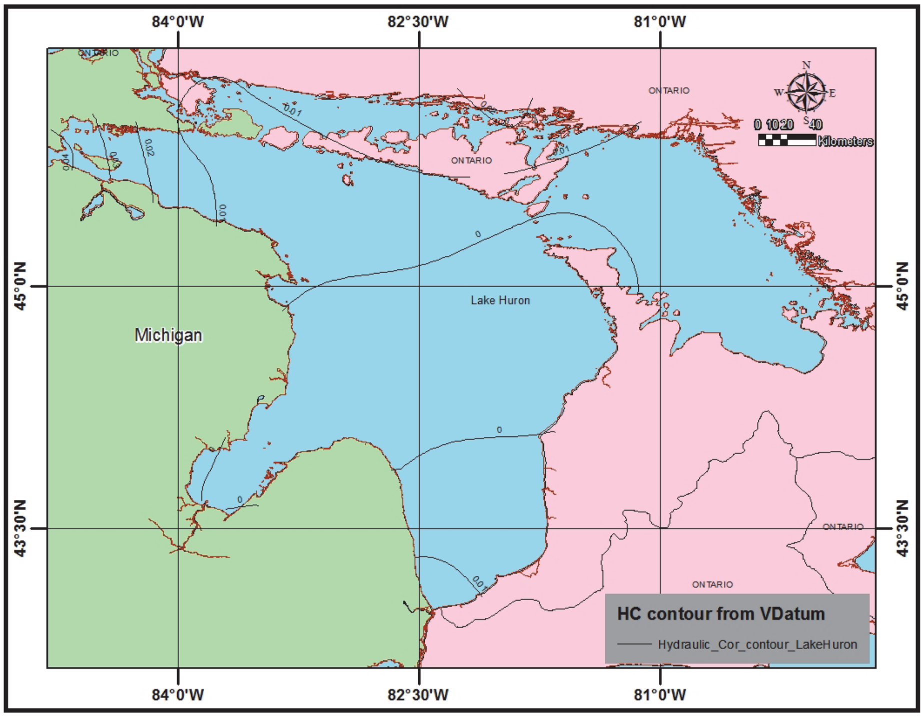


Figure 32. Interpolated Hydraulic Correctors for Lake Huron.

The land in the northern portions of the lake is rising faster relative to the lake outlet on the southernmost end (Figure 33). The rates are especially high in the northern upper bays on the Canadian side, consistent with the contours for the absolute rates shown in Figure 2. CORS have been established at U.S. stations at Alpena (in 2006) and Harbor Beach (in 2002). In Canada, CORS are operating at Parry Sound (since 2002) and Little Current (since 2011).

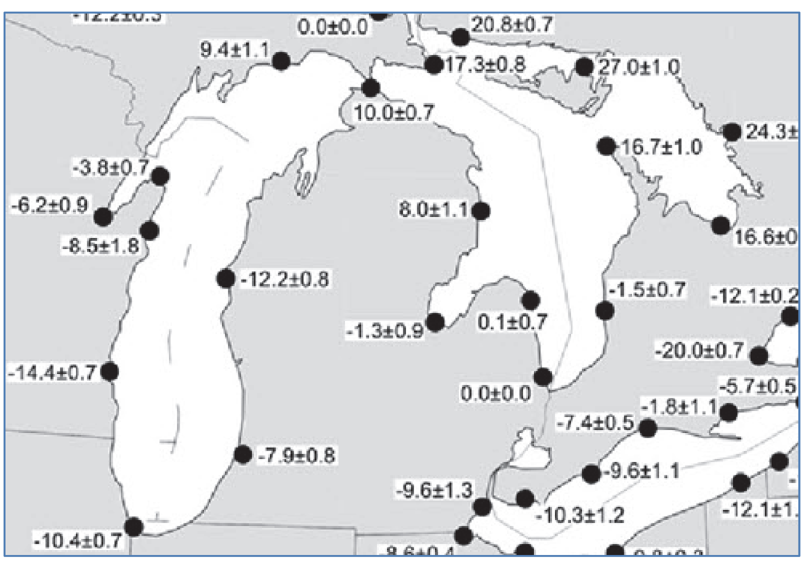


Figure 33. Vertical velocities (in cm/century) for Lake Michigan and Lake Huron (Mainville and Craymer [2005]) relative to the lake outlet.

There is an approximate 2.5 m-change in the elevation difference between NAD 83 and LWD from south to northern portions of Lake Huron (Figure 34). Ellipsoidal elevations at each station are derived from static GPS surveys at individual bench marks at each station. The apparent anomalous value at Essexville is expected due to the anomalous nature of the water level variations; however the seemingly anomalous value at Mackinaw City awaits further confirmation from future GPS surveys. Interpolation of these values across Lake Huron may be sufficient for hydrographic survey uncertainty targets; however, values from all stations would first be required.

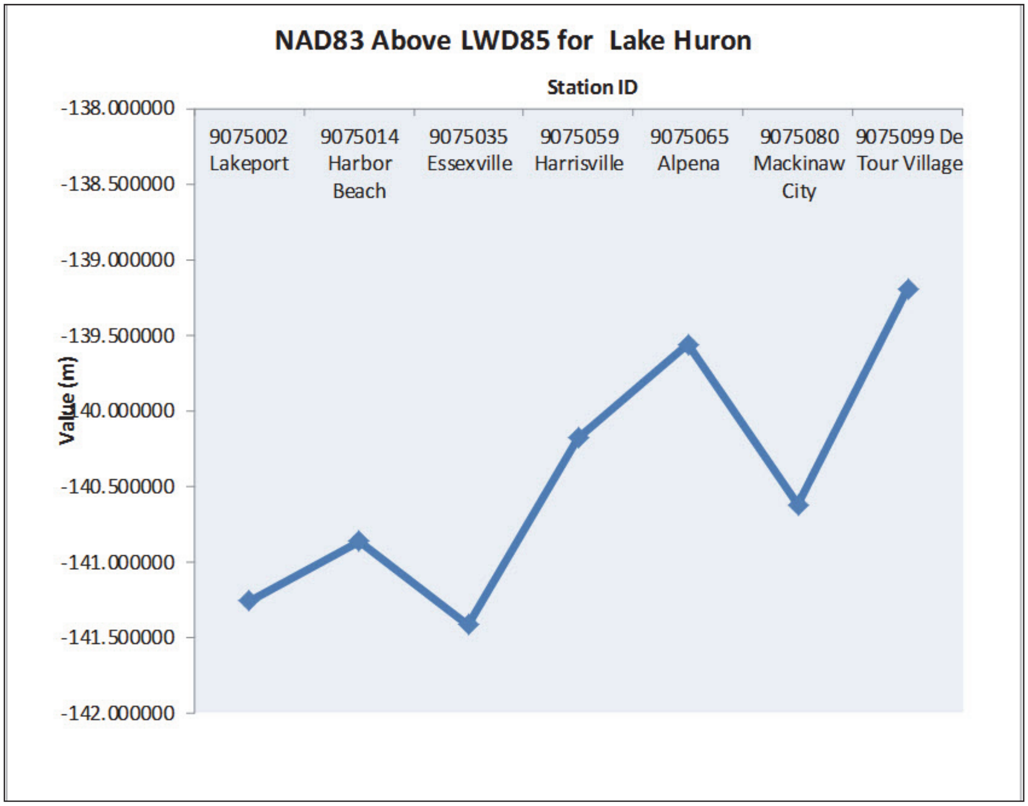


Figure 34. Relationship of LWD to NAD83 for Lake Huron.

4.4 Lake St. Clair

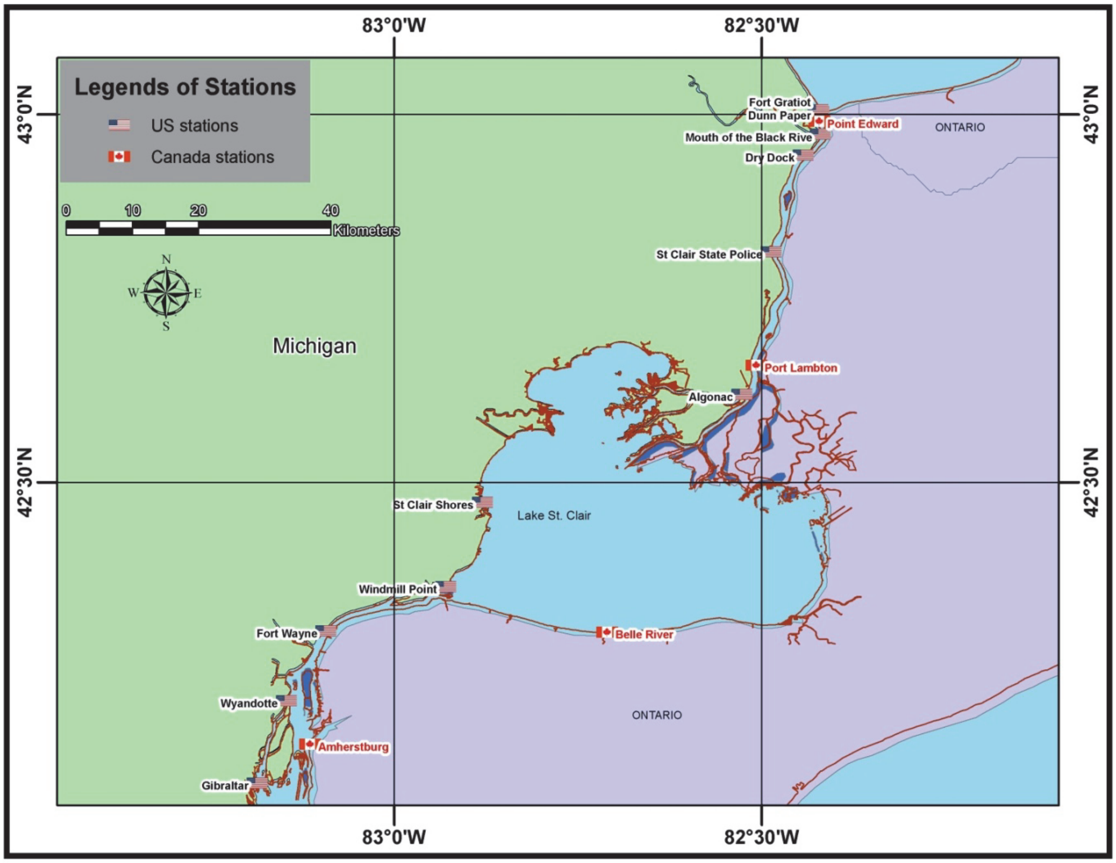


Figure 35. U.S. and Canadian Water level station locations for Lake St. Clair and vicinity.

Figure 35 (above) shows the locations of the U.S. and Canadian water level station networks for Lake St. Clair. Variations in daily mean water levels between the two stations on Lake St. Clair are very small (Figure 36 for June 2013), with the larger differences occuring during the time periods of higher frequency oscillations.

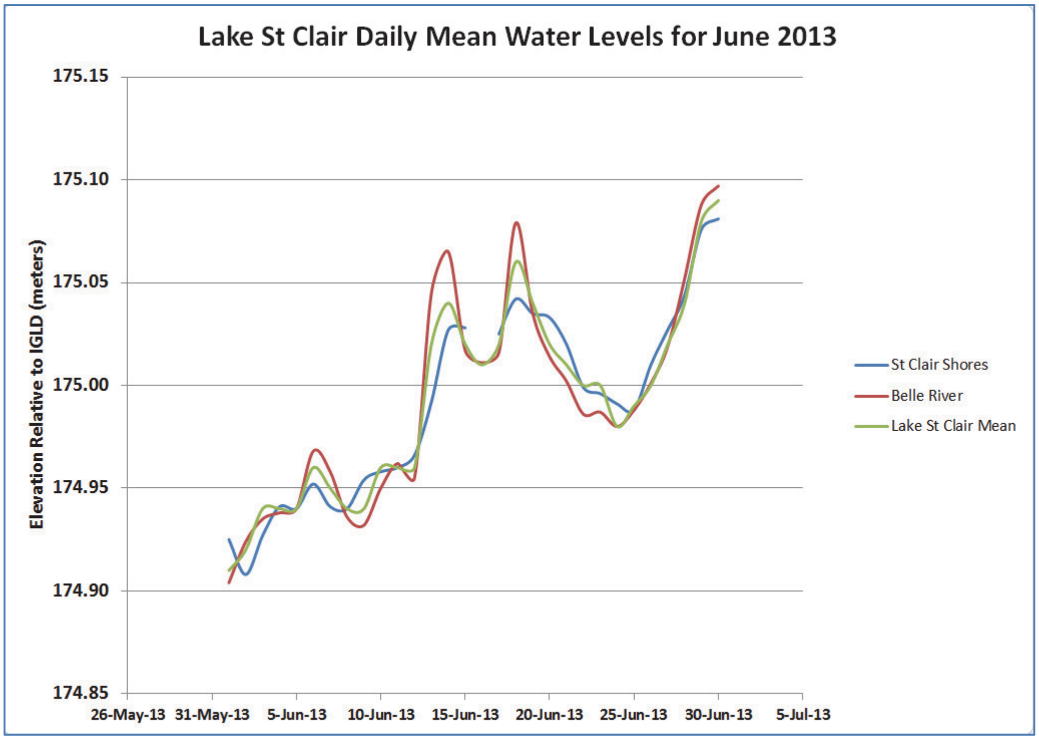


Figure 36. Lake St. Clair daily mean water levels for June 2013.

There are only two stations on Lake St. Clair: the U.S. station at St. Clair Shores and the Canadian station at Belle River. Although the mean difference of simultaneous data between St. Clair Shores and Belle River is 0.000 m, there is a large standard deviation in the hourly differences and a 0.96 regression coefficient. There are large differences in mean water levels between St. Clair Shores and Algonac and St. Clair Shores and Windmill Point; due to the fact that Algonac is located upstream of the lake on the lower St. Clair River and Windmill Point is downstream of the lake in the upper Detroit River. Comparisons of mean differences with those projected by vertical land movement velocities are not available for these stations.

Table 4. Comparison statistics for Lake St. Clair station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from U.S. and Canadian databases relative to IGLD 1985 (HCs required for Belle River only).

Lake St. Clair					
Station Pairs	**Mean Difference (m)**	**Standard Deviation(m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Algonac-St. Clair Shores	0.177	0.088	0.999	-0.138	0.788
St. Clair Shores-Windmill Point	0.064	0.023	0.310	-0.124	0.986
St. Clair Shores-Belle River	0.000	0.039	0.234	-0.452	0.957

4.5 Lake Erie

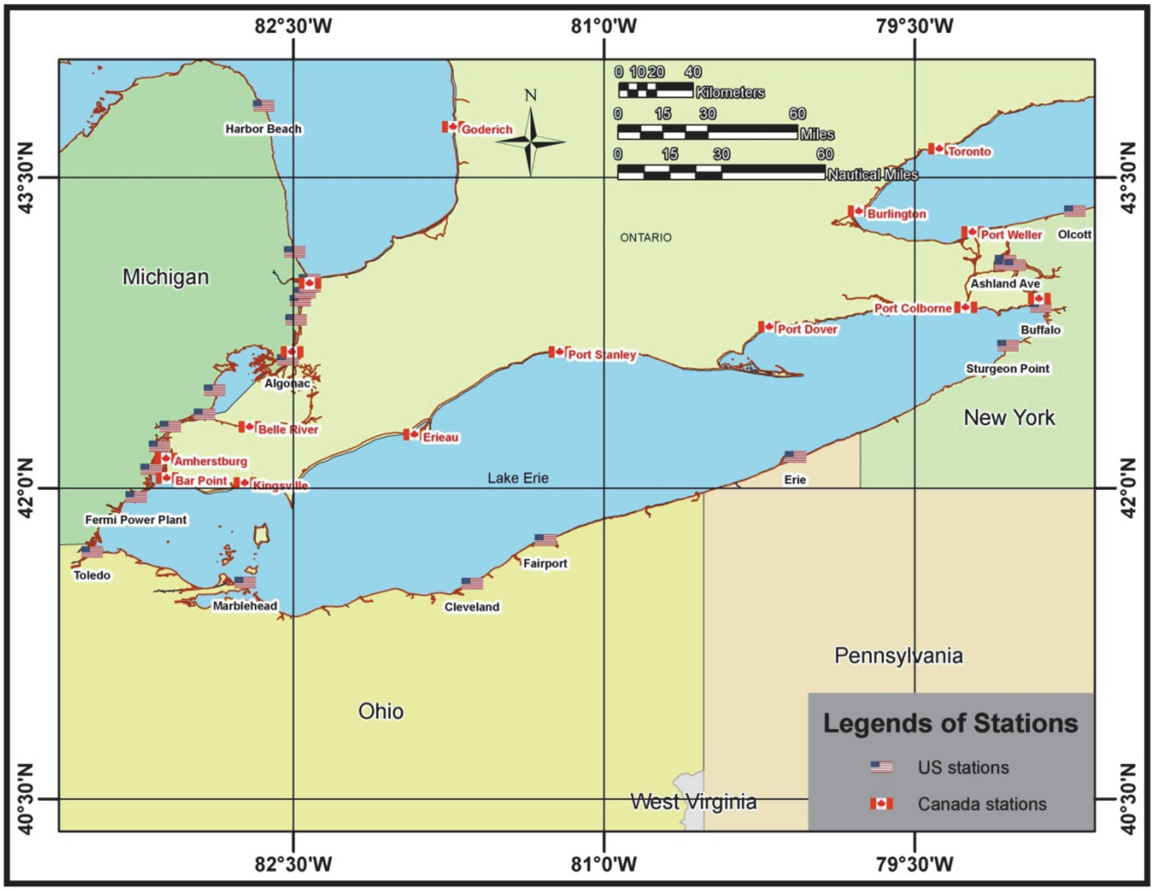


Figure 37. U.S. and Canadian water level station locations for Lake Erie and vicinity.

Figure 37 (above) shows the locations of the U.S. and Canadian water level station networks for Lake Erie. The effects of seiche action on Lake Erie are illustrated in Figure 38. The daily mean water levels at opposite ends of the lake (Toledo and Port Colborne) are negatively correlated and result in a tilting of the lake surface back and forth throughout the month in response to wind forcing. This tilting also has longer period seasonal variations. The daily means for stations in the middle of the lake are near the lake average because they are located near the physical nodal line of the east-west basin oscillation. There is also a lesser north-south oscillation during some events. The mean differences are also due to the effect of differences in relative vertical land movement between station pairs, as was found for the other lakes.

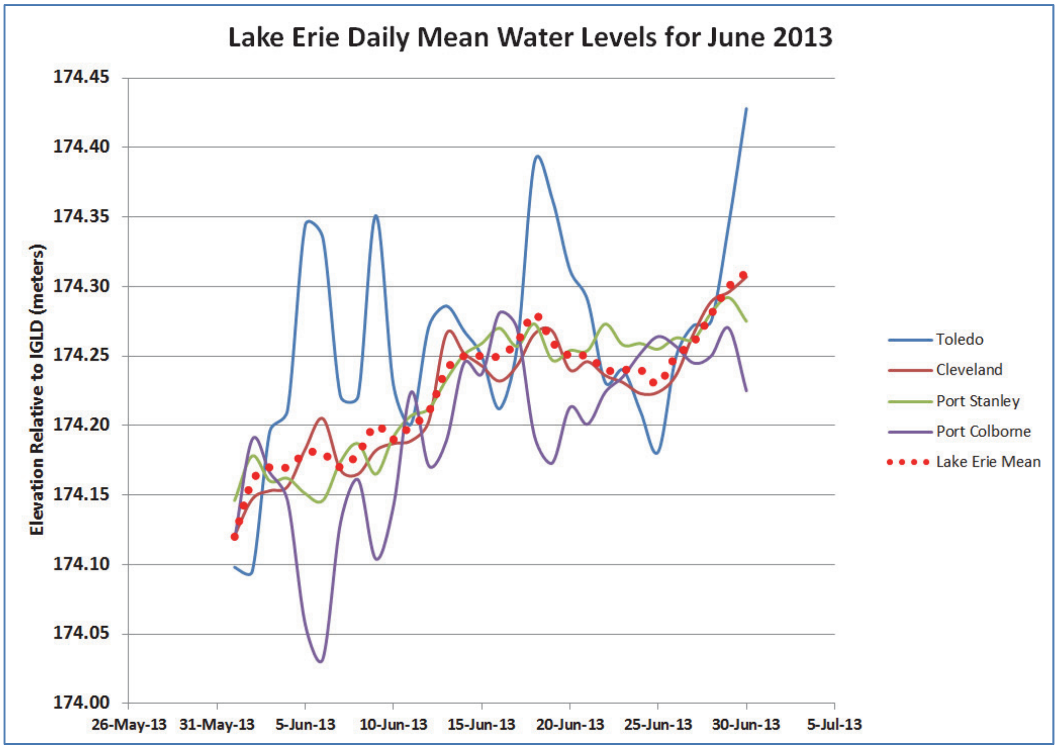


Figure 38. Lake Erie daily mean water Levels June 2013.

Replacement of Fairport gauging station as the Master Station for Lake Erie may be required due to the vertical land subsidence at Fairport resulting from mining operations. Cleveland has been suggested as the Master Station for the IGLD update as it was the Master Station reference for IGLD 1955. However, the Cordination Committee is actively discussing options. The correlations for Lake Erie station pairs shown in Table 5 and Figure 39 are relatively weaker than for other lakes due mainly to the high frequency of seiche events in the lake. The correlation coefficients are especially low and the mean differences are relatively high for the Cleveland-Erie and Fairport-Erie pairs. Differences in mean lake levels are fairly low and correlation coefficients are fairly high between the U.S. stations at Sturgeon Point and Buffalo and the closest Canadian station at Port Colborne. The analyses show an interesting feature of the western, central, and eastern station groups, which have relative high correlations amongst their geographic groupings but relatively low correlations between the three groups. This is a manifestation of the signficant east-west seiche action found in the lake. Projected mean differences using the differences in vertical velocities between station pairs are listed in italics next to each calculated difference over the seven-year period. Extra pairing analyses were performed for Port Colborne and Sturgeon Point to better understand the differences and similarities at the far eastern end of the lake.

Table 5. Comparison statistics for Lake Erie station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from U.S. and Canadian databases relative to IGLD 1985 (HCs applied). Projected mean differences are in italics.

Lake Erie					
Station Pairs	**Mean Difference(m)**	**Standard Deviation(m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Buffalo-Fermi	0.023 (*0.022*)	0.307	4.422	-1.756	0.040
Buffalo-Sturgeon Point	0.008 (*0.005*)	0.033	0.597	-0.375	0.982
Sturgeon Point-Erie	-0.010 (*-0.033*)	0.070	1.334	-0.475	0.902
Erie-Fairport	-0.031 (*n/a*)	0.101	1.724	-0.904	0.743
Fairport-Cleveland	0.044 (*n/a*)	0.041	0.687	-0.274	0.957
Cleveland-Marblehead	0.009 (*0.000*)	0.084	0.942	-0.451	0.875
Marblehead-Toledo	-0.013 (*0.000*)	0.097	1.538	-0.738	0.896
Toledo-Fermi	0.014 (*-0.002*)	0.062	0.536	-0.808	0.957
Fermi-Bar Point	-0.013 (*n/a*)	0.033	1.026	-0.858	0.984
Bar Point-Kingsville	0.01 (*n/a*)	0.05	0.41	-0.90	0.962
Kingsville-Erieau	0.00 (*0.00*)	0.08	0.47	-1.19	0.886
Erieau-Port Stanley	-0.02 (*-0.01*)	0.06	0.32	-0.69	0.916
Port Stanley-Port Dover	0.01 (*+0.01*)	0.09	0.70	-1.77	0.789
Port Dover-Port Colborne	-0.01 (*-0.01*)	0.06	0.32	-0.97	0.932
Port Colborne-Buffalo	-0.001 (*-0.013*)	0.04	0.47	-0.67	0.968
Sturgeon Point-Port Colborne	-0.007 (*-0.017*)	0.023	0.340	-0.271	0.989

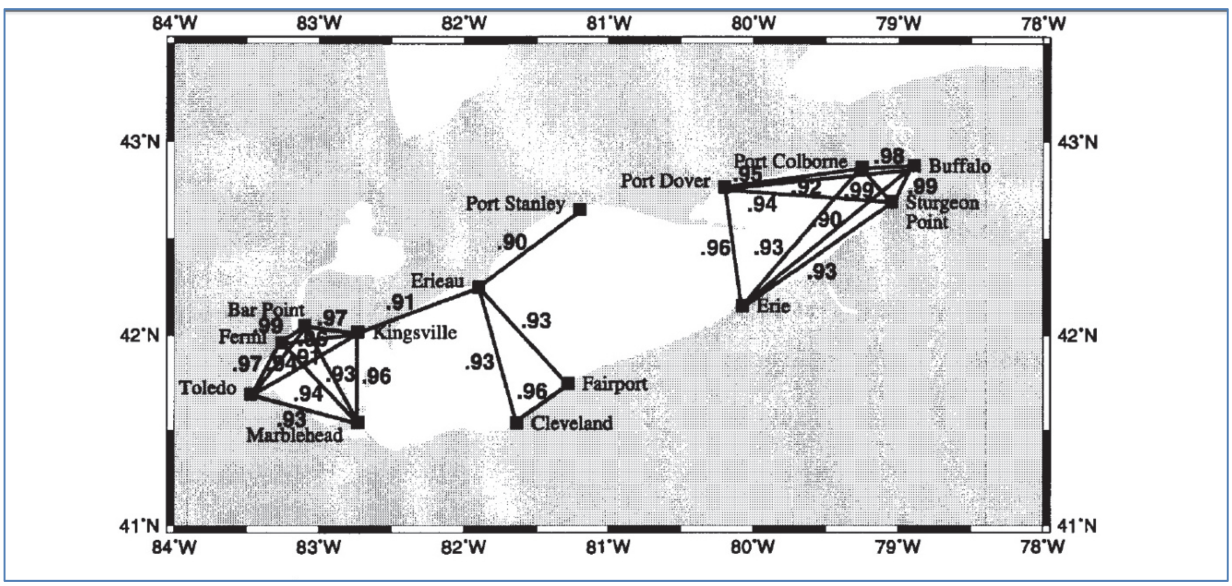


Figure 39. Lake Erie correlation coefficients from Zervas (1997).

The interpolated field for HCs at Lake Erie (Figure 40) show a longitudinally varying pattern away from the Master Station at Fairport in the center of the lake, however, the western end of the lake shows a more complicated latitudinal pattern that underlies uncertainty in the ability to interpolate.

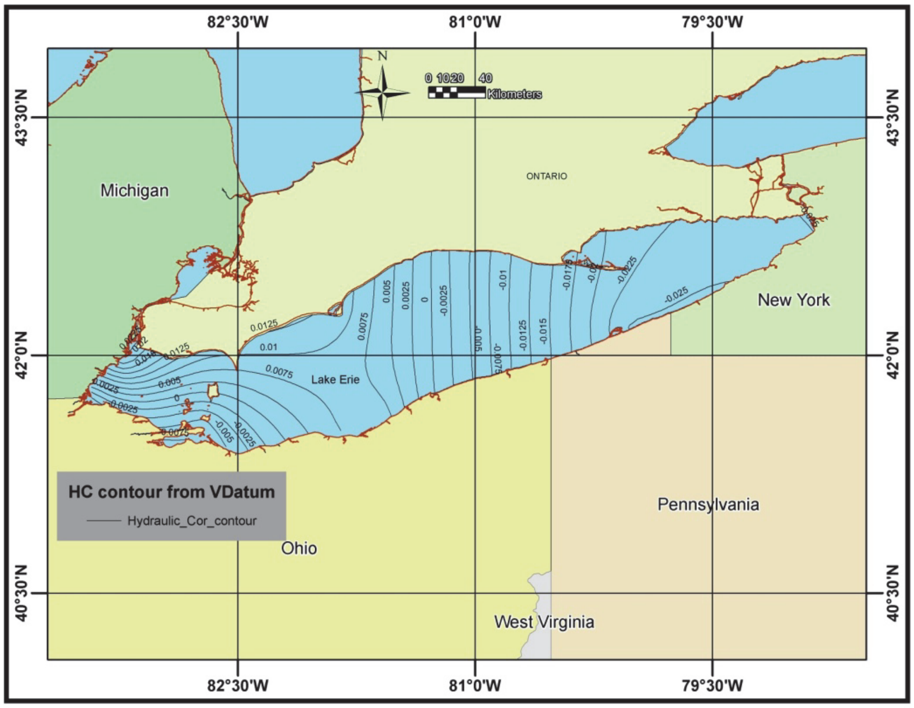


Figure 40. Interpolated Hydraulic Correctors for Lake Erie.

Lake Erie has the smallest changes in vertical land velocities relative to the lake outlet (Figure 41) of all of the Great Lakes because the vertical velocity gradient here (i.e., the differential movement rates) are less than in the more northerly located lakes as they were covered by a greater weight and longer period of glaciation than Lake Erie.

Here, the land at the western end of the lake is rising slower than the outlet at the eastern end of the lake, and therefore much of the lake appears to be moving downward, relative to the outlet. CORS have been established at U.S. stations at Buffalo (in 2002), Cleveland (in 2005), and Marblehead (in 2004). In Canada, a CORS is co-located at Kingsville (since 2011). A CORS is planned for installation at Fairport by the U.S.

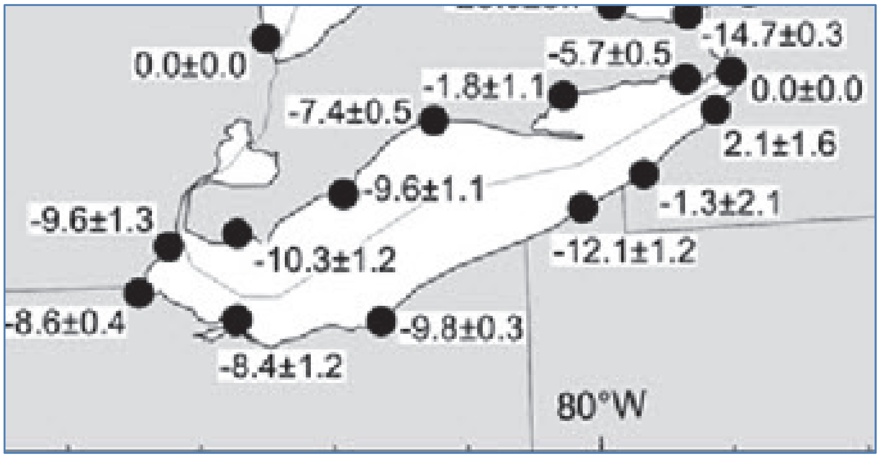


Figure 41. Vertical velocities (in cm/century) for Lake Erie (Mainville and Craymer [2005]) relative to the lake outlet.

The variation in the elevation difference between NAD 83 and LWD in Lake Erie varies only approximately 1.3 m from the western to eastern ends as shown in Figure 42. NAD 83 elevations are obtained by a GPS survey to one of the bench marks at each station. The anomalous drop in the value at Fairport is expected due to local subsidence; however, the source for the apparent anomalous value at Cleveland is unknown. Interpolation of the known values should be adequate for survey-on-the-ellipsoid purpose in Lake Erie; however, values for the Canadian stations should be first obtained to fully understand north-south variability.

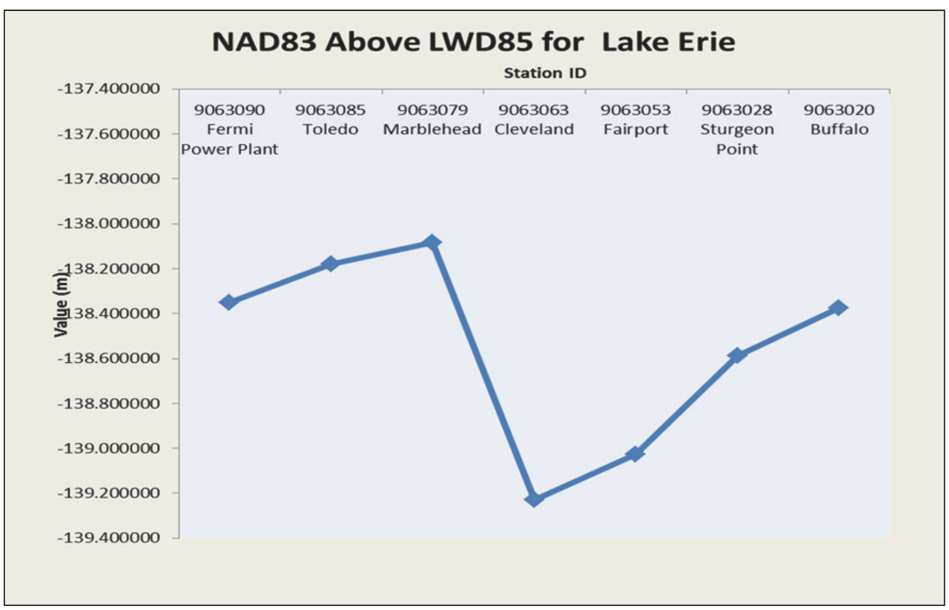


Figure 42. Relationship of LWD to NAD83 for Lake Erie.

4.6 Lake Ontario

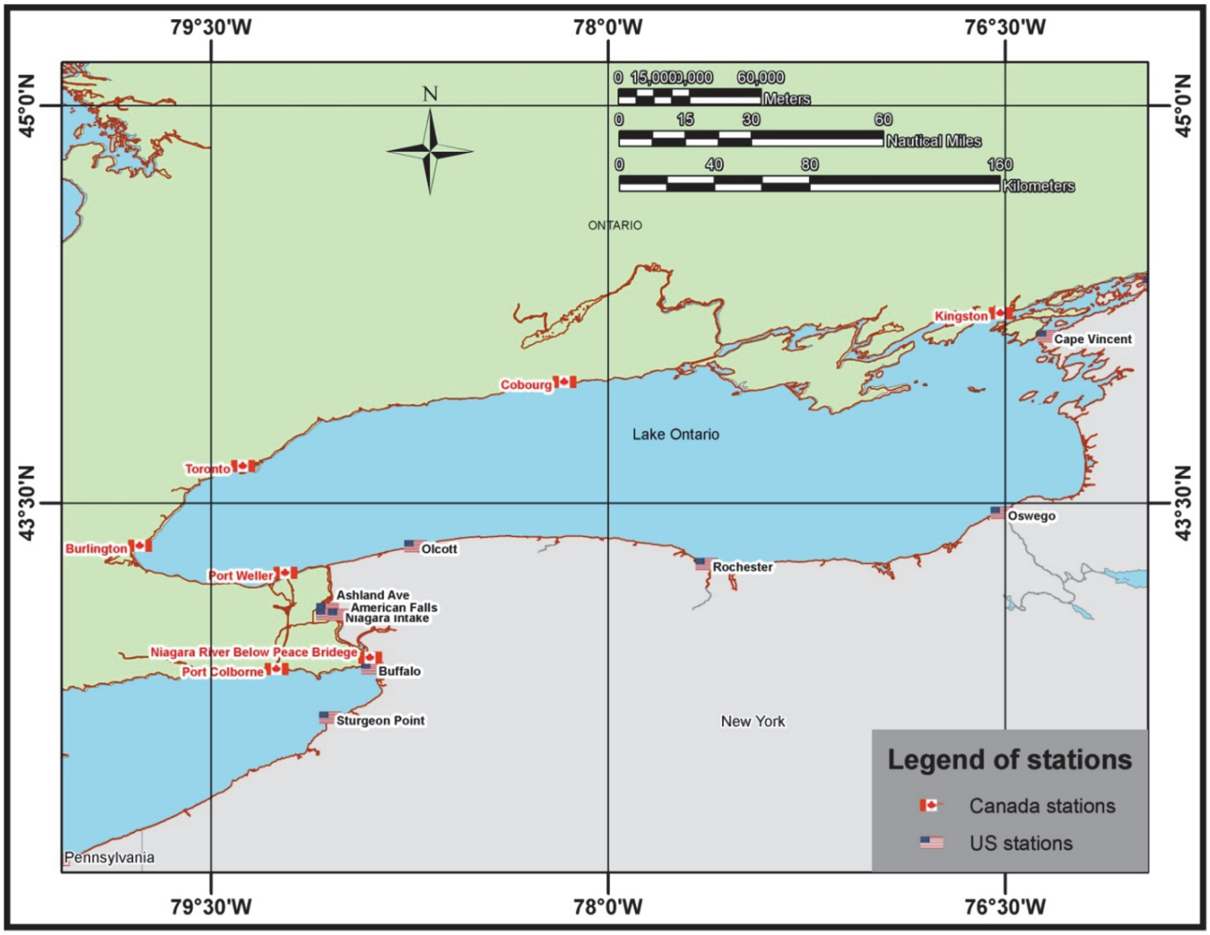


Figure 43. U.S. and Canadian water level Station locations for Lake Ontario.

Figure 43 (above) shows the locations of the U.S. and Canadian water level station networks for Lake Ontario. Lake Ontario daily mean water levels (Figure 44) show individual station differences of a few centimeters from the lake-wide mean over a given month (June 2013). Some of this difference is due to the difference in the velocities of vertical land movment across the lake. The figure illustrates that Lake Ontario, which is quieter than Lake Erie in terms of natural variability due to seiche forcing and does not exhibit large variability in seasonal extremes from the long-term mean, can still have cross-lake centimeter-level slopes in water levels on any given day.

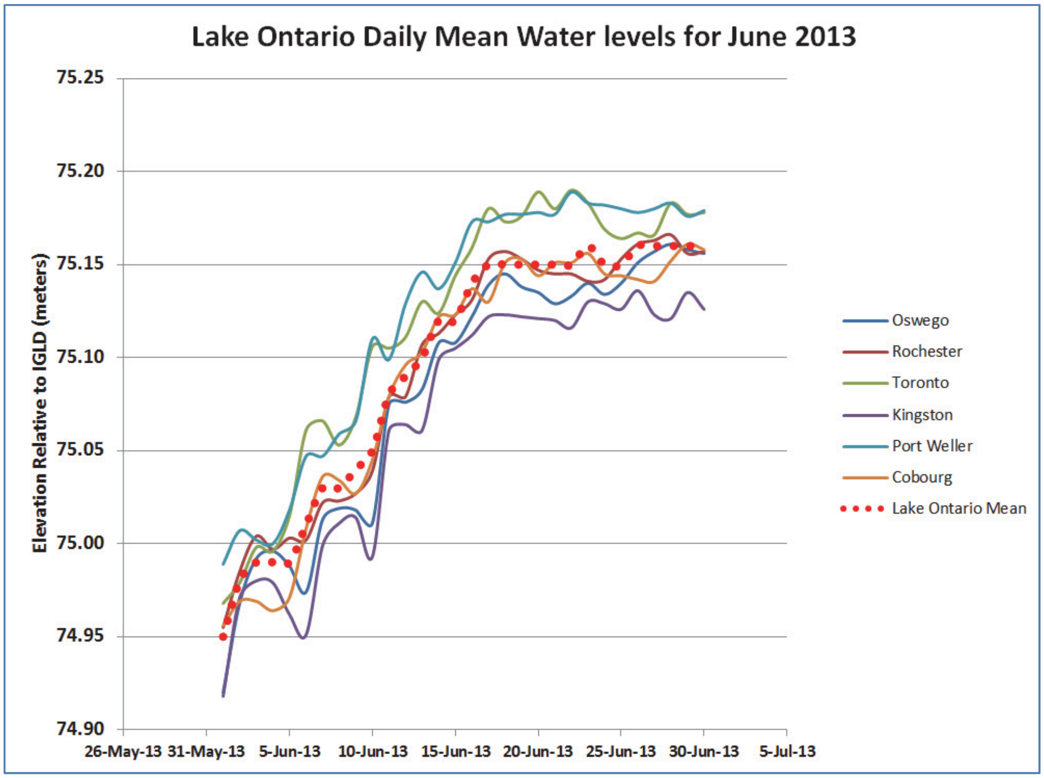


Figure 44. Lake Ontario Daily Mean Water Levels June 2013.

Both Table 6 and Figure 45 show most station pairs (except for comparison of stations at the extreme ends of the lake) have relatively small statistical differences and high correlation coefficients. Figure 45 has lines present between each station pair with very high correlation coefficients. This suggests that a high degree of overlap is present in the existing network for monitoring of lake levels and determining lake level means. The station pair of Port Weller and Olcott in particular shows very small mean differences and very high correlation coefficients. The lowest regression coefficient for Lake Ontario is found for the Canadian Cobourg-Kingston station pair, and the largest mean difference is found for the Toronto-Cobourg station pair. Similar for the other lakes (and shown in italics in Table 6), the mean differences are highly correlated with the projected elevation differences due to the differences in velocities of vertical land movement at the stations. Projected mean differences using the differences in vertical velocities between station pairs are listed in italics next to each calculated difference over the seven-year period.

Table 6. Comparison statistics for Lake Ontario station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from U.S. and Canadian databases relative to IGLD 1985 (HCs applied). Projected mean differences are in italics.

Lake Ontario					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Cape Vincent-Burlington	-0.048 (*-0.046*)	0.069	0.917	-0.768	0.922
Cape Vincent-Oswego	-0.019 (*-0.010*)	0.033	0.365	-0.853	0.979
Oswego-Rochester	0.001 (*-0.013*)	0.032	0.790	-0.310	0.981
Rochester- Olcott	-0.008 (*-0.002*)	0.028	0.377	-0.229	0.987
Olcott–Port Weller	-0.007 (*-0.008*)	0.017	0.137	-0.185	0.995
Port Weller-Burlington	-0.02 (*-0.01*)	0.03	0.22	-0.51	0.988
Burlington-Toronto	0.01 (*0.02*)	0.03	0.48	-0.27	0.982
Toronto-Cobourg	0.03 (*0.01*)	0.03	0.34	-0.35	0.980
Cobourg-Kingston	0.01 (*0.02*)	0.05	0.34	-0.59	0.964
Kingston-Cape Vincent	0.003 (*0.006*)	0.014	0.209	-0.232	0.996

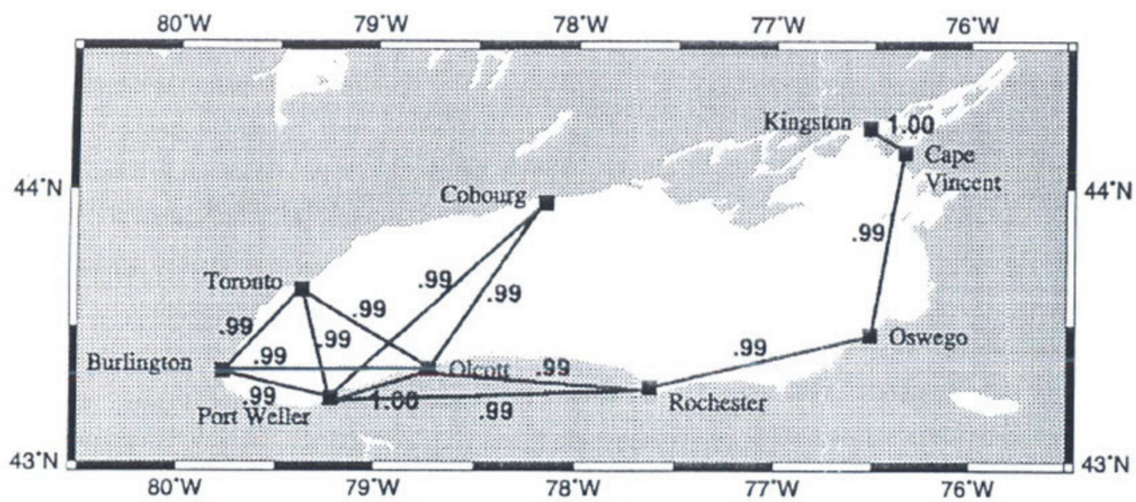


Figure 45. Lake Ontario correlation coefficients from Zervas (1997).

Differences in HCs across Lake Ontario (Figure 46) show a strong longitudinal pattern away from the Master Station at Oswego with very little change in the eastern two-thirds of the lake. The western end is more complicated and shows several centimeter differences illustrated by the closeness of the 0.025 m interval contour lines.

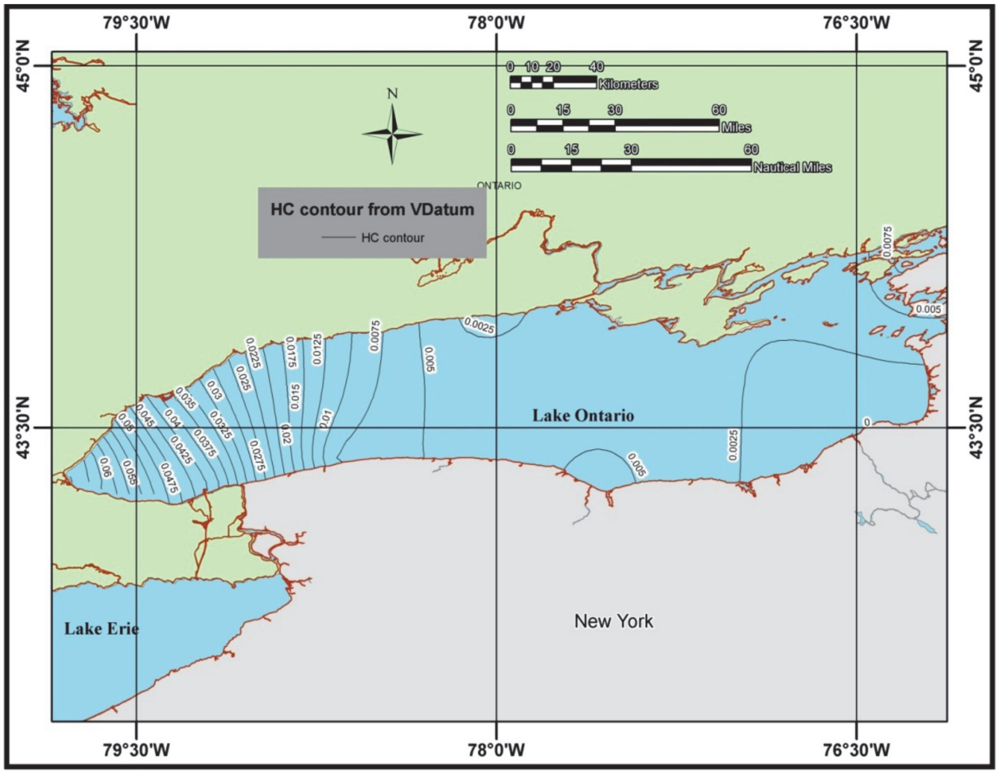


Figure 46. Interpolated Hydraulic Correctors for Lake Ontario.

Figure 47 shows a steady increase in the rate of relative vertical land velocities from the lake outlet westward up to -20 cm/century (0.02 mm/yr). This is consistent with Figure 2, which shows large differences in absolute rates of vertical land motion in an east-west transect across the lake in response to GIA. All of Lake Ontario appears to be moving up relative to the center of the earth, the western end is just moving up at a slower rate than the eastern end, and hence appears to be falling relative to the outlet. CORS have been established at the U.S. station at Oswego (in 2005) and in Canada at Port Weller (in 2002), Cobourg (in 2011), and Kingston (in 2002). These installations may soon provide accurate estimates of vertical land velocities after a few more years of data are accrued.

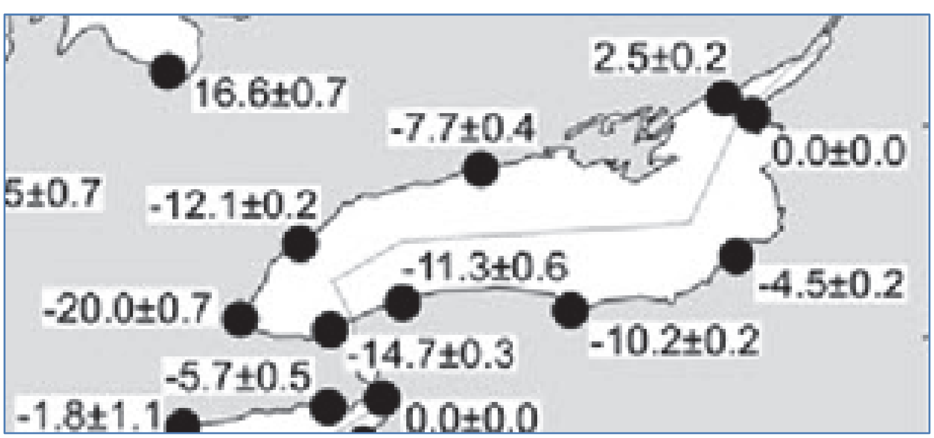


Figure 47. Vertical velocities (in cm/century) for Lake Ontario (Mainville and Craymer [2005]) relative to the lake outlet.

The variation in the elevation difference between NAD83 and LWD in Lake Ontario varies approximately 2.0 m from the western to eastern ends as shown in Figure 48. Individual station values are obtained using static GPS surveys on a bench mark for each station. Interpolation of the known values should be adequate for survey-on-the-ellipsoid purposes in Lake Ontario; however, values for the Canadian stations should be first obtained to fully understand north-south variability.

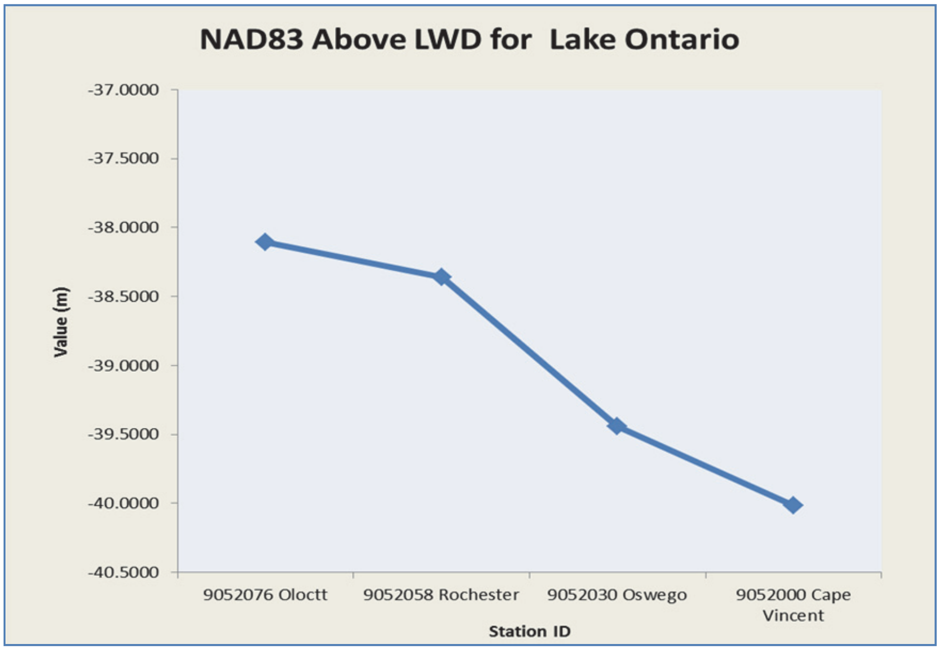


Figure 48. Relationship of LWD to NAD83 for Lake Ontario

4.7 Connecting Channels

Three connecting channels (St. Marys River, St. Clair River, and the Detroit River) as well as the navigation channel though Lake St. Clair require continuous maintenance dredging to ensure safe and navigable channels. The existing network of NWLON stations in these waterways, supplemented by Canadian and USACE water level stations, provide the vertical control necessary for precise and effective dredging operations.

Great Lakes Observing System (GLOS, 2013) assessments state that the water level network on the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence rivers is sufficiently dense; however, more information on horizontal current flows in these major river courses is required. There is no effort here to assess the water level network for spatial gaps, as that information is not required for understanding lake-wide averages and hydraulic correctors. Placement of the stations over time has been to fulfill the specific location-based need for maintenance dredging activities, navigation, and regulatory and ice management operations.

The following information provides statistical differences over the same period as was done for each lake in the previous section and gives a sense of the similarities and differences of the mean values and their correlations. Long-term data is not available online for the USACE stations; however, key Canadian network stations are included in the analyses for context.

St. Marys River

Figure 49. Location of NWLON, Canadian, and USACE water level stations on St. Marys River. Note: The station at Lookout #4 has been replaced by a nearby station at West Neebish Island. Little Rapids is now a NOAA-operated station (http://www.great-lakes.net/envt/water/levels/levels_current.html).

USACE water level stations (Figure 49 and Table 7) complement the NOAA and Canadian networks so that the key have coverage of the narrow and depth limited navigation channels. There are two Canadian and two U.S. stations upstream and downstream of the locks that provide direct control for lock operations. The station at Little Rapids is a recent addition to the NWLON and was established in 2009 and a new station at West Neebish has replaced the station at Lookout #4.

Table 7. Comparison statistics for St. Marys River station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from databases relative to IGLD 1985.

St. Marys River					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Maximum Difference (m)**	**Minimum Difference(m)**	**Regression Coefficient (m)**
Pt. Iroquois-S.W Pier	0.146	0.058	0.947	-0.522	0.896
U.S. Slip-Little Rapids (2009-2011 only)	0.045	0.019	0.204	-0.098	0.992
Little Rapids-W. Neebish (2009-2011 only)	0.135	0.073	0.542	-0.101	0.852
W. Neebish-Rock Cut	0.059	0.046	0.404	-0.195	0.938
Rock Cut-De Tour Vil.	0.032	0.044	0.469	-0.280	0.935

St. Clair River

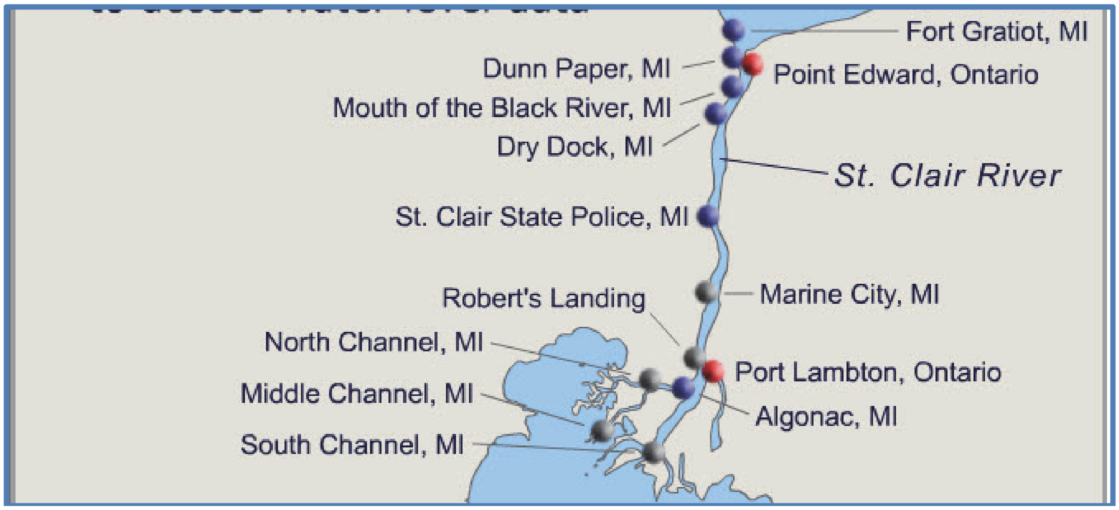


Figure 50. Locations of U.S. NWLON (blue), Canadian (red), and USACE (gray) water level stations on the St. Clair River (http://www.great-lakes.net/envt/water/levels/levels_current.html).

USACE operates several stations to provide control for their operations on the lower St. Clair River to complement the U.S. and Canadian stations (Figure 50). USACE data were not readily available for this study to properly assess the impacts of large differences in the mean values between the various station pairs as shown in Table 8. There are frequent anomalously large differences for some station pairs during the winter months when large amounts of ice in the river would inhibit normal flows.

Table 8. Comparison statistics for St. Clair River station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from database relative to IGLD 1985.

St. Clair River					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Ft. Gratiot-Dunn Paper	0.105	0.024	0.373	-0.129	0.986
Dunn Paper-Point Edward	0.048	0.023	0.306	-0.188	0.982
Point Edward-Mouth of Black River	0.021	0.018	0.248	-0.194	0.987
Mouth of Black R.-Dry Dock	0.098	0.022	0.275	-0.136	0.983
Dry Dock-St. Clair Police	0.298	0.068	1.041	-0.028	0.829
St. Clair Police-Port Lambton	0.306	0.054	0.858	-0.064	0.883
Port Lambton-Algonac	0.056	0.039	0.509	-0.042	0.932

Detroit River

Figure 51. Locations of U.S. (blue), Canadian (red), and USACE (gray) water level stations on the Detroit River (http://www.great-lakes.net/envt/water/levels/levels_current.html).

USACE operates only one additional station on the Detroit River (see Figure 51). There are expected significant elevation differences for all station pairs because the rivers are sloped surfaces.

Table 9. Comparison statistics for Detroit River station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from database relative to IGLD 1985.

Detroit River					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Windmill Pt.-Ft. Wayne	0.188	0.039	0.449	-0.139	0.960
Ft. Wayne-Wyandotte	0.104	0.028	0.368	-0.095	0.982
Wyandotte-Amherstburg	0.08	0.02	0.24	-0.02	0.993
Amherstburg-Gibraltar	0.243	0.069	0.853	-0.086	0.935

Niagara River

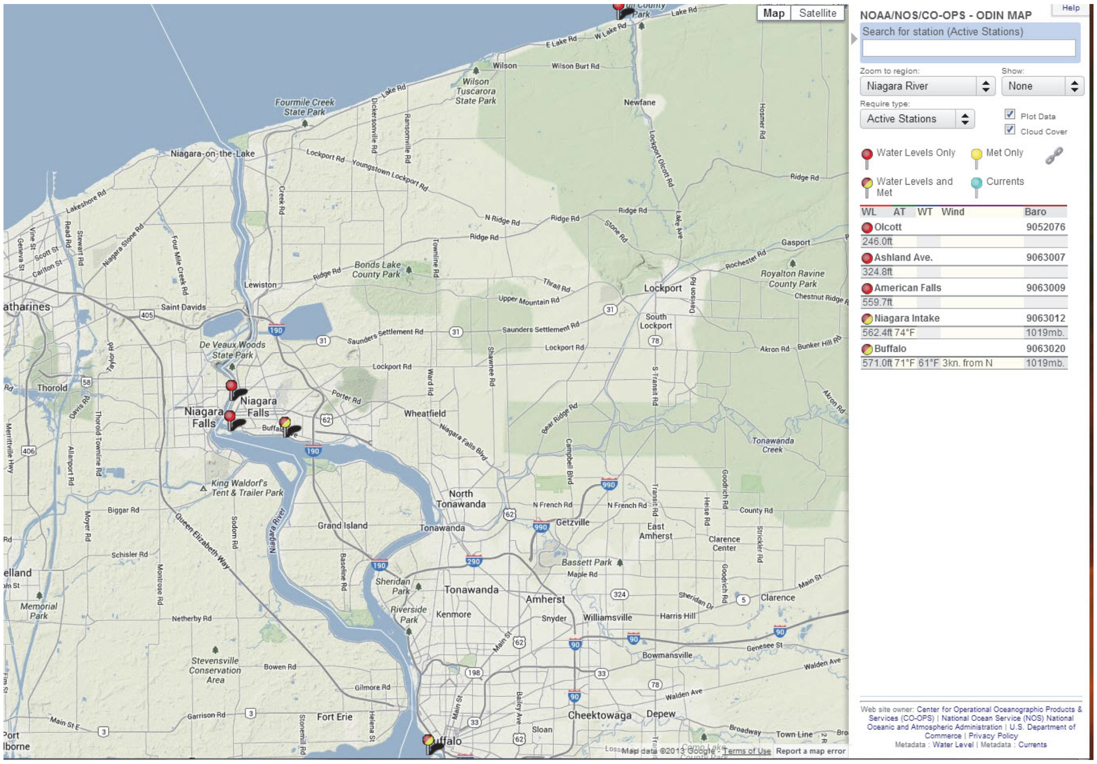


Figure 52. Location of U.S. Stations on the Niagara River (http://tidesandcurrents.noaa.gov/map/).

The stations shown in Figure 52 (and Table 8) are located at very specific locations to aid in the monitoring of the water levels used for international water management purposes. These gauge locations are part of a program to verify the gauge ratings used to determine flows in support of the Boundary Water Treaty of 1909 and the 1950 Diversion of the Niagara River Treaty between Canada and the United States of America concerning uses of the waters of the Niagara River.

Table 10. Comparison statistics for the Niagara River station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from database relative to IGLD 1985.

Niagara River					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Buffalo-Niagara Intake	2.888	0.207	5.047	1.821	0.208
Niagara Intake-American Falls	0.842	0.084	1.691	0.586	0.520
Ashland Avenue-Olcott	22.937	1.312	29.437	20.728	0.154

St. Lawrence River

Figure 53. Location of NWLON and Canadian Stations in the international section of the St. Lawrence River. Note: Stations at Kingston and Cape Vincent are on Lake Ontario and are included in the analyses for that Lake. Power entity and Seaway Authority Stations are not included (http://www.great-lakes.net/envt/water/levels/levels_current.html)

The station pairs in this portion of the river (Table 11) all have large correlation coefficients and small standard deviations. As expected on sloped river surfaces, there are significant drops in elevation going down the river from Lake Ontario as exhibited by the mean differences found in Table 11.

Table 11. Comparison statistics for the St. Lawrence River station pairs using seven years of hourly height data from 2005-2011. Elevations were obtained from database relative to IGLD 1985

St. Lawrence River					
Station Pairs	**Mean Difference (m)**	**Standard Deviation (m)**	**Maximum Difference (m)**	**Minimum Difference (m)**	**Regression Coefficient**
Cape Vincent-Alexandria Bay	0.121	0.031	0.560	-0.211	0.984
Alexandria Bay-Brockville	0.126	0.033	0.456	-0.127	0.980
Brockville-Ogdensburg	0.056	0.015	0.150	-0.081	0.996

5.0 SUMMARY OF FINDINGS AND RECOMMENDATIONS

This assessment of the Great Lakes NWLON evaluates the variability of key physical parameters through the Great Lakes system and assesses how well these variations are understood and monitored in order to meet the requirements for water level vertical control. The key parameters include: statistical summaries of hourly height comparisons among station pairs, comparisons of daily mean water levels, spatial variations in hydraulic correctors, spatial variations in long-term rates of vertical land motion, and cross-lake variations in the elevation differences of Low Water Datum to the Ellipsoid. Gaps can be identified by a lack of coverage for one or a combination of these parameters. In addition to the analysis of updated data sets, this analysis draws upon previous analyses of the variability of the key parameters in lake-wide, two-day average lake levels and one-year averages of hourly heights. This report intends to show the context of the contribution of U.S. stations to the bilateral network requirement, so the analysis thus needs to consider the geographical and hydrological context for each lake. Canadian stations were included in the statistical analyses for this purpose.

Lake Superior

The existing NWLON network in Lake Superior appears to be adequate in number and spatial distribution to meet requirements, however there is very little network overlap. The Gros Cap-Point Iroquois station pair could be considered to exhibit a very high degree of overlap in coverage; however, there is a slight difference with their relative vertical velocities that needs to be monitored. Agency subject matter experts have recommended pursuing the installation of a new station near the northern tip of the Keweenaw Peninsula due to stakeholder requests and the strategic location near the geographic center of the lake. Putting a priority on installation of a seasonal gauge at that location would assist in understanding lake level differences with nearby stations and its value to understanding lake level dynamics.

Lake Michigan/Lake Huron

Lake Michigan has two areas of significant network weakness where gaps in NWLON coverage exist. The gaps in coverage are in the lower southeast corner between Calumet and Holland and between Ludington and Mackinaw City on the northeast shore. This assessment is based on using information from Table 2 and Figure 20 showing large statistical differences and low regression and correlation coefficients between the station pairs. Differences in vertical velocities are also quite large in these areas, especially along the shore between Ludington and Mackinaw City. Initial analyses and stakeholder contacts lead to a recommendation for new NWLON stations in the vicinity of Burns Harbor (in the southeast) and Charlevoix (in the northeast).

Green Bay has significantly different water level variations than the rest of Lake Michigan due to a resonant seiche in that body of water. The Green Bay water level station provides necessary control for inside Green Bay; however, Green Bay variations are so anomalous that those data have limited value in computing lake-wide means for most applications.

The existing station Kewaunee has been recommended for relocation, moving it further south to Manitowoc, WI for a variety of logistical and stakeholder needs. This relocation would also serve to better distribute the station pair differences along the western shore of Lake Michigan.

Lake Huron appears to have adequate coverage in number and distribution to meet NWLON network requirements, however it is noted that Saginaw Bay (covered by Essexville) has significantly different water level variation than the main body of the lake. Essexville provides necessary local control for Saginaw Bay, but the Essexville data are so anomalous that they have very limited value in computing lake-wide means for most applications. The northern shore station pairs show some relatively smaller correlations and higher standard deviations between station pairs. However, the differences do not appear large enough to warrant recommending additional stations.

Lake St. Clair

There is an NWLON gap in water level and datum information in the Anchor Bay region of northwestern Lake St.Clair as illustrated in Table 4 by the large difference in elevation, large standard deviation and low correlation statistics between St. Clair Shores and Algonac. Developing water level zoning for hydrographic survey reducers will remain challenging in this area until additional data are obtained. This gap is consistent with the findings of Kelley (1976) in which additional gauges were recommended for Lake St. Clair in the northern and eastern areas of the lake to increase the accuracy of BOM lake levels. The location for a new long-term station could be determined by placing a seasonal gauge in the area and examining the data for differences with the existing station at St. Clair to the south and upstream at Algonac.

Lake Erie

Resolving large seiche oscillations for purposes of lake–wide means and monitoring requires a proper spacing of stations around Lake Erie. The existing NWLON network has an adequate number of stations to meet these requirements; however, the distribution of the stations requires adjustment. The long-term station at Fairport has been experiencing significant local subsidence due to nearby mining operations, and use of the data from this station has very limited use for lake-wide averages and datum control. It is recommended that the Fairport station be replaced with a new NWLON station between the existing stations at Fairport and Erie. This would also help to spatially resolve the lake level differences between existing stations at Fairport and Erie by providing another data point. Since lake level parameters vary in a longitudinal direction in Lake Erie, this new location would assist in further understanding the lake level differences between Port Stanley and Port Colborne along the Canadian shore.

Lake Ontario

The existing NWLON network in Lake Ontario has an adequate number and distribution of stations to meet requirements. Lake Ontario water levels are regulated, and there is significant overlap in the existing network for short-term mean lake level determination. The northern shore station pairs have the largest level differences and lowest correlations, but these are not large enough to recommend an additional station. The existing network size is still required to monitor the GIA in the lake basin and the distribution of the interpolated HCs for the western one-third of the lake are very complex and not well understood.

Connecting Waterways

Assessment of the observing networks in connecting waterways, especially for the upper Great Lakes, has been the subject of increased studies due to the recent extended period of significantly below normal lake levels. While there is apparent adequate density of water level stations (NWLON, Canadian, and USACE networks) for operational and regulatory purposes, there are gaps in information related to waterway flows, collection of which would require the installation of current meters and flow meters. Just as for each lake basin (except for Lake Michigan), the total water level station network is a shared responsibility with Canada in most of the connecting waterways. The requirements for the stations in the connecting waterways are very different from the networks in each lake basin, but an engineering/hydraulic analysis is beyond the scope of this report.

Monitoring Effects of GIA

The impact of differential vertical land velocities on the hydraulic characteristics of the lakes and on the update of vertical reference systems will continue to be of significant concern. The correlation of seven-year mean water level differences between station pairs with projected differences due to differential vertical land movement underscores this and justifies the urgency for planning an IGLD update. Figure 54 compares the projected elevation differences from vertical velocities with the calculated mean differences for all of the station pairs in each of the lakes (excluding Lake St. Clair and the interconnecting waterways) and shows a fairly strong linear relationship.

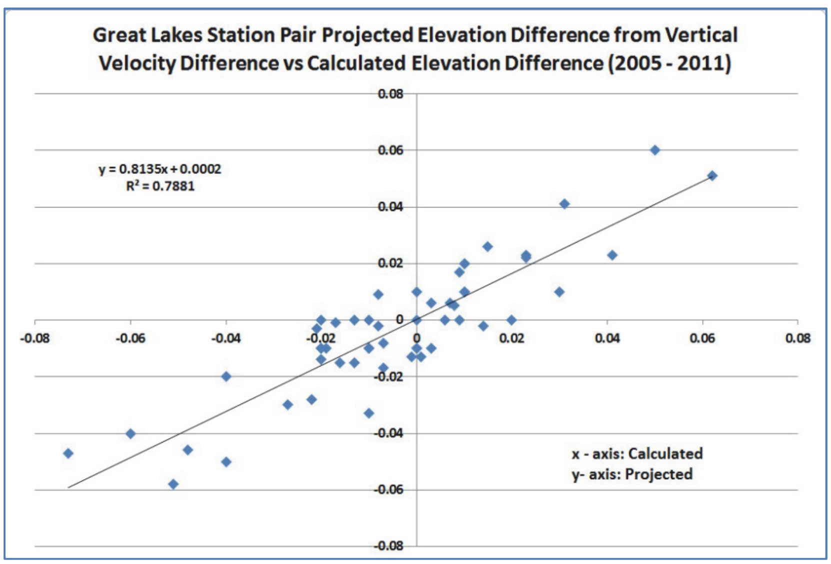


Figure 54. Relationship of projected elevation differences from vertical velocities to calculated mean elevation differences 2005 – 2011 for station pairs in the five major lakes.

The ongoing upgrade of the observing system in the Great Lakes with repeat GPS surveys and the co-location of CORS with water level stations should continue. Some of the CORS stations are just now accruing long enough time series to determine accurate estimates of vertical land velocities. A comprehensive analysis of the water level data, the GPS survey data, and the CORS data need to be undertaken to inform the GIA/PGR model and to better understand the differential rates and their impacts. An improved model will also better determine the location of gaps in the geodetic and water level observing systems. As these geodetic research and observing systems come on line, continuation of the existing network configuration on the lakes is vitally important for monitoring water level differences and relationships that contribute to the understanding the impacts of GIA here and elsewhere in the Great Lakes.

Network Operations

The Great Lakes system is a complex interaction of hydrological, climatological, geological, hydraulic, and human-induced forces. The need for long-term monitoring of lake levels, flows, meteorological parameters, and vertical land motion is critical to understanding the system, managing the resources, and using the system strategically and safely for sustainable economies and coastal communities. Operation of such a network must be sustained and upgraded over time to meet user demands. Investment in station configuration with annual inspections, infrastructure upgrade, new technology, backup systems, and active applied research and product development are all required over the long term. Large portions of the Great Lakes system are covered by a bare-bones network, and loss of any one station(s) operation will put the required water level network for a given entire lake or connecting channel at risk and impairs the ability to manage the Great Lakes. Strengthening each station to ensure continuous operation helps mitigate this risk.

The uncertainty in the interpolation of hydraulic correctors on each lake has highlighted the need for an updated seasonal gauging program in which additional locations are occupied for short durations and IGLD elevations are determined to supplement the permanent gauge networks. The last determination of this seasonal gauging program was for the IGLD 1955 update. The lack of precise updated datum elevations at these additional ports and harbors remains a significant gap.

ACKNOWLEDGEMENTS

The author would like to acknowledge the technical reviews of draft versions of this report by several subject matter experts, who have significantly improved the content and technical clarity from earlier drafts. These reviewers include scientists and engineers from the NOAA/NOS Center for Operational Oceanographic Products and Services; from Environment Canada; from the U.S. Army Corps of Engineers, Detroit District; and from the NOAA Great Lakes Environmental Research Laboratory. Assistance is also very much appreciated from Helen Worthington in final technical editing and review and from Brenda Via in report production and publication.

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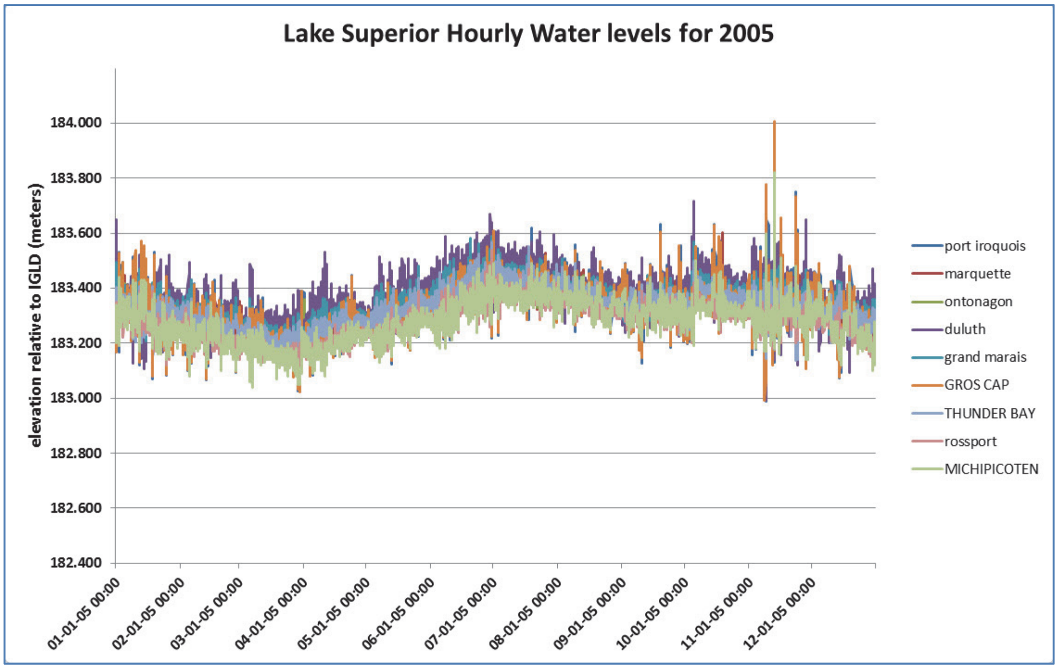
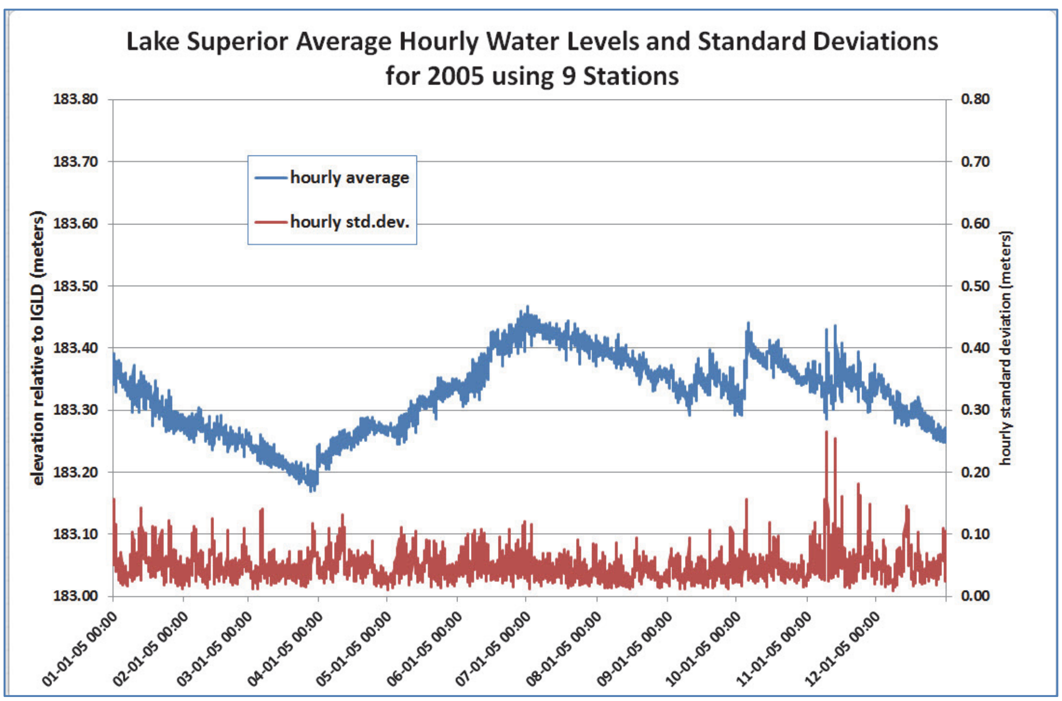
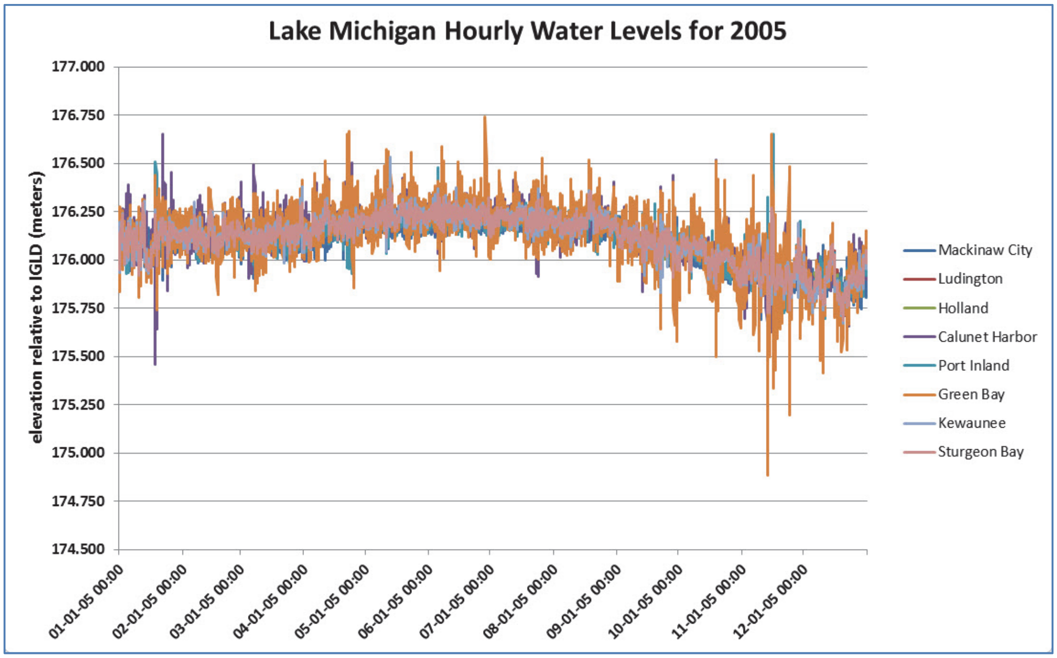
APPENDIX 1. Hourly Water Levels for each Great Lake from Calendar Year 2005

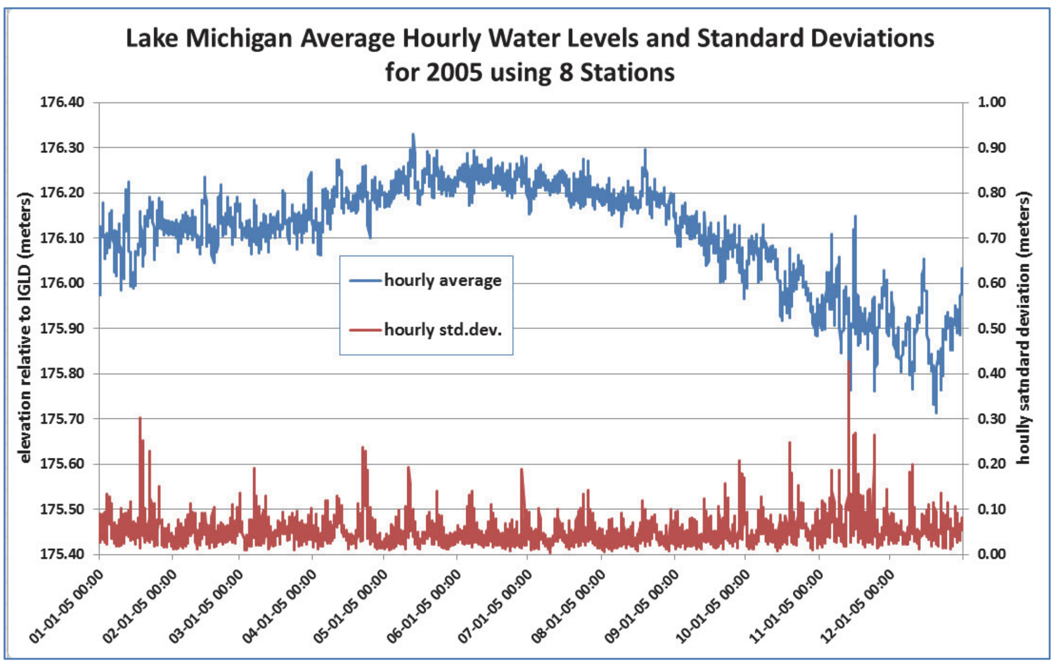
Note: the standard deviations used here are the standard deviation around the hourly mean obtained from averaging over the number of stations used for each lake.



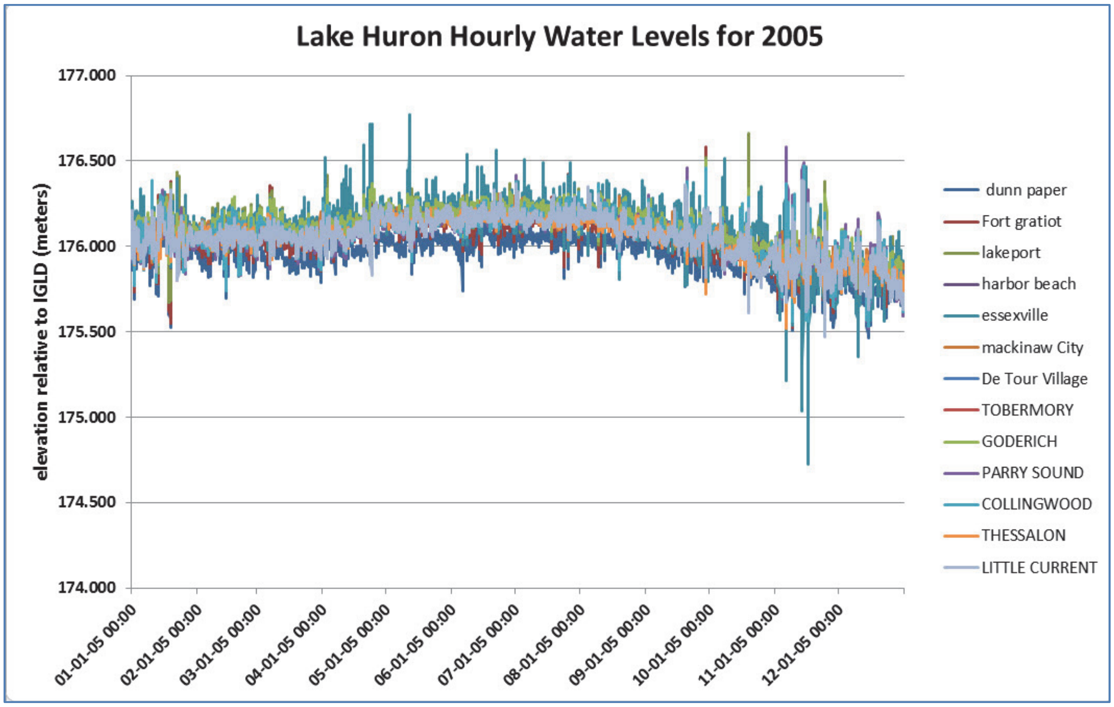


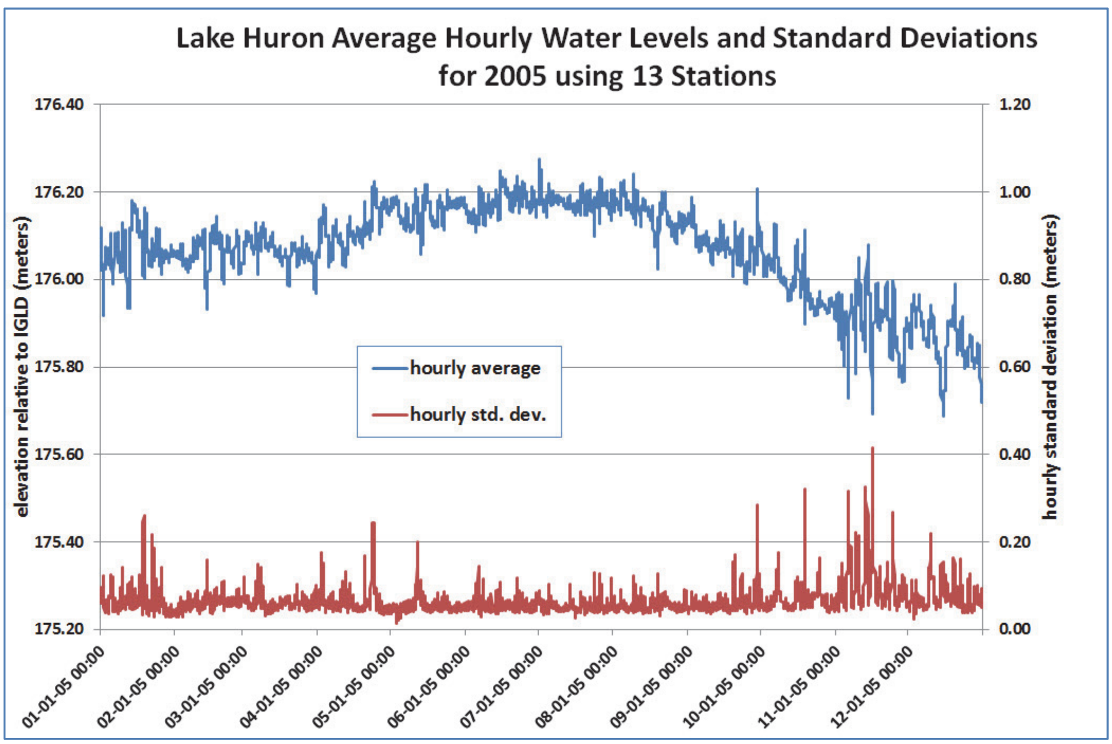


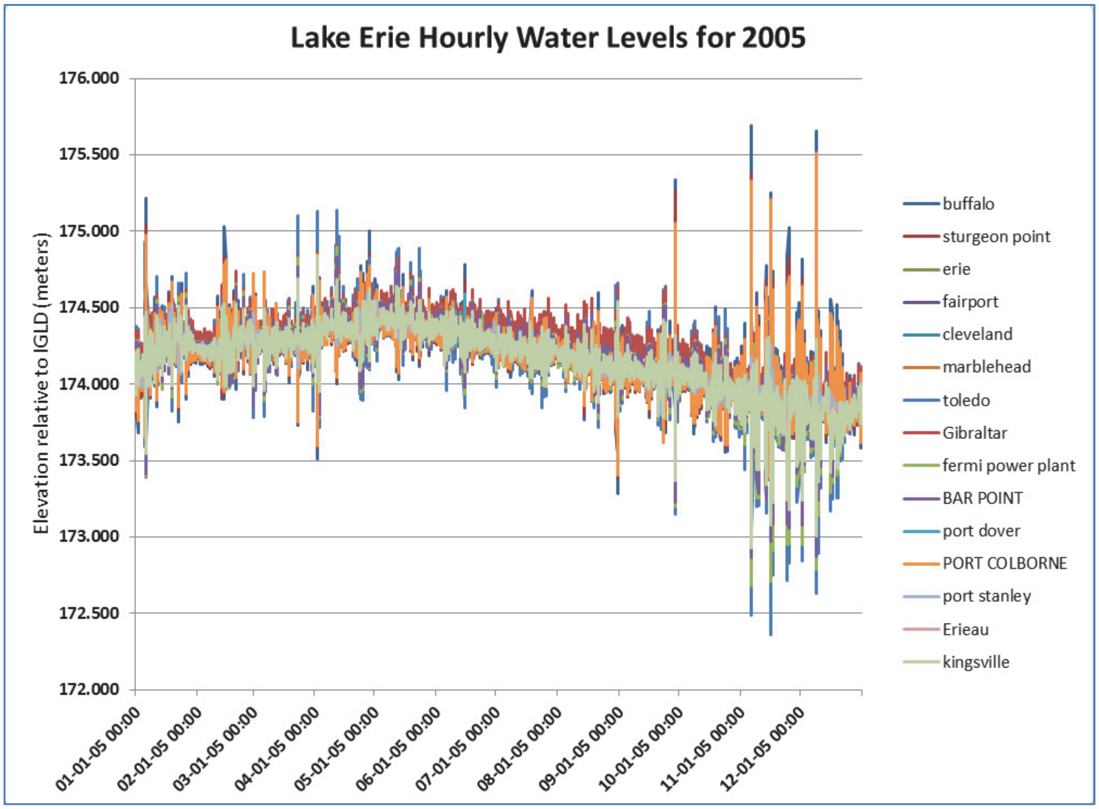
Lake Michigan Hourly Water Levels for 2005
elevation relative to IGLD (meters)
177.000
176.750
176.500
176.250
176.000
175.750
175.500
175.250
175.000
174.750
174.500
01-01-05 00:00
02-01-05 00:00
03-01-05 00:00
04-01-05 00:00
05-01-05 00:00
06-01-05 00:00
07-01-05 00:00
08-01-05 00:00
09-01-05 00:00
10-01-05 00:00
11-01-05 00:00
12-01-05 00:00
Mackinaw City
Ludington
Holland
Calunet Harbor
Port Inland
Green Bay
Kewaunee
Sturgeon Bay

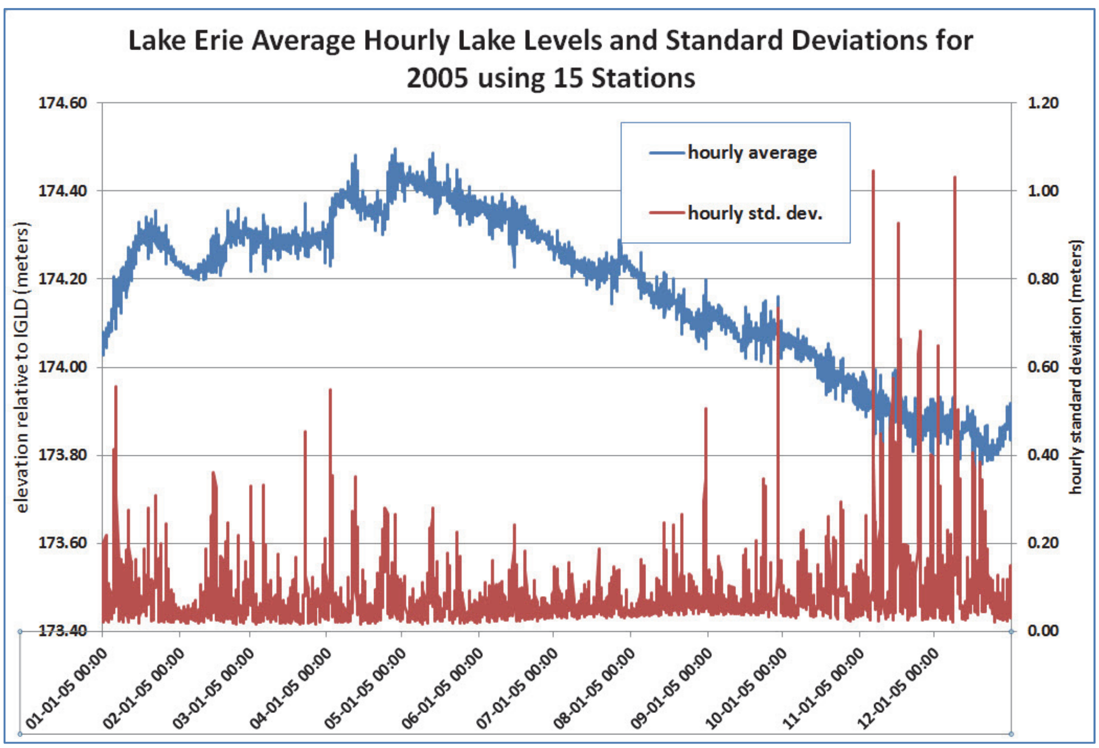


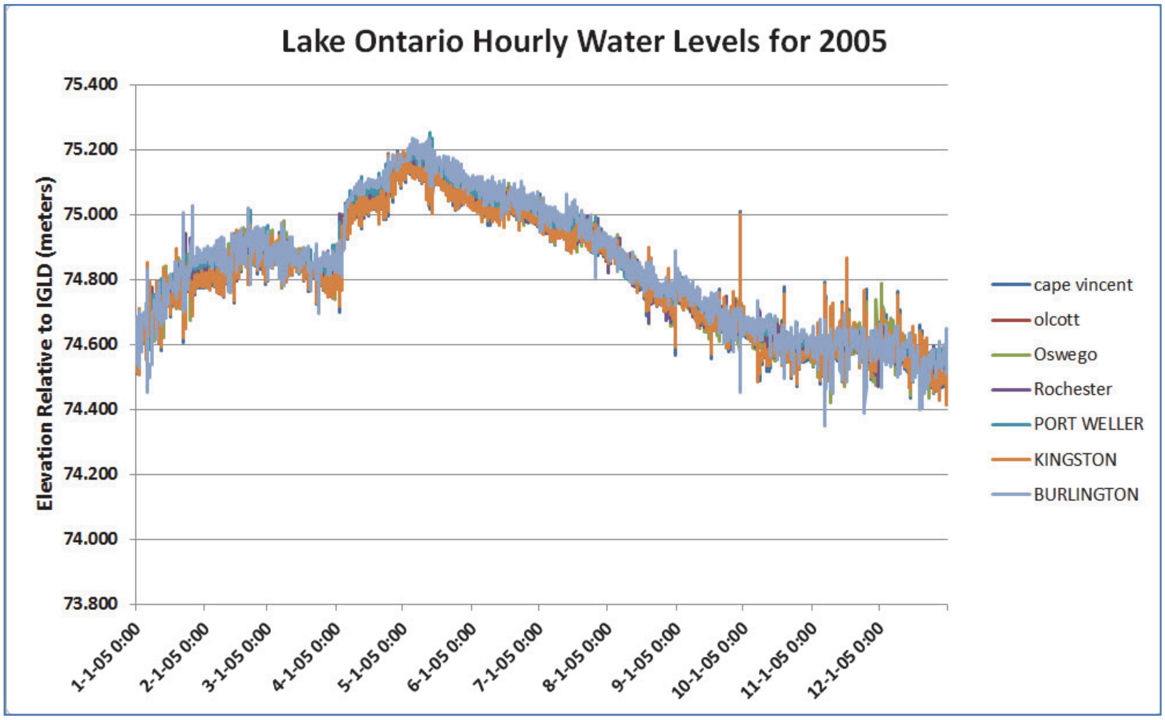
Lake Michigan Average Hourly Water Levels and Standard Deviations for 2005 using 8 Stations
elevation relative to IGLD (meters)
176.40
176.30
176.20
176.10
176.00
175.90
175.80
175.70
175.60
175.50
175.40
hoully satndard deviation (meters)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
hourly average
hourly std.dev.
01-01-05 00:00
02-01-05 00:00
03-01-05 00:00
04-01-05 00:00
05-01-05 00:00
06-01-05 00:00
07-01-05 00:00
08-01-05 00:00
09-01-05 00:00
10-01-05 00:00
11-01-05 00:00
12-01-05 00:00

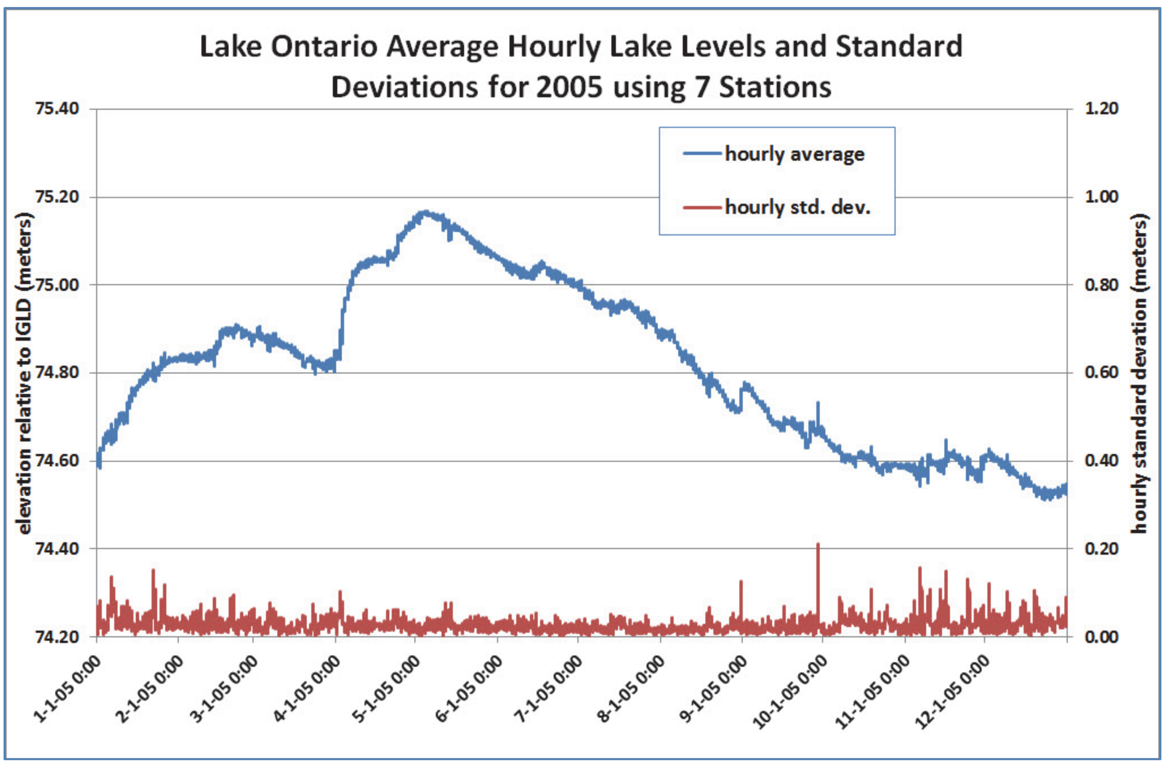

Lake Huron Hourly Water Levels for 2005
elevation relative to IGLD (meters)
177.000
176.500
176.000
175.500
175.000
174.500
174.000
01-01-05 00:00
02-01-05 00:00
03-01-05 00:00
04-01-05 00:00
05-01-05 00:00
06-01-05 00:00
07-01-05 00:00
08-01-05 00:00
09-01-05 00:00
10-01-05 00:00
11-01-05 00:00
12-01-05 00:00
dunn paper
Fort gratiot
lakeport
harbor beach
essexville
mackinaw City
De Tour Village
TOBERMORY
GODERICH
PARRY SOUND
COLLINGWOOD
THESSALON
LITTLE CURRENT


Lake Huron Average Hourly Water Levels and Standard Deviations for 2005 using 13 Stations
elevation relative to IGLD (meters)
hourly standard deviation (meters)
176.40
176.20
176.00
175.80
175.60
175.40
175.20
1.20
1.00
0.80
0.60
0.40
0.20
0.00
hourly average
hourly std. dev.
01-01-05 00:00
02-01-05 00:00
03-01-05 00:00
04-01-05 00:00
05-01-05 00:00
06-01-05 00:00
07-01-05 00:00
08-01-05 00:00
09-01-05 00:00
10-01-05 00:00
11-01-05 00:00
12-01-05 00:00


Lake Erie Hourly Water Levels for 2005
Elevation relative to IGLD (meters)
176.000
175.500
175.000
174.500
174.000
173.500
173.000
172.500
172.000
01-01-05 00:00
02-01-05 00:00
03-01-05 00:00
04-01-05 00:00
05-01-05 00:00
06-01-05 00:00
07-01-05 00:00
08-01-05 00:00
09-01-05 00:00
10-01-05 00:00
11-01-05 00:00
12-01-05 00:00
buffalo
sturgeon point
erie
fairport
cleveland
marblehead
toledo
Gibraltar
fermi power plant
BAR POINT
port dover
PORT COLBORNE
port stanley
Erieau
kingsville


Lake Erie Average Hourly Lake Levels and Standard Deviations for 2005 using 15 Stations
elevation relative to IGLD (meters)
hourly standard deviation (meters)
174.60
174.40
174.20
174.00
173.80
173.60
173.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
hourly average
hourly std. dev.
01-01-05 00:00
02-01-05 00:00
03-01-05 00:00
04-01-05 00:00
05-01-05 00:00
06-01-05 00:00
07-01-05 00:00
08-01-05 00:00
09-01-05 00:00
10-01-05 00:00
11-01-05 00:00
12-01-05 00:00


Lake Ontario Hourly Water Levels for 2005
Elevation Relative to IGLD (meters)
75.400
75.200
75.000
74.800
74.600
74.400
74.200
74.000
73.800
1-1-05 0:00
2-1-05 0:00
3-1-05 0:00
4-1-05 0:00
5-1-05 0:00
6-1-05 0:00
7-1-05 0:00
8-1-05 0:00
9-1-05 0:00
10-1-05 0:00
11-1-05 0:00
12-1-05 0:00
cape vincent
olcott
Oswego
Rochester
PORT WELLER
KINGSTON
BURLINGTON


Lake Ontario Average Hourly Lake Levels and Standard Deviations for 2005 using 7 Stations
elevation relative to IGLD (meters)
hourly standard devation (meters)
75.40
75.20
75.00
74.80
74.60
74.40
74.20
1.20
1.00
0.80
0.60
0.40
0.20
0.00
hourly average
hourly std. dev.
1-1-05 0:00
2-1-05 0:00
3-1-05 0:00
4-1-05 0:00
5-1-05 0:00
6-1-05 0:00
7-1-05 0:00
8-1-05 0:00
9-1-05 0:00
10-1-05 0:00
11-1-05 0:00
12-1-05 0:00

LIST OF ACRONYMS AND ABBREVIATIONS

BOM	beginning of the month
cm	centimeters
CO-OPS	Center for Operational Oceanographic Products and Services
CORS	Continually Operating Reference Stations
EOF	Empirical Orthogonal Function
ERS	Ellipsoidally Referenced Hydrographic Surveys
GIA	Glacial Isostatic Adjustment
GLERL	Great Lakes Environmental Research Laboratory
GLOS	Great Lakes Observing System
GPS	Global Positioning System
HC	Hydraulic Correctors
in	inches
IGLD	International Great Lakes Datum
IJC	International Joint Commission
km	kilometer
LWD	Low Water Datum
m	meter
MWL	Mean Water Level
NAD	North American Datum
NAVD	North American Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NWLON	National Water Level Observation Network
PBM	Primary Bench Mark
PGR	Post-Glacial Rebound
USACE	United States Army Corps of Engineers