Updating the International Great Lakes Datum: Enabling the Integration of Water and Land Management in the Great Lakes Region

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Key words: Vertical reference frames; Dynamic heights; Integrated land and water management

SUMMARY

The Great Lakes - St. Lawrence River system is one of the world's greatest freshwater resources and has important environmental, cultural and economic value for the United States and Canada. The use and management of these resources requires knowledge and measurement of water levels, depths, volumes and flows throughout the region. A fundamental requirement for coordinated management of this data is a common height reference system or vertical datum by which these measurements can be meaningfully related to each other. The International Great Lakes Datum (IGLD) is such a common height reference system that is defined and maintained under the auspices of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, a bi-national committee with representatives from the Governments of Canada and the United States.

The first IGLD datum was the International Great Lakes Datum of 1955 (IGLD (1955)) which was later updated to IGLD (1985). These datums used dynamic heights and were defined by spirit leveling, an expensive method susceptible to the accumulation of systematic errors. To ensure the datums can provide sufficiently accurate heights, they must be updated every 25-30 years to account for the effects of glacial isostatic adjustment (GIA) throughout the Great Lakes region. A new IGLD (2020) is now presently under development and planned for release in 2025. Unlike previous IGLDs, IGLD (2020) will use a geoid-based vertical datum referenced to a geometric reference frame that will be accessible using modern GNSS technology. This will provide the capability for millimeter-level measurements of water levels in support of safe navigation, regulation of waters & flows, lake level forecasting, hydroelectric power generation, and many other land and water management and development activities in the Great Lakes and St. Lawrence River region.

IGLD (2020) consists of four main attributes: (1) a reference zero equivalent to that already in use by the Canadian Geodetic Vertical Datum of 2013 and that being adopted for the new North American - Pacific Geopotential Datum of 2022 (NAPGD2022); (2) a realization of the reference surface (geoid model) that will also be equivalent to that being adopted for NAPGD2022 and referenced to its companion geometric datum, the North American Terrestrial Reference Frame of 2022; (3) a reference epoch of 2020.0 equal to the central epoch of the water level observation period (2017-2023); and (4) the use of dynamic heights for management of water levels. We discuss the efforts related to the development and implementation of IGLD (2020) and the new method of accessing the datum. We also briefly mention the evaluation and modeling of lake topography, referred to as hydraulic correctors.

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1. INTRODUCTION

The Great Lakes, located along the border between the United States and Canada, comprise the largest supply of surface freshwater in the world. Along with being the largest freshwater ecosystem in the world, this system is a vital resource for drinking water as well as agriculture, shipping, power generation, mining, timber and industry. This region supports a population of over 40 million people in 8 U.S. states (Minnesota, Wisconsin, Michigan, Illinois, Indiana, Ohio, Pennsylvania and New York) and 2 Canadian provinces (Ontario and Quebec). The five Great Lakes and their connecting channels flow out to the Atlantic Ocean through the St. Lawrence River.

Figure 1: The Great Lakes-St. Lawrence waterway.

Joint use of these waters by the people of Canada, the United States, First Nations and Native Americans requires internationally coordinated basic hydraulic and hydrologic data. The aptly named Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (Coordinating Committee) is responsible for this effort. The Coordinating Committee is an ad hoc group made up of experts from federal government agencies in Canada and the United States. It was formed in 1953 and is presently comprised of four subcommittees: Hydraulics, Hydrology, Regulation and Routing Model and Vertical Control-Water Levels (VCWL-SC). VCWL-SC is responsible for overseeing the maintenance of the International Great Lakes Datum (IGLD).

The IGLD is a common height reference system that provides a framework for water levels in the Great Lakes system to be meaningfully related to each other. Its definition consists of four main attributes: a reference zero, a realization of the reference surface (geoid model), a reference epoch and dynamic heights. IGLD is used in many applications, including those related to navigation, water management, shoreline use planning, outflow regulation, surveying and mapping. Due to vertical crustal motion resulting from glacial isostatic adjustment (GIA) since the end of the last ice age about 12,000 years ago (Mainville & Craymer, 2005), the IGLD needs to be updated every 25 to 30 years (see Figure 2).

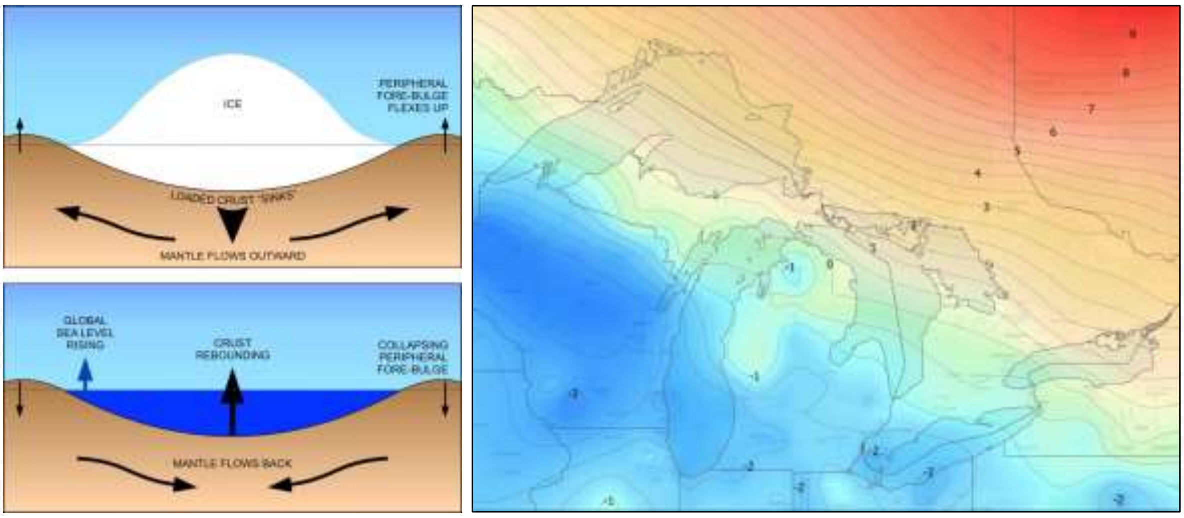

Figure 2: The process of glacial isostatic adjustment (GIA) and vertical velocities across the Great Lakes region in mm/yr as determined directly from high accuracy GPS measurements.

2. HISTORY OF IGLD

2.1 IGLD (1955)

While vertical datums in the Great Lakes date back to leveling work in the mid-19th century (Blust, 2015), the first joint datum between both countries was IGLD (1955) (Coordinating Committee, 1979). The reference zero was local mean sea level at the Pointe-au-Père, Québec tide gauge near the mouth of the St. Lawrence River, as observed over the period 1941–1956. This datum was established using spirit leveling and water level gauge observations collected over the 7-year period 1952–1958, with the middle reference epoch being 1955. The reference surface was determined by performing first-order leveling along the St. Lawrence River from

Pointe-au-Père to Lake Ontario and between each of the lakes along the rivers and interconnecting channels. Water level transfers between the termini of each lake were used to connect the leveled sections. Access to IGLD (1955) was through published elevations of bench marks.

IGLD (1955) and subsequent iterations of IGLD were the first datums in the Great Lakes to use dynamic heights. Dynamic heights are constant along a level or equipotential surface while orthometric heights are not. This makes dynamic heights essential in the determination of hydraulic head, an important quantity in the management of hydraulic and hydrological water systems like the Great Lakes.

2.2 IGLD (1985)

The Great Lakes datum currently in use is IGLD (1985) (Coordinating Committee, 1995). Like IGLD (1955), IGLD (1985) was realized using spirit leveling and sea level observations from a tide gauge at the mouth of the St. Lawrence River. Water level data collected between 1982 and 1988 were used in this case, with a reference epoch of 1985. The reference for the zero height was established using a combination of mean sea level data over the 1970-1988 tidal datum period first from the tide station located at Pointe-au-Père and then from a new station 5 km upstream at Rimouski, Québec, after the deterioration of the Pointe-au-Père station. The same reference zero is used for the North American Vertical Datum of 1988 (NAVD 88) which was developed in concert with IGLD (1985) (Zilkoski 1989). Although NAVD 88 was adopted as the national vertical datum of the United States, it was never adopted by Canada due to a tilt in the datum across the country. The systematic errors that build up in leveling over large distances resulted in a tilting of the datum of about 35 cm over the entire IGLD network from Pointe-au-Père to Thunder Bay on the northwest side of Lake Superior, at the head of the Great Lakes Basin.

IGLD (1985) is accessed through leveling from bench marks with published IGLD (1985) or NAVD 88 dynamic heights. Dynamic heights in IGLD (1985) are equivalent to dynamic heights in NAVD 88 except that so-called hydraulic correctors (HCs) are applied to the heights of water levels on lakes for the regulated management of water levels and flows. They are not applied on rivers or interconnecting channels, nor for benchmarks. The HCs are used to reduce the observed water level at each gauge on a lake to a surface representative of the master gauge on that lake. The HCs effectively make a lake appear flat.

Hydraulic correctors are determined by considering the water level of each Great Lake to be an equipotential surface, meaning that the geopotential value and dynamic height should be the same across the entire lake. This is not the case, however, due to variations in lake topography and the tilt in the NAVD 88 datum. The HC effectively makes the heights of the water levels at each gauge to be the compatible with that for a designated master gauge on each lake.

For a single lake, the HC at a water level station is estimated from the difference of the mean water level over the 7 year observation period centered at the 1985 reference epoch (MWL_{sub}), and the mean water level of a designated master station for the lake (MWL_{master}); i.e.,

$$HC = MWL_{sub} - MWL_{master} \tag{1}$$

HCs have been determined and published for each water level station on a lake with respect to its master station. Values range from 0 to +6 cm on Lake Ontario and -10 to +8 cm on Lake Superior, where their effect is greatest (see Figure 3).

IGLD dynamic height information is available from databases in both Canada and the U.S. Hydraulic correctors used for water levels can also be predicted and applied to dynamic heights using a model of HCs (Milbert, 2002).

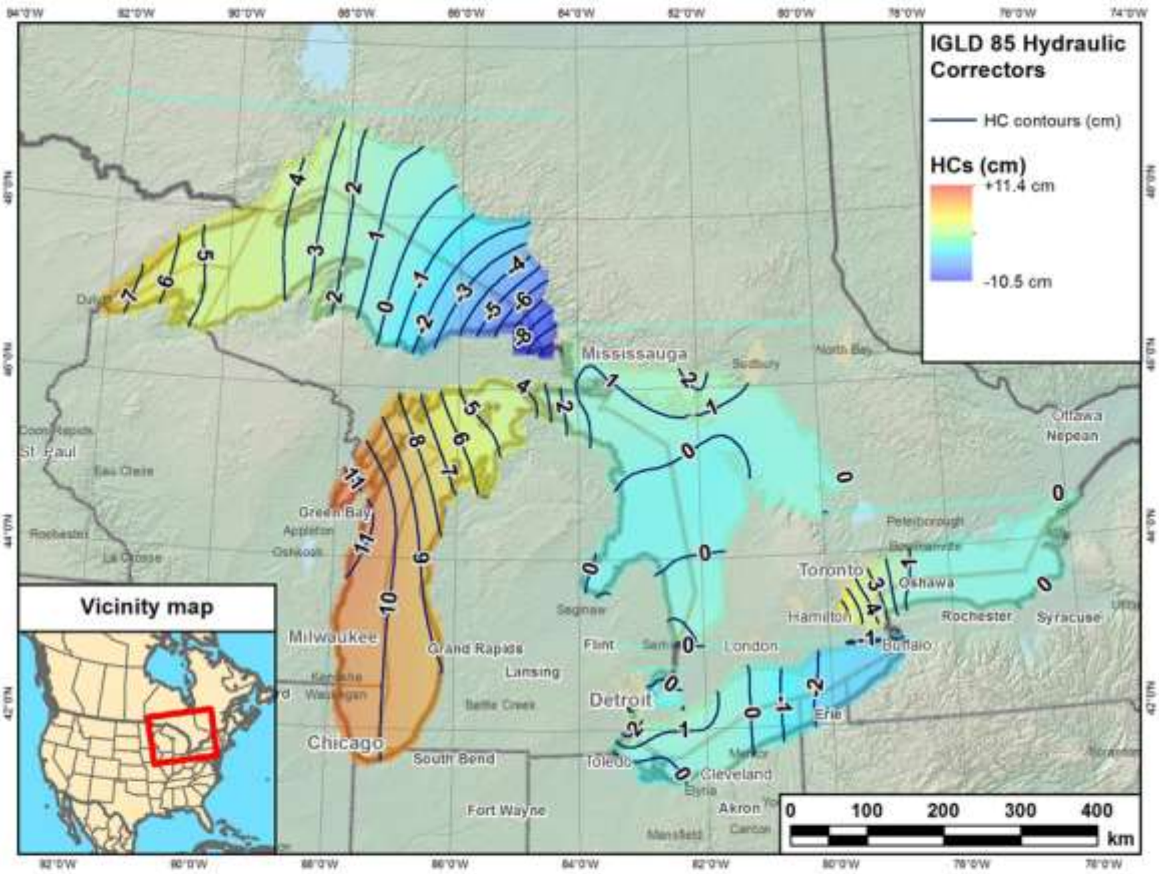

Figure 3: Magnitudes of hydraulic correctors in IGLD (1985).

3. IGLD (2020) DEVELOPMENT

Due to ongoing crustal motion driven by GIA, the IGLD needs to be updated every 25-30 years. Although originally planned for 2015, the updating of IGLD (1985) was delayed to 2020 primarily because of three issues: (1) the extreme low water conditions during the beginning of the 2012-2018 water level observation period, (2) the expected implementation of a new North American vertical datum in 2022 (now delayed), and (3) a lack of available funding (Coordinating Committee, 2017). The datum is now in development and is expected to be released in 2025. Unlike the previous two IGLDs, this datum update will use a geoid-based vertical datum that will be accessible using GNSS techniques.

3.1 Definition of IGLD (2020)

Four attributes will define IGLD (2020): (1) a reference zero as the base elevation for heights, (2) a realization of the reference surface (geoid model) aligned to the reference zero, (3) a reference epoch, and (4) dynamic heights.

3.1.1 Reference Zero

For IGLD (2020) the Coordinating Committee has adopted the same geopotential value (W_0) as the reference zero that the U.S. and Canada have adopted for the new geoid-based North American-Pacific Geopotential Datum of 2022 (NAPGD2022) (NGS, 2021a). The common W_0 value of 62,636,856.00 m^2/s^2 was chosen to closely approximate mean sea level around the coasts of North America and results in a surface 31 cm higher than the mean sea level used for IGLD (1985). The W_0 coincides with the value used for the existing geoid-based Canadian Geodetic Vertical Datum of 2013 (CGVD2013) and thus CGVD2013 is defined in exactly the same way that both IGLD (2020) and NAPGD2022 will be. This W_0 value differs from the IAG-adopted value for the International Height Reference System (62,636,853.4 m^2/s^2). That value more closely approximates global mean sea level.

3.1.2 Realization of the Reference Surface

The reference surface for IGLD (2020) will be a geoid model that represents the reference zero everywhere over the Great Lakes – St. Lawrence River system and not only where leveling and bench marks exist. The geoid is an equipotential surface that can be determined both consistently and accurately on continental scales. It is defined in relation to a reference ellipsoid, making it more compatible with space-based positioning technologies such as GNSS and satellite radar altimetry. Use of modern GNSS measurement techniques is far more efficient in terms of cost, effort, and accuracy. IGLD (2020) will use the same geoid being developed for NAPGD2022 and be aligned to the same W_0 geopotential value as CGVD2013, resulting in complete compatibility among vertical datums across North America. It is expected that Canada will also update its realization of CGVD2013 using the new North American geoid that will be referred to as GEOID2022.

3.1.3 Reference Epoch

IGLD (2020) will have a reference epoch of 2020.0. This is expected to coincide with the next realization of the global International Terrestrial Reference Frame that the new North American Terrestrial Reference Frame of 2022 (NATRF2022) will be based on. It is also the central epoch of the 7-year water level observation period of 2017–2023. Data for this period from water level stations around the Great Lakes will be used in analyzing the surface topography of each lake for the possible determination of hydraulic correctors (see below).

3.1.4 Dynamic Heights

As with previous versions of the International Great Lakes Datum, IGLD (2020) will use dynamic heights instead of orthometric heights traditionally used for elevations on land. Figure 4 illustrates the difference between orthometric and dynamic heights. The dynamic height represents the difference in potential above the reference surface and is the same at all points on a level surface. Orthometric height represents the actual physical distance above the reference surface which may change due to differences in gravity caused by the convergence of equipotential surfaces toward to the poles. Dynamic heights are therefore required for the proper management of water levels and flows in compliance with international regulations and treaties.

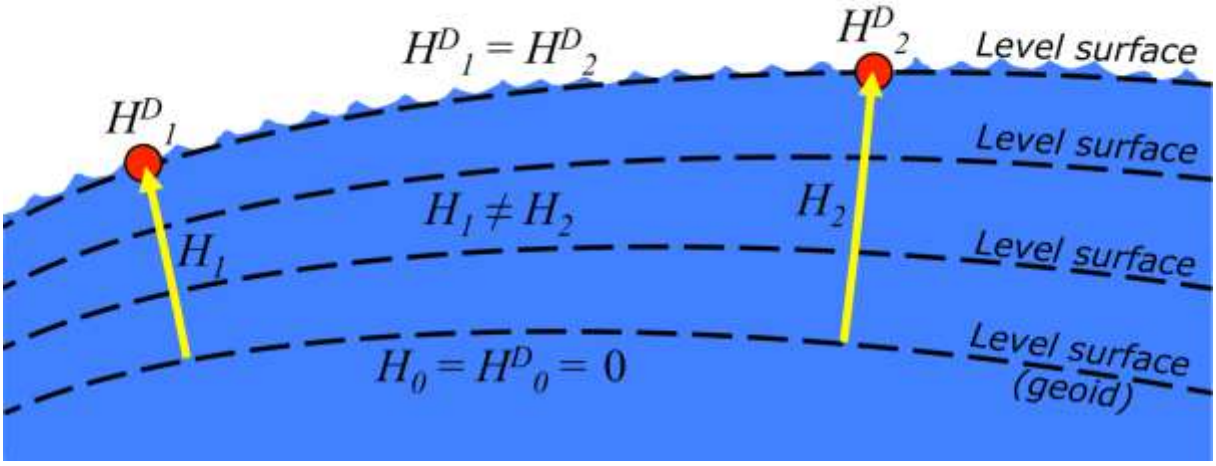

Figure 4: Dynamic heights, H^D*, and orthometric heights,* H*.*

Both dynamic and orthometric heights are fundamentally based on geopotential numbers (C), which are the difference in gravitational potential measured from a reference surface (geoid) to the equipotential surface passing through a point on the surface of the Earth. Differences in gravitational potential are what determine the flow of water. However, the units of potential numbers (kGal m = 10 m^2/s^2) are not easily understood. Consequently, for practical purposes, potential numbers are scaled by gravity (gravitational acceleration) to give units of distance that are more readily understood.

Orthometric height (H) is the geopotential number divided by the mean value of gravity ($\bar{g}$) between the geoid and the point measured along the plumb line:

$$H = \frac{C}{\bar{g}} \tag{2}$$

Mean gravity is estimated from the surface gravity value g at that location using the well-known Helmert height reduction formula:

$$\bar{g} = g + 0.0424 * H \tag{3}$$

Both Canada and the U.S. have existing gridded models of surface gravity with sufficient accuracy to use in the conversion from orthometric to dynamic heights. A common North American gravity grid (GRAV2022) will also be developed as part of the work on NAPGD2022. Because gravity on an equipotential surface is not constant over large areas, neither are orthometric heights.

Dynamic height, H^D, is the geopotential number divided by normal gravity at 45 degrees latitude, γ_{45}, which has a constant value of 980.6199 gals = 9.806199 m/s^2 as used for IGLD (1985):

$$H^D = \frac{C}{\gamma_{45}} \tag{4}$$

Because normal gravity is a constant, dynamic heights are just a scaled version of geopotential numbers, expressed in linear units proportional to the geopotential, they are constant along an equipotential surface. Consequently, dynamic heights are especially useful in hydrologic and hydraulic systems like the Great Lakes because only differences in dynamic heights can provide a direct measurement of the hydraulic head between locations which is critical for water management and power generation.

The significant tilting of the datum in NAVD 88 and IGLD (1985) will not be an issue for the geoid-based IGLD (2020). And because a major component of the hydraulic correctors in IGLD (1985) represented the tilt in NAVD 88, it is expected that if hydraulic correctors are used in IGLD (2020), they will be much smaller than in IGLD (1985) and more representative of the lake topography.

3.2 Realization of IGLD (2020)

Previous realizations of IGLD used spirit leveling to determine orthometric heights at a network of thousands of bench marks. Unfortunately, spirit leveling is a laborious, cost prohibitive, time-consuming and error-prone process. Although spirit leveling is very accurate over shorter distances, modern GNSS methods using an accurate geoid model has many advantages over leveling.

Instead of running spirit leveling circuits around the lakes to determine heights between bench marks located at water level gauges, as was done for the development of previous IGLDs, IGLD (2020) will be realized by GNSS observations at GNSS bench marks at all permanent and seasonal water level stations in the Great Lakes and St. Lawrence River system. Originally planned for 2020, this major survey campaign has been postponed twice due to travel restrictions arising from the global pandemic. The campaign is now planned for the summer of 2022.

The velocity model will be based on continuous GNSS observations from the NOAA Continuously Operating Reference Station (CORS) Network (NCN) in the U.S. and the Canadian Active Control System (CACS) network in Canada. In addition, the high-accuracy GNSS survey campaigns on bench marks at the permanent water level stations throughout the Great Lakes region in 1997, 2005, 2010 and 2015 will be used to improve model of crustal motion throughout the region. After the major campaign in 2022, a follow up campaign is planned for 2025 or 2026.

Water level data will also be collected at 230 permanent and season water level gauges during the 7-year observation period of 2017–2023. This data will be used to determine mean water levels across the lakes to assess the magnitude of lake topography and the need for hydraulic correctors in IGLD (2020).

4. DETERMINING HEIGHTS IN IGLD (2020)

In previous realizations of IGLD, spirit leveling was used to determine geopotential numbers which were converted directly to orthometric heights that could then be converted to dynamics heights using equation 4.

In the geoid-based IGLD (2020), heights will be primarily determined through GNSS techniques which provide a direct measure of ellipsoidal height. Although spirit leveling is more accurate over shorter distances, GNSS methods combined with an accurate geoid model are capable of providing more accurate heights over moderate to longer distances at a small fraction of the cost of leveling.

An orthometric height, *H*, above the geoid is obtained from a GNSS-derived ellipsoidal height, *h*, above the reference ellipsoid using the geoid height or undulation, *N*, of the geoid above the reference ellipsoid. This is represented by the simple equation:

$$H = h - N \tag{5}$$

Using equations (2) - (5), the dynamic height can be obtained from the GNSS-derived ellipsoidal height using:

$$H^D = \frac{\bar{g} * (h - N)}{\gamma_{45}} \tag{6}$$

For IGLD (2020), the geoid height, *N*, will be provided by GEOID2022 which will be used to define NAPGD2022 and the expected update to CGVD2013. IGLD (2020) dynamic heights will therefore be equivalent to dynamic heights in NAPGD2022 and CGVD2013 at the 2020 reference epoch. For IGLD (2020) heights of water levels, hydraulic correctors may also need to be applied.

An important advancement in the development of the new IGLD and North American datums will be the availability of an accurate crustal velocity model that can propagate ellipsoidal heights between different reference epochs. This will enable heights determined at any epoch to be propagated back to the adopted 2020 reference epoch used for IGLD (2020). This will effectively obviate the need to update the entire IGLD datum for the effects of GIA for a much longer period of time, except for incremental improvements to the velocity model and updates to the reference epoch.

5. SUMMARY

The International Great Lakes Datum provides a framework for water level management in the world’s foremost resource of surface freshwater. The current datum, IGLD (1985), is being updated and replaced by IGLD (2020). This updated datum will be fundamentally different in terms of definition and access to the datum. The datum will be identical to the new NAPGD2022 North American geopotential datum and will be compatible with the existing CGVD2013 (if not identical as well) at the reference epoch of 2020. IGLD (2020) is expected to be released in 2025 at about the same time as NAPGD2022. Access to both frames will be primarily through GNSS techniques. This will lead to more consistent heights across the entire Great Lakes region. Further information about the IGLD update can be found on the Coordinating Committee website at http://GreatLakesCC.org.

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BIOGRAPHICAL NOTES

Jacob Heck is a geodesist at the U.S. National Geodetic Survey within the National Oceanic and Atmospheric Administration (NOAA), where he serves as the Great Lakes Regional Geodetic Advisor. He holds a Ph.D. in Geodetic Science from The Ohio State University and a B.Sc. in Surveying Engineering from Michigan Technological University. He is a member of the Vertical Control - Water Levels Subcommittee of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

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