Dynamic Heights for the International Great Lakes Datum of 2020

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Key words: Dynamic Heights, hydrology, reference system, water topography

SUMMARY

The Great Lakes in North America serve as a valuable resource of freshwater, hydropower and a means of navigation from interior North America to international markets. As such, maintaining a consistent reference system has been essential to both Canada and the United States. The border between the two countries is roughly 8900 km and extends through the middle of many of the Lakes. Treaties also emphasize equal access to the waters in the Lakes. Hence, adoption of a common reference system is essential. The International Great Lakes Datum of 1985 (IGLD 85) has served for this for over 30 years. Due to changes from Global Isostatic Adjustment and improvements in positioning technology, IGLD 85 must be updated. The International Great Lakes Datum of 2020 (IGLD 2020) will replace IGLD 85 in about 2025. IGLD 2020 will use the same geopotential model as the North American-Pacific Geopotential Datum of 2022 (NAPGD 2022). NAPGD2022 is being realized as both a geoid height model and a gravity field model at one arcminute. These models will be combined with GNSS observations of mean water surfaces throughout the Great Lakes to determine dynamic heights. Comparisons will be made on each Lake to estimate the potential for a permanent water topography that would indicate the need for hydraulic correctors (HCs). In IGLD 85, there was a need for HC's to account for over 30 cm of residual tilt across the Lakes that were believed to be due to a datum defect in NAVD 88. In this paper, we provide a preliminary analysis of relative water levels at gauges across the Great Lakes. We identify, estimate, and correct for variations due to relative motion, elastic deformation associated with changes in water loading, and wind effects between gauges. The analysis demonstrates that, after these corrections are made, annual changes in water levels between gauges on each Lake agree at the cm level. As such, this method provides a tool for removing biases due to relative motion between gauges and ensures that these biases will not be a significant source of error in the final evaluation of absolute dynamic heights for Lake water levels. However, the analysis also demonstrates that dynamic topography due to the prevailing winds is present and may create enough of a persistent topography to require hydraulic correctors. The absolute extent of the wind effects will be evaluated in the future once GNSS and leveling data is finalized and absolute dynamic heights can be calculated.

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1. **INTRODUCTION**

The United States and Canada share the longest international border in the world – 8893 km. Significant portions of that border are encompassed by bodies of water, which are shared and must be jointly managed per the Boundary Waters Treaty signed by Canada and the United States in 1909. The Treaty steers the actions of the International Joint Commission (IJC), which has several regional committees focused on different lakes and river systems. One of these is the Great Lakes-St. Lawrence River Adaptive Management Committee (GLAM).

The Great Lakes system is particularly complex and large. The drainage basin covers more than 1,000,000 km^2 (400,000 square miles) from Duluth, MN to Trois Rivières, QC. Eight U.S. states and two Canadian provinces border this vast system of shared waters. Thus, further coordination between U.S. and Canadian agencies is required.

The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, or Great Lakes Coordinating Committee (GLCC), is a collaboration of the Governments of the United States and Canada for the purpose of agreeing upon the basic hydraulic, hydrologic, and vertical control data that is required to manage the Great Lakes and St. Lawrence River. While no formal ties exist between the GLCC and GLAM, many of the members who sit on the GLAM committee also sit on the GLCC. The GLCC is an ad hoc committee being supported by the following agencies: United States Army Corps of Engineers, Environment and Climate Change Canada, National Oceanic and Atmospheric Administration, National Resources Canada, United States Geological Survey, and Department of Fisheries and Oceans Canada.

The GLCC formed in 1953 and developed the International Great Lakes Datum of 1955 or IGLD 55 (GLCC 1979). This datum unified measurements and management for both nations – particularly for flood control and hydroelectric generation. IGLD 55 was replaced by IGLD 85 based on updated leveling and a model of geopotential heights developed with the North American Vertical Datum of 1988 or NAVD 88 (Zilkoski et al. 1992, Zilkoski 1989).

Other studies (Roman and Li 2016, Roman 2020) have shown significant systematic issues with NAVD 88 that also impacted IGLD 85. The water surfaces as determined by IGLD 85 were found to have dm's of relative differences across the various Lakes. Ideally the Lake surfaces would be flat – having the same dynamic height value. Hence, it was necessary to develop a model of hydraulic correctors to ensure consistency between gauges for better management of the Great Lakes system.

A new datum, IGLD 2020 (GLCC 2017), will be released in the next few years. This model will be based on the North American-Pacific Geopotential Datum of 2022. NAPGD2022 derives from satellite, airborne and surface gravity data and has improved accuracy at all distance scales. While this will reduce inconsistencies in Lake surfaces due to datum defects, water topography will likely still exist due to westerly winds and the Lake shore contours.

To develop IGLD 2020, water levels at gauging stations throughout the Great Lakes will be analyzed. Supplemental and focused observations have been made for these past seven years. To provide adequate geodetic control for these stations, campaign GNSS was collected on adjacent bench marks with spirit leveling connecting the bench marks to the stations. All data will be analyzed to determine optimal dynamic heights for potential hydraulic correctors.

This paper will cover the initial analysis between water gauging stations around the Great Lakes. Section 2 covers the methodology and information collected at gauging stations (water levels, physical leveling from bench marks and GNSS on bench marks). Section 3 covers a relative analysis of water levels on the Lakes and a formula for determining long term trends and any potential water topography. Section 4 summarizes and discusses the results.

2. METHODOLOGY AND DATA COLLECTION

Without disturbing forces, the expectation is that a Lake surface would conform to the same geopotential surface - it would be flat. Each Lake should have a constant dynamic height, but water levels in the Great Lakes are complicated by many factors.

Water flows into the basin from many sources, flows down through the Lakes and eventually reaches the Atlantic Ocean via the St. Lawrence Seaway. Constrictions from Lake beds, inflow, outflow, evaporation, rainfall and weather events create enough complications for modeling the behavior of the Lake surfaces. Furthermore, persistent westerly winds cause the Lake surfaces to develop a standing topography that is affected by the orientation of the Lake beds. Additionally, a long period signal exists because of Glacial Isostatic Adjustment (GIA). Averaging over a longer period of time mitigates the impacts of the seasonal variations and storm events but then brings in a longer period signal due to the GIA signal (Mainville and Craymer 2005). To understand all of these factors, sufficient and redundant information is needed to evaluate if the Lake surfaces are sufficiently described as flat or if some hydraulic corrector model is required as was the case for IGLD 85 (GLCC 1995).

Water level gauges are deployed around the Great Lakes region (Figure 1) in both the U.S. and Canada. These stations provide a long-term collection of water heights relative to the existing IGLD 85. Leveling and GNSS observations have been made over the past seven years to collect sufficient, redundant information for this analysis (Hippenstiel et al. 2023).

Figure 2 highlights a typical setup seen at the Mackinaw City, MI water station. The left image shows the outside setup complete with meteorological and GNSS collection. The

middle image shows the inside of the building and highlights the station datum (the table) from which the water measurements are made. The right image shows the stilling well where water is admitted from a submerged pipe that is well below areas where ice may form. Water level measurements are made from the datum to the water surface in the well and are archived at the NOAA Center for Operational Oceanographic Products and Services (CO-OPS).
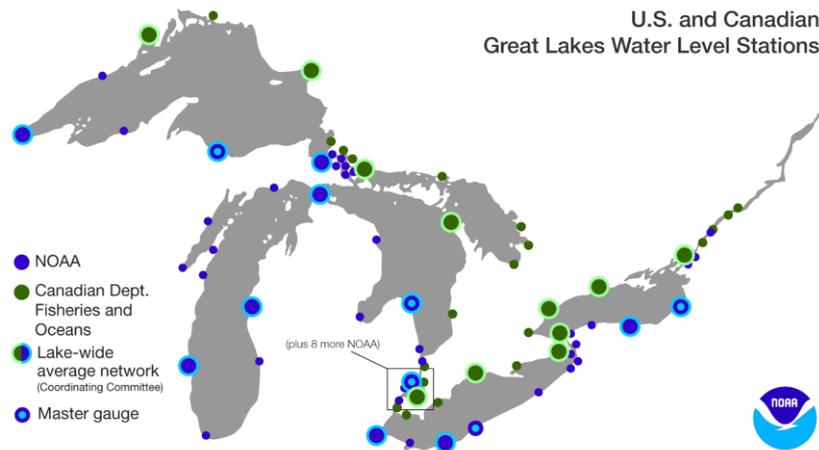
Figure 1 Distribution of 53 U.S. (NOAA) and 34 Canadian (CHS) Water Level Stations in the Great Lakes region. These sites collect continuous water level measurements. A few have collocated CORS.

Figure 2 NWLON station at Mackinaw City, MI (courtesy Jeff Oyler, CO-OPS and USACE). Station setup includes numerous antennas including a NOAA CORS Network receiver (left). Inside, measurements are made from the table datum (middle) into the stilling well (right

Multiple bench marks surround each building to provide redundant geodetic control for the water level observations. Every couple of years, level surveys determine the height differences between the bench marks and the datum. Roughly every five years, a GNSS campaign on the bench marks provides geometric coordinates including ellipsoidal heights. The leveled height differences transfer the ellipsoidal heights to the datum. Water level measurements can now be applied to reduce the geometric coordinates from the datum to the water surface - at whatever averaging interval is deemed correct. Determining the best value for a mean water level is a separate analysis covered in section 3. Geometric coordinates are converted to dynamic heights using a geopotential model. If all parameters are well modeled,

the dynamic heights at each water station should have the same value for an individual Lake. If some systematic effect remains, then a model of hydraulic correctors will be needed.

2.1 Water Gauge Station

Data collection at a water gauge station requires the connection of the geodetic bench marks through the datum to the water surface. In Figure 3, benchmarks surround the gauge building. These are in open air and are ideally available for GNSS occupation. The leveled height differences from the bench marks are used to transfer the ellipsoidal height (from the GNSS solutions) to the datum. The extra marks provide redundancy to eliminate outliers.
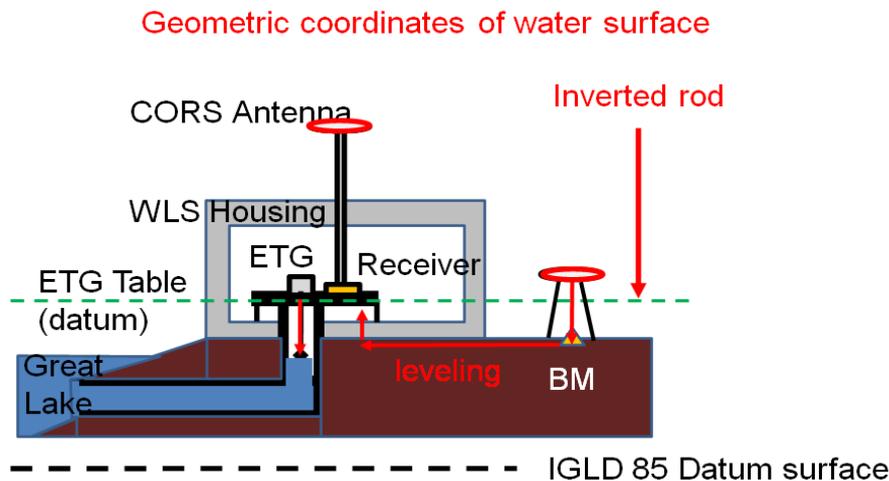
Figure 3 Mockup of a water level station on a Great Lake. GNSS and leveling from adjacent bench marks transfer heights to the ETG Table datum. An inverted rod measurement from the CORS antenna also serves for positioning if available.

Note that the CORS station itself can also be used in this process. Several water gauge stations have a NOAA CORS Network station mounted onto the building (see left image of Figure 2). The CORS station provide the constraints for the solutions of the Campaign GNSS on the bench marks. Hence, they provide very accurate geometric coordinates. An inverted rod measurement can be made from the CORS antenna to the ground and then to the datum. This also transfers the ellipsoidal height to the datum and provides redundancy.

The water level height in the stilling well is determined from the electronic tape gauge (ETG) Table Datum. In most places this takes the form of a physical measurement to the water surface using an ETG. Microwave sensors are being examined as an alternative method for this measurement. The intent though is to measure the time-varying height of the water. The stilling well does calm much of the weather-related disturbances but many signals can impact the water level observations. Section 3 will examine a model that can describe the relative changes in water surfaces between gauging stations. Once the leveling and campaign GNSS data are adjusted and finalized, then an absolute comparison can be made.

2.2 Data Collection

Continuous water level measurements are available for many decades, whereas the leveling and Campaign GNSS are more periodic. A brief description of the water level measurements is provided in 2.2.1. GNSS observations are covered in 2.2.2 and the leveling data are discussed in 2.2.3. Only a cursory discussion is provided here. See Hippenstiel et al. (2023) for more details on these data and their ongoing adjustment. The expectation is that remaining leveling will be collected and processed by the end of 2023 along with a final adjustment of the GNSS data.

2.2.1   Water Measurements

NOAA's Great Lakes Environmental Research Laboratory (GLERL) researches, monitors and models many aspects of the Great Lakes. It coordinates a significant amount of the data from multiple agencies. Great Lakes water levels are continuously monitored by U.S. and Canadian federal agencies in the region through a binational partnership. NOAA-GLERL relies on this water level data to conduct research on components of the regional water budget and to improve predictive models. Water level monitoring stations are operated by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) and the Department of Fisheries and Oceans' Canadian Hydrographic Service. The U.S. Army Corps of Engineers (Detroit, Chicago, Buffalo) and Environment and Climate Change Canada play crucial roles in research, coordination of data and operational seasonal water level forecasts for the basin.

NOAA water level observations are available at specific locations, as described on the Monitoring Network (Figure 1) or as a lake-wide average. These lake-wide averages are based on a select set of U.S. and Canadian station data as determined by the GLCC. For more details, see the GLERL water levels page.

2.2.2   Global Navigation Satellite Systems (GNSS) observations

The final data set will include GNSS observations and metadata for 365 bench marks, 179 for Canada and 186 for the US. These data have been collected but are still being processed. The Campaign GNSS observations are collected over the span of several months and working in tandem across the Lakes between U.S. and Canadian field crews. These data will ultimately determine the geometric coordinates for the bench marks. While the GNSS have been collected and evaluated, it is necessary to wait on the completion of the leveling data before these data can be finalized and used for further analysis.

2.2.3   Spirit Leveling

Leveling connects the bench marks to the Datums at each station and provides an orthometric height difference between the two. The leveling data must be finalized to assign Permanent ID's (PID's) to the bench marks for entry into databases. The PID's ensure that the leveling to

the Datum corresponds to the correct GNSS observations. The leveling effectively transfers the geometric heights on the bench marks to the datum. Over such short distances as exists between the bench marks and the water gauge buildings (100's of meters), the orthometric and ellipsoidal heights are essentially equivalent.

3. **RELATIVE WATER LEVEL DATA**

While other data must still be processed, water gauge measurements from 2000 to 2022 are available now for the 5 Great Lakes. For this preliminary analysis, we use 9 stations on Lake Superior, 8 stations on Lake Michigan, 11 stations on Lake Huron, 13 stations on Lake Erie, and 9 stations on Lake Ontario.

Comparing dynamic water heights between gauges across a lake requires a method for obtaining representative mean water levels at each gauge. This is a challenge as instantaneous gauge levels deviate from the lake-wide mean due to factors such as waves, wind, seiches, and local vertical motion of the land that the gauges are fixed to. The purpose of this section is to identify the primary factors that cause gauges to deviate from the mean lake level and to correct for these factors when possible.
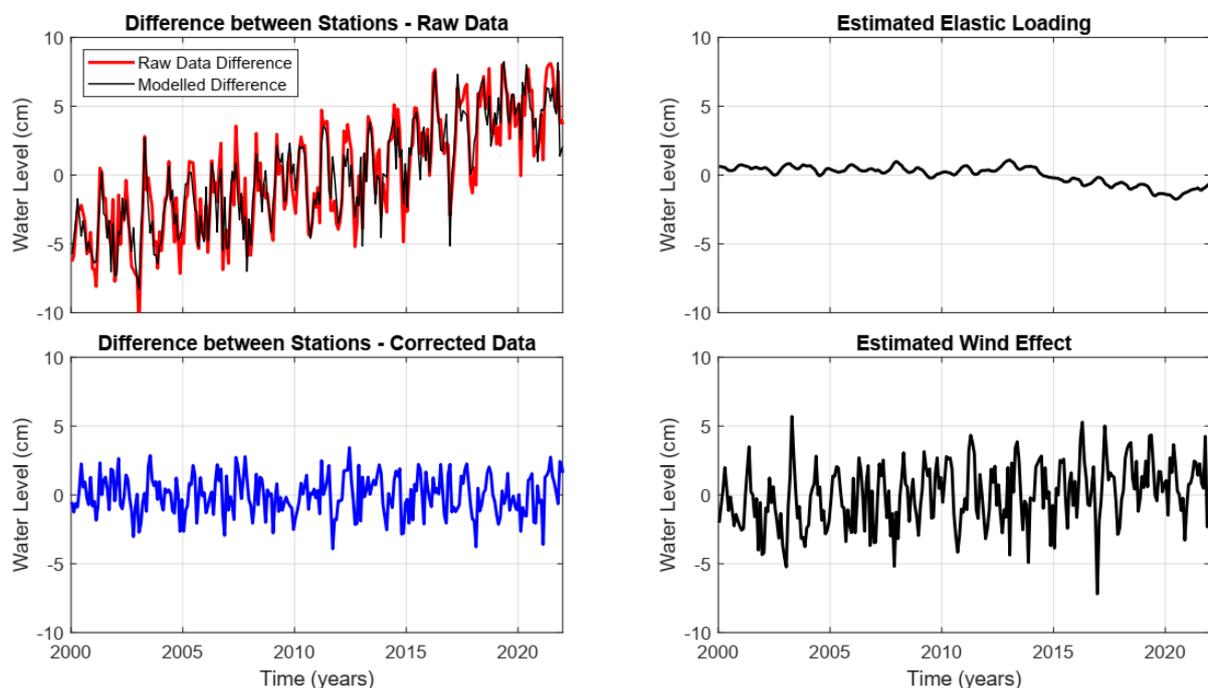
Figure 4 The monthly difference between water levels at Duluth and Michipicoten before (top left, red) and after (bottom left) corrections. The modeled corrections (top left, black) explain the long-term trend and also short-term variability due to wind.

One approach to mitigating the transient signal from waves, wind, and seiches is to average over a sufficiently long time series to eliminate short term variability. However, large-scale vertical land motion, due to processes such as glacial isostatic adjustment (GIA), causes

gauges to move vertically relative to each other and this relative motion creates an apparent drift in water levels. For example, a gauge experiencing vertical uplift will move away from the mean surface of the lake, causing the observed water level to appear to be decreasing with time. Averaging over too long a period of time introduces biases due to the relative vertical motion between gauges. The top left panel of Figure 4 shows the difference in monthly averaged water levels between gauges on opposite sides of Lake Superior and located at Duluth and Michipicoten. In the absence of relative vertical motion and dynamic topography (waves, wind, etc.), both gauges would be expected to track the same changes in lake level with respect to time and the difference should be zero. As Figure 4 clearly shows, this is not the case and there are decimeter differences depending on the time period selected. The differences in water levels between this station pair highlights the short-term variability (waves, wind, etc.) as well as the long-term trend that arises due to relative vertical motion between gauges.

In the past (GLCC 1995), the optimum averaging duration was found to be 7 years. Averages taken over less than 7 years were sensitive to short term variability in lake levels while averages taken over more than 7 years were found to be biased by relative motion between gauges. In order to improve estimates of mean water levels at gauges, we propose a model that is capable of determining both relative vertical motion between gauges as well as the effects of sustained winds across the Great Lakes.

3.1 Physical Model for Water Level at an Individual Gauge

In order to estimate and remove the effects of relative vertical motion and wind, we model the water level at a specific gauge on a lake as

$$w_i(t) = W_L(t) + v_i \cdot t + \sum_{L=S,M,H,E,O} a_{i,L} W_L(t) + b_i \, \Delta W_{MH}(t) + c_i \qquad (3.1)$$

where $w_i(t)$ is the water level at gauge i on Lake L, $W_L(t)$ is the mean lake level of lake L (L=Superior, Michigan, Huron, Erie, or Ontario), v_i is the vertical velocity of the water surface relative to the gauge, and t is time. The third and fourth terms on the right-hand side (RHS) of equation 3.1 account for elastic loading and wind and will be discussed in more detail shortly. Finally, c_i represents a constant offset from the mean lake level. As the current analysis is strictly focused on relative changes between lake gauges in time, we will ignore these constants for this paper. However, once GNSS, leveling, and geoid and gravity models are available, this analysis will be repeated in absolute dynamic heights and this term will represent both unmodelled dynamic topography as well as model and analysis errors.

3.2 Relative Motion due to GIA and Elastic Deformation

Both large scale tectonic processes such as GIA and smaller scale processes linked to local subsidence/uplift can cause a gauge to move vertically over time with respect to the mean water level of the lake. A gauge that is moving downwards will get progressively closer to the

water surface and this will show up in the data as an apparent increase in water level. As such, a positive velocity v_i represents a situation in which a gauge is experiencing downwards relative motion.

We also consider vertical motion associated with loading changes from water within the Great Lakes Basin (GLB) and these changes are not linear with time. Argus et al. (2020) demonstrated, using both GNSS time series for stations across the GLB and GRACE satellite gravity data, that changes in water level in the Great Lakes can be large enough to cause cm level vertical elastic deformation in the basin. Water levels in the Great Lakes increased by over a meter from mid-2012 to 2020. Spread across the 5 large Great Lakes, this amounted to a change of approximately 300 km^3 or 300 trillion liters of water. This increase in water caused the land beneath the Great Lakes to sink by as much as 3 cm. Elastic displacements were found to be largest near the center of the GLB and smallest near the edges. As such, different gauges on any given lake experienced different amounts of vertical elastic deformation and therefore relative motion.

Argus et al. (2020) used a two-dimensional elastic loading model to calculate deformation across the GLB. We take a different approach and use lake level observations to extract Green's functions for relative motion between gauges. A Green's function relates the response of a system to a given forcing. In this case the forcing is the change in loading (water) within a given lake and the response is the vertical elastic deformation. Elastic deformation is a linear process when considering small deformations over large distances (cms over hundreds of kms). The linearity of the problem means that if a given station on Lake Superior sinks by 1 cm due to an increase of 1 m of water in Lakes Michigan and Huron, then that same station will sink by 2 cm if there is an increase of 2 m of water in Lakes Michigan and Huron. We exploit this linearity to construct a simple model that is capable of detecting and correcting for these elastic displacements. The third term on the RHS of equation 3.1 captures the linear physics of elastic loading. The coefficient $a_{i,L}$ is a constant parameter of proportionality, to be solved for, that relates the vertical elastic deformation experienced at gauge i to the change in water loading within lake L.

3.3 Effects of Wind and an Empirical Wind Proxy

The fourth term in equation 3.1 accounts for gradients across the lake due to the prevailing winds. This correction has the same linear form as the elastic loading. However, instead of being proportional to the change in water level in one of the Great Lakes, it is proportional to the difference in lake level between Lakes Michigan and Huron. Lakes Michigan and Huron are attached at their northern extent. In the absence of wind, and when considering monthly timescales, the two lakes should be at the same water level. But they are not, and this is due to the prevailing winds that blow from the west to the east. These winds create a gradient in height across the lakes and push water from Lake Michigan into Lake Huron, resulting in a difference in water level between the two lakes that provides an effective proxy for the wind strength. The parameter b_i is a constant parameter that relates the change in water height at

gauge i to the strength of the wind, as provided by the difference in water level between Lakes Michigan and Huron, $\Delta W_{MH}(t)$.

3.4 Solution Approach

The parameters v_i, $a_{i,L}$, b_i and c_i are solved for using a simple linear least squares approach for all gauges on a lake. The calculation is carried out separately for each lake. The mean water level for each lake is calculated by averaging all gauges on the lake:

$$W_L(t) = \frac{1}{N}\sum_{i=1}^{N} w_i(t) \tag{3.2}$$

The observation matrix is composed of the water level observations, w_i, for all gauges on the lake. The design matrix contains the time and mean lake levels linked to the elastic deformation and the wind proxy. Finally, the model coefficient vector contains the parameters v_i, $a_{i,L}$, b_i and c_i for all gauges on the lake. The calculation is performed independently for each lake. Further details regarding the least squares approach are beyond the scope of this paper. We define the corrected water level for each gauge, $wc_i(t)$, as the observed water level with all estimated vertical motion (linear and elastic) and wind effects removed:

$$wc_i(t) = w_i(t) - v_i \cdot t - \sum_{L=S,M,H,E,O} a_{i,L} W_L(t) - b_i \, \Delta W_{MH}(t) - c_i \tag{3.3}$$

3.5 Results

Figure 4 shows the relative difference between two gauges on Lake Superior (top left), the difference between the corrected gauges (bottom left), and the calculated corrections for both elastic loading (top right) as well as wind across the lake (bottom right). The black curve in the top left panel shows the calculated corrections and demonstrates how well the differences between the gauges are explained by a vertical velocity, elastic loading and the estimated wind correction. Application of the corrections for the two gauges reduces the standard deviation of their differences from 4.0 cm to 1.4 cm and removes long term trends associated with GIA and other long-term processes. The correction for elastic loading reveals a change in relative height between the two gauges of ~2.5 cm between 2012 and 2020 due to the increased water levels in the Great Lakes. Correcting the vertical positions for both long term tectonic deformation as well as elastic loading is critical for avoiding biases between gauges when averaging over more than a few years.
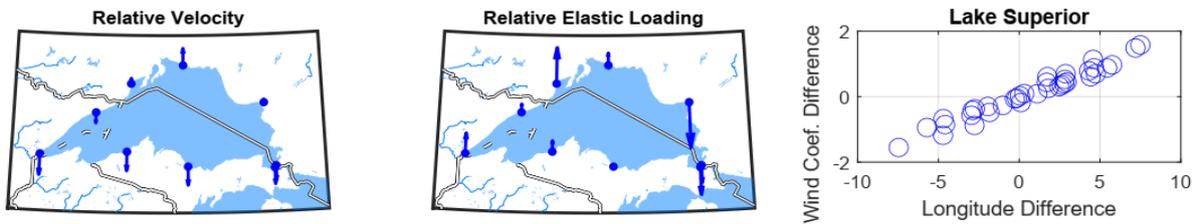
Figure 5 Calculated relative velocities (left) and displacements between 2013 and 2020 (middle) for gauges on Lake Superior. Minimum and maximum velocities are -2.4 mm/year and 1.9 mm/year. Minimum and maximum elastic loading displacements are -2.0 cm and 1.6 cm. The difference in wind coefficients between all pairs of gauges vs the difference in gauge longitude (right) reveals a linear trend, indicating that the gradient in lake surface height due to wind driven topography is nearly constant across the lake.

Figure 5 shows the relative velocities and elastic displacements calculated for the gauges on Lake Superior. Without absolute dynamic heights, these relative motions are with respect to the mean lake level, which will also move in time. Nonetheless, these velocities and deformations show general trends that match expectations. Stations on the southern part of the lake are sinking with respect to those on the northern part, which agrees with general GIA trends. And elastic displacements reveal a spatial trend in which stations closer to the center of the GLB sink more due to water loading than those further away. A more complete analysis of relative velocities and elastic loading deformation is beyond the scope of this paper and will be completed once GNSS data and absolute heights becomes available.
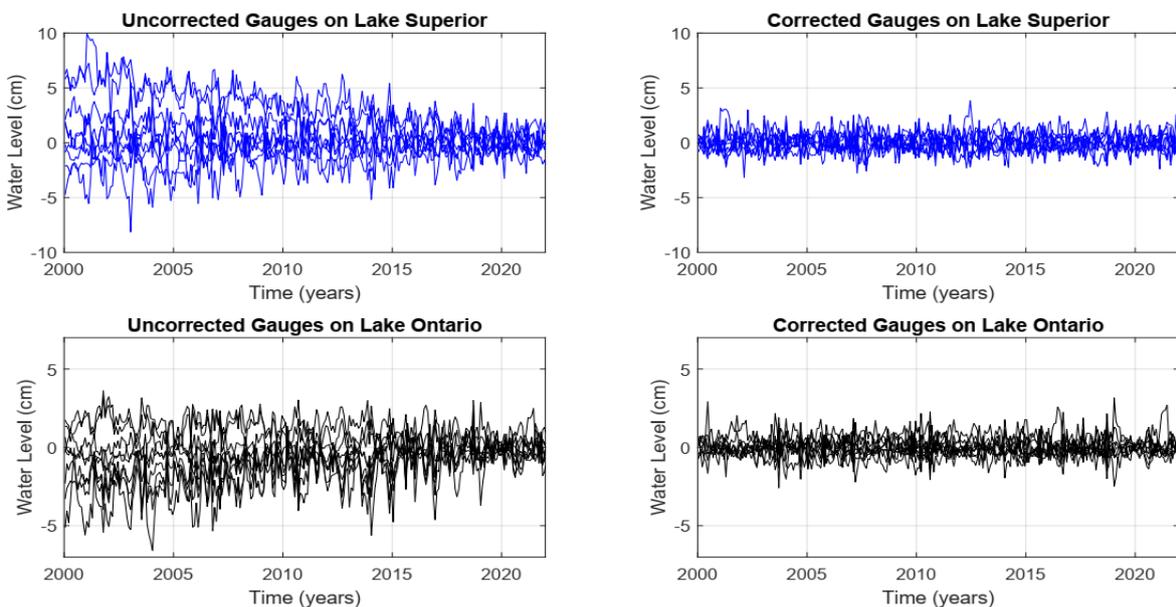
Figure 6 Uncorrected (left) and corrected (right) water gauge time series for gauges on Lake Superior (top) and Lake Ontario (bottom).

Figure 6 shows the uncorrected (left) and corrected (right) monthly deviations from mean lake level for the gauges on Lakes Superior (top) and Ontario (bottom). The mean deviation for 2020 has been removed for each gauge to highlight the divergence that occurs in the

uncorrected historical water levels due to relative vertical motion. The corrected signals do not suffer from this divergence and have significantly reduced short term variability due to the wind correction. The resulting corrected signals are stable through time and show a level of agreement that is at the cm level.

To quantify the level of agreement between the gauges, Table 1 presents a summary of the standard deviation (STD) between annually averaged water levels from gauge pairs on each Lake. For each Lake, we calculate the STD of the difference between all permutations of pairs of gauges on the Lake. Table 1 provides the minimum, maximum, and mean STD between the gauges. Essentially, these values represent the best, worst, and average agreement between gauges on the Lake. These values are calculated for four different scenarios. The first two scenarios consider the STD of the gauge differences over the 7-year period between 2015 and 2022 for the uncorrected and corrected water levels. The third and fourth scenarios consider the STD of the gauge differences over the 22-year period between 2000 and 2022, again for the uncorrected and corrected gauge water levels. In general, the results with the corrected gauges are almost always better - often significantly better. Furthermore, the uncorrected results from the 22-year time series are always worse than the 7-year time series. This is due to the divergence of the uncorrected signals in time, as shown in Figure 6. Unless relative motions are corrected, differences between gauges will continue to increase as the length of the time series increases. The results for the corrected signals are almost identical for both the 7-year and 22-year time series. This indicates that, once systematic trends are accounted for and removed, the level of background noise is stable over the 22-year time series (this is also seen in Figure 6).

Table 1 Minimum, maximum, and mean standard deviation (STD) of water level differences between all gauge pairs on each lake for annually averaged water levels (cm).

	Lake Superior			Lake Michigan			Lake Huron			Lake Erie			Lake Ontario		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
7 year	0.1	1.6	0.7	0.2	1.3	0.6	0.2	1.0	0.5	0.1	2.9	1.1	0.1	0.8	0.5
7 year Cor.	0.1	0.6	0.3	0.2	1.0	0.5	0.2	0.9	0.5	0.2	2.6	1.3	0.1	0.7	0.4
22 year	0.2	3.4	1.5	0.3	1.5	0.8	0.3	3.3	1.3	0.3	2.3	1.1	0.3	1.8	0.8
22 year Cor.	0.2	0.6	0.4	0.2	0.7	0.5	0.2	1.0	0.5	0.3	1.9	1.0	0.2	0.6	0.4

The 22-year time series offers more than 3 times the data available from the 7-year time series. As the noise levels have been demonstrated to be stable over time, averaging over the 22-year corrected time series should reduce the random errors in the mean water level by a factor of approximately $\sqrt{22/7} \sim 1.8$, compared to using the 7-year time series. Table 1 demonstrates that the average agreement between gauges on the Lakes, when considering

annual averages, is 0.5 cm or better for Lakes Superior, Michigan, Huron, and Ontario. Even for Lake Erie, with considerably more noise, gauges agree on average to the cm level. This level of agreement suggests that the mean water level for the gauges, when averaged over the 22 years of data, should provide mm level agreement and should not be a significant source of error in the determination of hydraulic correctors.

4. SUMMARY AND OUTLOOK

The Great Lakes are shared and administered jointly by the United States and Canada through treaties, commissions and committees. This is necessary for reasons including commerce, navigation, recreation and safety of life. The behavior of these waters is complicated by long term trends such as the continental scale Glacial Isostatic Adjustment tilting the Lake beds, to inter-seasonal variability of rainfall (flood and drought), to seasonal variations and ice formation, to short period fluctuations due to storms prevalently from the West. Modeling these is a complicated process, especially if dynamic heights are desired that are consistent with the intended new vertical datum for the surrounding land masses. Previous dynamic height datums were IGLD 55 and IGLD 85. IGLD 2020 is the newest datum and will derive from the North American-Pacific Geopotential Datum of 2022 (NAPGD 2022). This paper continues the analysis to determine if IGLD 2020 will need hydraulic correctors like IGLD 85 did.

Water level stations exist on both the U.S. and Canadian sides of the Lakes, where geodetic control determines the geometric coordinates of the water surface. A geopotential model can then be used to transfer this into dynamic heights. Any persistent dynamic height differences would indicate a water topography that would require hydraulic correctors to address.

For this analysis to occur, adjustment of GNSS and leveling data must be finalized. While it is not yet possible to assess the dynamic heights in an absolute datum, this paper has focused on a relative comparison of water level differences between stations and has taken into account the long period tilting due to GIA, the loading effects on individual Lakes and adjacent Lakes, and the effects of the prevailing winds. A formula was developed to describe these processes and observation equations formed to estimate the parameters involved. A model containing relative velocities, linear elastic deformation, and wind effects was found to explain all major discrepancies between gauges on the Great Lakes and demonstrated that, once these corrections were made, annual changes in Lake levels between gauges across the Lakes agree at the cm level.

An apparent slope exists from west to east on each Lake due to the effects of the westerly winds. If there is little to no wind, the Lake is flatter. If the wind is stronger, then the fetch over the Lake surface produces more water topography. As the prevailing winds blow primarily in one direction, this process does not have a zero mean effect and produces an average gradient across the Lakes. The preliminary assessment is then that some hydraulic correctors will be needed for IGLD 2020 to account for this. This will have to wait for the

final adjustments of the leveling and GNSS observations to properly assess the absolute height differences as the current analysis can only reveal relative differences. Then, with a model in hand, seasonal gauges that were occupied only for one year during the summer will be used to test the reliability of the models.

Additional work will also be to examine if ICESat-2 altimetry data can be used to model dynamic heights across the Lake surfaces. These will be stacked over many years to minimize seasonal and storm variations. This information may help to refine any hydraulic corrector model in between the limited set of water level stations on the Lakes as interpolation over those distances may not capture all of the signal variability.

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BIOGRAPHICAL NOTES

Daniel Roman graduated from the Ohio State University with a Master of Science in Geodetic Science and Surveying in 1993 and a Ph.D. in Geological Sciences (geophysics) in 1999. He then joined the National Geodetic Survey as a Research Geodesist leading geoid modeling efforts for 10 years. He served as Chief of Spatial Reference System Division for three years and as Chief Geodesist for seven years. He is now the Senior Leader for Geodesy involved in international collaboration and guiding U.S government agencies in implementing the new National Spatial Reference System for 2022.

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