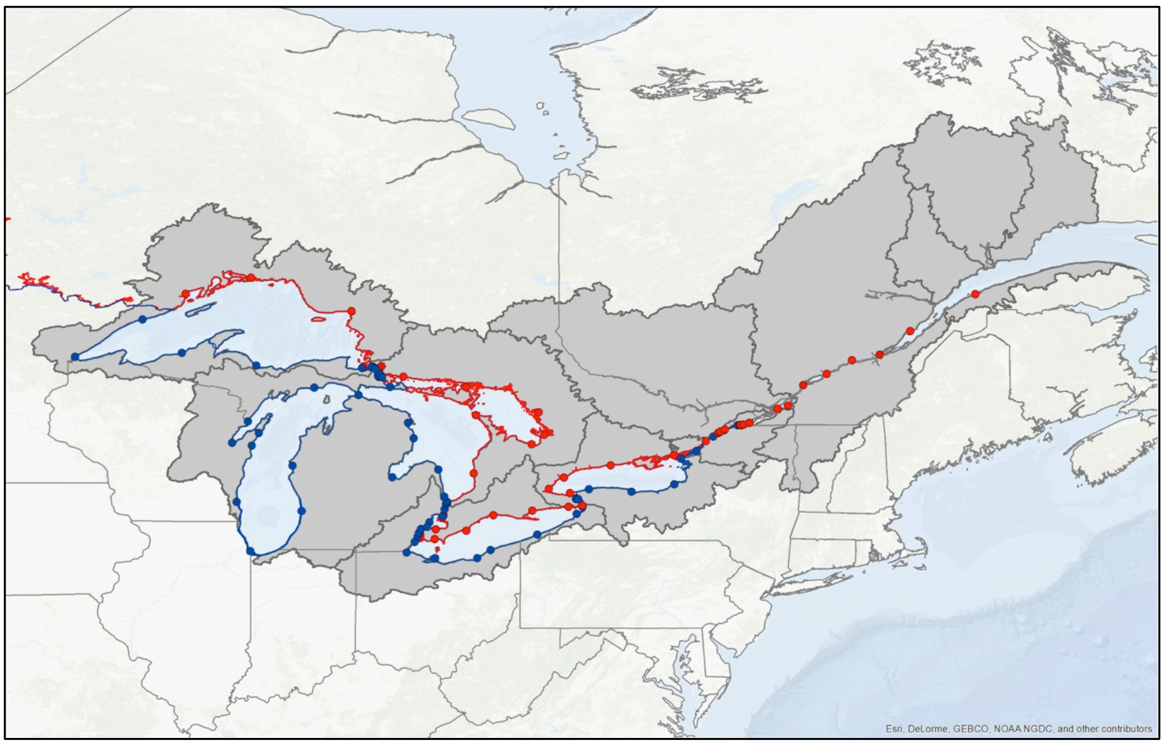
Coordinating Committee on Great Lakes
Basic Hydraulic & Hydrologic Data

Updating the International Great Lakes Datum (IGLD)



Prepared by the
Vertical Control – Water Levels Subcommittee
on behalf of the
Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data

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Executive 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 Canada and the United States. The Great Lakes have long been an economic driver for both nations ($180 billion in Canada-U.S. trade). An analysis found that more than 1.5 million jobs are directly connected to the Great Lakes, generating $62 billion in annual wages. The Midwest has recently suffered economic hardships but, thanks to the Great Lakes, the region still generated 27% of the U.S. gross domestic product and 24% of the country's exports in 2009. It is estimated that marine shipping on the Great Lakes moves 164 million metric tons of essential raw materials and finished products annually. A slight decrease in the depth of a waterway means that a vessel must decrease its draft (i.e., reduce the amount of cargo that it's carrying). The Great Lakes Information Network estimates that a 1,000-foot vessel will need to reduce its cargo by about 270 tons for each inch decrease in its draft (a 300-m vessel needs to reduce its cargo by 100 tons for each centimeter decrease in draft).

Use of Great Lakes freshwater resources by the people of Canada, the United States, First Nations and Native Americans, requires knowledge and measurement of water levels, depths, volumes and flows throughout the region. The joint, harmonious use of these waters requires international coordination of many aspects of their management. The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (Coordinating Committee) is an *ad hoc* committee of experts from Federal agencies of the United States and Canada that is responsible for coordinating the collection, compilation, use, and dissemination of data related to hydraulics, hydrology, vertical control and water levels for the Great Lakes – St. Lawrence River System. A fundamental requirement for coordinated management is a common height reference system or "vertical datum" by which water levels can be measured and meaningfully related to each other. The first such common datum was the International Great Lakes Datum of 1955 (IGLD (1955)), later updated to IGLD (1985). To ensure that the vertical datum can provide sufficiently accurate heights, it must be adjusted every 25-30 years to account for the effects of glacial isostatic adjustment (GIA) described below.

Presently the Coordinating Committee is undertaking the development of the next IGLD, referred to here as IGLD (2020). This document outlines the scope of work involved. The Vertical Control-Water Levels Subcommittee of the Coordinating Committee is overseeing this important work. Unlike the previous two IGLDs, this datum update will use a geoid-based vertical datum that will be accessible using global navigation satellite systems (GNSS) such as the Global Positioning System (GPS). The same GNSS used for diverse applications that include navigation of ships, aircraft, spacecraft, and ground vehicles, is employed to monitor millimeter-level shifts of the Earth's surface. GNSS technology will also provide the capability for millimeter-level measurements of water levels in support of safe navigation, regulation, lake level forecasting, international cooperative treaties and agreements, riparian interests, hydroelectric power generation, construction, dredging, litigation, and many other environmental, water resources management and development activities. The water level datum

(IGLD) and gauge infrastructure are key components to both nations' transportation and logistics network information. A reliable port and inland waterway system ensures that commercial goods can move quickly, affordably, and safely to facilitate trade and benefit the economies of both countries.

The International Great Lakes Datum update will consist of four main attributes:

> Reference Zero: The reference zero for a vertical datum is usually some determination of mean sea level. For IGLD (2020) the Coordinating Committee has adopted the same reference zero that the U.S. and Canada have adopted for the new geoid-based North American vertical datum expected to be implemented in 2022.
>
> Reference Surface (Equipotential Surface): For both IGLD (1955) and IGLD (1985), the reference surface was determined from elevations on bench marks established using a network of geodetic leveling loops anchored to the reference zero at Pointe-au-Père, Québec. Although geodetic leveling remains very precise locally, it cannot achieve the accuracy required for present and expected future applications on regional and national scales. Distortions in IGLD (1985) arise from systematic errors in the NAVD 88 leveling network that accumulate in a tilting of the datum of about 35 cm over the entire network from Pointe-au-Père to Thunder Bay. Furthermore, geodetic leveling is cost prohibitive, time consuming, laborious, and error prone. Consequently, Canada and the U.S. are redefining their national vertical reference systems using a geoid as a reference surface for the datum. The geoid is a stable surface that can be determined both consistently and accurately across the entire continent. 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. Canada has already adopted a geoid for their Canadian Geodetic Vertical Datum of 2013. The U.S. is expected to adopt a North American geoid for their new vertical datum in 2022 and Canada is expected to update their datum to the new N.A. geoid. It is recommended to adopt the same N.A. geoid as the reference surface for the new IGLD (2020) to maintain consistency with the national vertical datum in both Canada and the U.S.
>
> Reference Epoch: IGLD (2020) will use a base water level observational period of 2017–2023 with a central water level reference epoch of 2020. In addition to a reference epoch for water levels, heights in the new IGLD (2020) will also need to be referenced to a common epoch because of the effects of crustal motion. It is expected the same 2020 epoch will be used.
>
> Dynamic Heights: Knowledge of the hydraulic head in the Great Lakes system is critical for water level management and power generation. Traditional orthometric heights do not provide a measure of hydraulic head while dynamic heights do. Dynamic heights therefore need to be used on all large bodies of water in the Great Lakes Basin, their connecting channels, and the St. Lawrence River. Dynamic heights are geopotential numbers scaled by a constant value of gravity, allowing them to be expressed in units of distance proportional to the geopotential and providing a direct indication of hydraulic

head between locations. It needs to be ascertained how accurately dynamic heights can be determined in a geoid-based datum. Because gravity values are used in the process of determining dynamic heights, it also needs to be determined if new surface gravity measurements will be required or if the interpolation of existing gravity measurements will be sufficiently accurate.

In addition, the following issues related to the development and implementation of a new IGLD need to be resolved:

Hydraulic Correctors: The water surfaces within each of the Great Lakes are considered geopotentially equal and, therefore, the dynamic height of the mean water level on a particular lake should be the same everywhere. However, due to variations in lake topography and errors in leveling, this is not the case in practice. Hydraulic correctors are used to account for these variations and errors by adjusting the observed water level heights at gauging stations on a lake so they agree with each other over a given time period. Errors in height are expected to be much smaller for a more accurate, geoid-based vertical datum, resulting in hydraulic correctors that will be both smaller and more representative of actual lake topography than they have been in the past. Whether or not hydraulic correctors are still required for IGLD (2020) needs to be determined. This will require water level observations at additional (seasonal) gauges, the location and number of which also needs to be determined.

Crustal Motions and Their Effect on Heights: It is a well-documented fact that crustal movement due to GIA affects the Great Lakes region. The northern parts of the Great Lakes Basin are uplifting while the southern parts are subsiding, representing an overall north-south tilting of the entire basin of about 5–7 mm/yr. After a few decades height differences become out of date by as much as 21 cm over the entire basin, thereby necessitating a redefinition of the heights and IGLD in general. To determine these movements, permanent GNSS stations (referred to as Continuously Operating Reference Stations (CORS) in the U.S. and Canadian Active Control Stations (CACS) in Canada) have been installed at key permanent water level gauging stations. Realizing that it takes several years to obtain an accurate estimate of the vertical motion, such new sites should be installed in targeted locations at the earliest opportunity to obtain accurate velocity estimates as soon as possible to improve the modeling of GIA. To determine GIA movements at all of the other permanent water level gauges, specially designed, high-accuracy GPS campaign-style surveys have been performed in 1997, 2005, 2010, and 2015. A new GNSS survey is planned for 2020 to coincide with the central epoch of the new IGLD. Comparing repeated, high-accuracy, GNSS-derived ellipsoid heights can provide further estimates of crustal movement (velocities) at the reference bench marks. Using the velocity estimates from the CORS, CACS and campaign surveys, it will be possible to model the crustal motion and propagate heights to an adopted common reference epoch. It will also be possible to update the heights to future reference epochs to keep pace with the crustal motion. This will require the development of procedures and algorithms for using vertical rates of movement for projects that require high-accuracy heights.

Determining Heights in a Geoid-Based Datum: GNSS-based height determination in a geoid-based datum has been widely used for many years and can provide high-accuracy heights and height differences in a more efficient and cost-effective manner than traditional geodetic spirit leveling. This enables one to achieve more consistent and accurate heights on water level gauges and their reference bench marks across the entire region. Permanent GNSS stations (CORS and CACS) have been installed at many key water level stations. Such stations are connected directly to the same structure as the gauge reference, enabling the accurate (millimeter-level) determination of the absolute heights of water levels without the adverse effects of any local movements of the reference bench mark network. They also provide more accurate estimates of crustal motion and enable more accurate GNSS-surveys at nearby gauges. The network of CORS and CACS will need to be maintained and further expansion needs to be considered. The heights on all permanent and seasonal water level gauges and their reference bench marks need to be determined using GNSS-style survey campaigns. Appropriate internationally coordinated survey methodologies also need to be determined to achieve the required accuracies in the new IGLD. In addition to GNSS surveys at the permanent water level stations, additional surveys will also be required for the seasonal water level stations. In future it is envisaged that all water level gauges will use permanent GNSS installations to determine the height of the gauge reference points (e.g., ETG or gnomon) in near real-time without the need for any reference bench mark network and its regular monitoring. It is expected this would reduce operational costs in the long term while enabling more accurate determinations of water levels, in addition to any crustal motion.

Updating Low Water Datum: The LWD (or chart datum) is the geopotential elevation for each of the Great Lakes, their connecting channels, and St. Lawrence River to which the depths shown on navigational charts and the authorized depths for navigation improvements are referred. By definition, LWD is supposed to identify a surface so low that the water level will seldom fall below it. The historical record of water levels has not been reviewed in the context of re-evaluating LWD since their original determination in 1933. Since then, the Great Lakes region has experienced historically high and low water levels. Considerable changes to water level regulation plans, as well as hydraulic and hydrologic conditions, have left in question the suitability of the existing LWD determination for present-day and future use. Re-evaluating the determination of LWD on each lake is therefore recommended, along with the LWD steps along interconnecting channels and the St. Lawrence River.

Other Impacts of a New IGLD: In addition to updating the Low Water Datum, the establishment and implementation of a new IGLD will have a significant impact on a great many other operations, products and services, including navigation, water level regulation, water management, shoreline use planning, surveying, and mapping (see the Great Lakes Commission Resolution on the IGLD Update in Appendix 1). A list of some of these impacts is given in Table 1 of Section 3.3. An outreach plan will need to be constructed to prepare for and mitigate the effects of an updated IGLD. Two of the most important impacts are the updating and determination of low water datum discussed above and the determination of IGLD (2020) heights at the many gauge references other than those operated by the National Oceanic and Atmospheric Administration and Canadian Hydrographic Service through their inclusion in the 2020 GNSS survey campaign.

Transforming Between IGLD (2020) and Other Datums: There are many products using the older IGLD and other datums that will need to be updated to IGLD (2020). In many cases, it will not be possible to regenerate such products in the new datum without collecting new data. In cases where it is not possible to collect new data, transformation models and tools will be required to update these products to IGLD (2020). This task will require heights at common points in both the new and old datums in digital form.

Resource Requirements: A wide range of resources, knowledge, and skills will be needed to develop and implement IGLD (2020). These are identified in the body of the report for the activities involved and summarized in Table 1 below. GNSS data will need to be collected at all permanent and prioritized seasonal gauges. Additional funding may also be required to address some of the outstanding questions identified above. Personnel resources will be required from the geodetic and water management agencies in both countries to complete the analysis and research required for the update to IGLD (2020).

Outreach: A significant amount of coordinated outreach will be needed in relation to the update. Coordinating Committee member agencies will need to inform and educate stakeholders of the IGLD update and its impact through such means as publications, webinars, etc. A collaborative outreach and communication strategy needs to be developed by the Coordinating Committee to ensure that these stakeholder groups are identified and included.

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List of Abbreviations

BM	Bench mark
CACS	Canadian Active Control System
CCG	Canadian Coast Guard
CGG2013	Canadian Gravimetric Geoid of 2013
CGS	Canadian Geodetic Survey
CGVD2013	Canadian Geodetic Vertical Datum of 2013
CHS	Canadian Hydrographic Service
CO-OPS	Center for Operational Oceanographic Products and Services
CORS	Continuously Operation Reference Stations
CSDL	Coast Survey Development Laboratory
DFO	Fisheries and Oceans Canada
ECCC	Environment and Climate Change Canada
GIA	Glacial isostatic adjustment
GIS	Geographic Information System
GLAM	Great Lakes – St. Lawrence River Adaptive Management
GLC	Great Lakes Commission
GLERL	Great Lakes Environmental Research Lab
GNSS	Global navigation satellite system
GPS	Global Positioning System
GRS80	Geodetic Reference System of 1980
HC	Hydraulic corrector
HWL	High water line
IGLD	International Great Lakes Datum
IJC	International Joint Commission
LWD	Low water datum
MWL	Mean water level
NAVD 88	North American Vertical Datum of 1988
NGS	National Geodetic Survey
NHS	National Hydrologic Services
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
OCM	Office of Coastal Management
OCS	Office of Coast Survey
OHWM	Ordinary high water mark
SLSDC	U.S. St. Lawrence Seaway Development Corporation
SLSMC	Canadian St. Lawrence Seaway Management Corporation
TCARI	Tidal Constituent and Residual Interpolation
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

1. Introduction

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 Canada and the United States. Today, the system boasts an extensive urban area with some 44 million Americans and Canadians. The Great Lakes stretch about 3,766 km (2,340 miles) and the shoreline totals 17,017 km (10,210 miles) – longer than the U.S. East and Gulf coasts combined. In combination, the Great Lakes have a surface area of 245,759 square km (94,000 square miles), most of which is navigable. Their water volume, 22,809 cubic km (5,500 cubic miles), is enough to submerge the continental United States in over 2.9 m (9.5 feet) of water. This gives the Great Lakes the distinction of being Earth's largest single supply of surface fresh water. The five lakes possess 90% of the U.S. surface fresh water supply, 21% of the world's supply, and provide drinking water to one-third of all Canadians.

The Great Lakes have long been an economic driver for both nations ($180 billion in Canada-U.S. trade). An analysis found that more than 1.5 million jobs are directly connected to the Great Lakes, generating $62 billion in annual wages. The Midwest has recently suffered economic hardships but, thanks to the Great Lakes, the region still generated 27% of the U.S. gross domestic product and 24% of the country's exports in 2009. Eleven percent of all water withdrawn from the Great Lakes Basin is for industrial uses. It is estimated that marine shipping on the Great Lakes moves 164 million metric tons of essential raw materials and finished products annually. A slight decrease in the depth of a waterway means that a vessel must decrease its draft (i.e., reduce the amount of cargo that it's carrying). The Great Lakes Information Network estimates that a 1,000-foot vessel will need to reduce its cargo by about 270 tons for each inch decrease in its draft (a 300-m vessel needs to reduce its cargo by 100 tons for each centimeter decrease in draft).

The Great Lakes Basin also constitutes the largest freshwater ecosystem in the world. The basin is home to 3,500 species of plants and animals and over 170 species of fish. These flora and fauna not only contribute to the environmental integrity, resilience, and character of the region, they also support impressive Great Lakes tourism and recreation industries. Residents and tourists alike spend nearly $16 billion annually on boating trips and equipment in the Great Lakes, and the region draws an impressive 37 million anglers, hunters, and bird watchers each year. The Great Lakes' beauty and ecological diversity belie their vulnerability to biological and chemical stresses. In reality, years of degradation from toxic contamination, destruction of coastal wetlands, nonpoint source pollution, and invasive species have left the ecosystem at a tipping point. In many areas of the Great Lakes Basin, 50% to 90% of coastal wetlands have been lost due to development, pollution, invasive species, water level fluctuations, and climate change impacts.

Use of these Great Lakes resources by the people of Canada, the United States, First Nations and Native Americans, requires knowledge and measurement of water levels, depths, volumes and flows throughout the region. The joint, harmonious use of these waters requires international coordination of many aspects of their management. The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (Coordinating Committee) is an ad hoc committee of experts from Federal agencies of the United States and Canada that is responsible for coordinating the collection, compilation, use, and dissemination of data related to hydraulics, hydrology, vertical control and water levels for the Great Lakes – St. Lawrence River System. A fundamental requirement for coordinated management is a common height reference system or "vertical datum" by which water levels can be measured and meaningfully related to each other.

The first common vertical datum between Canada and the United States was the International Great Lakes Datum of 1955 (IGLD (1955)) (Coordinating Committee, 1979). It is recognized that, over time, the vertical datum may need to be updated due to wide-ranging and significant physical changes. In the Great Lakes region, the dominant physical change is one of ongoing vertical crustal movement. The crustal movement is in response to the loss of the weight of the ice sheets and the collapse of the glacial fore-bulge since the last ice age, a process known as glacial isostatic adjustment (GIA). As a result, there is land uplift in the northern areas of the Great Lakes – St. Lawrence River Basin and subsidence in the southern areas, which directly influence the observed water levels. In order to keep pace with the rates of movement of the Earth's crust, the vertical datum used to define water levels within the basin must be adjusted every 25 to 30 years (Coordinating Committee, 1995).

The current datum is known as the International Great Lakes Datum of 1985 (IGLD (1985)) (Coordinating Committee, 1995). Although originally planned for 2015, the updating of IGLD (1985) was delayed to 2020 because of the extreme low water conditions during the beginning of the 2012-2018 water level observation period, the expected implementation of a new North American vertical datum in 2022 and a lack of funding. As described in this report, IGLD (1985) will be updated over the course of the 2017-2023-time period, with an expected release date of 2025.

The International Great Lakes Datum consists of four main attributes:

> <u>Reference Zero</u>: The reference zero for a vertical datum is usually some determination of mean sea level; i.e., heights above mean sea level. Mean sea level can be determined in various ways, from that determined at a single tide gauge (local sea level) to an average from many gauges (regional, continental, or global sea level). For IGLD (1955), the reference zero was local mean sea level established at the tide gauge at Pointe-au-Père, Québec near the mouth of the St. Lawrence River using observations from 1941 to 1956. For IGLD (1985), the reference zero was established using a combination of mean sea level data from a time period between 1970 and 1988 (a tidal datum epoch) from the gauge at Pointe-au-Père and a newer station 5 km upstream at Rimouski, QC (Coordinating Committee, 1995). This was necessary due to the deterioration of the gauge at Pointe-au-Père. The bench marks at these stations were connected using first-order leveling. For IGLD (2020) the Coordinating Committee has adopted the same reference zero that is equivalent to the mean sea level from tide gauges around the coasts of North America. Canada has adopted this value for its Canadian Geodetic Vertical Datum of 2013 (CGVD2013) datum, and both the U.S. and Canada plan to adopt it for

the new North American vertical datum in 2022 (see Appendix 1). This reference zero is approximately 31 cm above the mean sea level at Pointe-au-Père used for IGLD (1985).

Reference Surface (Equipotential Surface): The vertical reference surface is the equipotential (level) surface passing through the reference zero; i.e., it is an extension of the reference zero over a region. For both IGLD (1955) and (1985), the reference surface was determined from elevations on bench marks established using a network of geodetic leveling loops from the reference zero at Pointe-au-Père up the St. Lawrence River and around the entire Great Lakes Basin and back. Although geodetic leveling remains very precise locally, it cannot achieve the accuracy required for present and expected future applications on regional and national scales. Distortions in the present North American Vertical Datum of 1988 (NAVD 88) and, consequently IGLD (1985), arise from systematic errors in the leveling network and accumulate in a tilting of the datum that amounts to 35 cm between Pointe-au-Père and Thunder Bay, Ontario, as determined from comparisons with the more accurate, geoid-based CGVD2013 datum (see Figure 1).

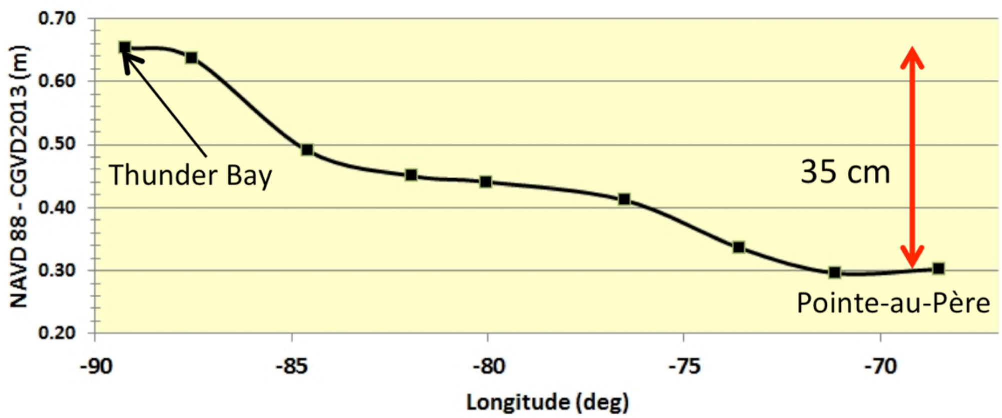

Figure 1. Errors in NAVD 88 heights as determined from comparisons with heights in the more accurate, geoid-based CGVD2013 along a mainly east-west leveling profile from Pointe-au-Père, Québec to Thunder Bay, Ontario. IGLD (1985) hydraulic correctors somewhat compensate for these errors around individual lakes.

Furthermore, the maintenance and re-observation of the vertical network by geodetic leveling is cost prohibitive, time consuming, laborious and remains error-prone over long distances. Consequently, the Canadian Geodetic Survey (CGS) and the U.S. National Geodetic Survey (NGS) are redefining their national vertical reference systems using a geoid model as a reference surface for the datum that is both consistent and accurate everywhere across both countries. The geoid is a fairly static surface that can be determined accurately all across the entire continent. It is determined in relation to a reference ellipsoid (geoid height = height above the reference ellipsoid), making it compatible with space-based positioning technologies (e.g., global navigation satellite systems (GNSS) and satellite radar altimetry). This enables the determination of precise elevations using modern GNSS measurement techniques that are far more efficient both in terms of cost, effort, and accuracy. GNSS and localized leveling will be the main tools used for height referencing in the future. This new approach will also reduce the dependency on networks of bench marks for height determination, thereby reducing the need for maintaining thousands of bench marks in and around the Great Lakes Basin. The IGLD update, referred to here as IGLD (2020), will use the same geoid model that will be adopted by the U.S. and Canada for the new North American vertical datum in 2022. This model is expected to be compatible with that used for CGVD2013.

Reference Epoch: IGLD (1955) was established using water level observations and survey measurements for a base 7-year period of 1952–1958 with a defined average reference epoch of 1955. IGLD (1985) was similarly established using a base period of 1982-1988 with a central reference epoch of 1985. IGLD (2020) will also use the 7-year base observational period from 2017-2023 with a central water level reference epoch of 2020. In addition to a reference epoch for water levels, heights in the new IGLD (2020) will need to be referenced to a common epoch because of the effects of crustal motion. Any reference epoch can be used if it is the same for all heights to ensure consistency and compatibility. It is expected that the height reference epoch will be the same as the water level reference epoch (i.e., 2020) and that both will coincide with the reference epoch adopted for the new North American vertical datum in 2022.

Dynamic Heights: The surveying and mapping community uses different types of heights. Two types of heights, orthometric and dynamic, are relevant to the establishment of an IGLD. Both are based on geopotential numbers (C), which are the difference in gravitational potential measured from a reference surface (i.e., the geoid) to the equipotential surface passing through a point. 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. For practical purposes, potential numbers are scaled by gravity (gravitational acceleration γ) to give units of distance (m) that are more readily understood for heights. Orthometric heights (H) are geopotential numbers divided by the mean value of gravity ($\bar{g}$) between the geoid and the point measured along the plumb line: $H = C/\bar{g}$. However, because gravity is not constant over large areas, orthometric heights for an equipotential surface are not constant. Dynamic heights (H^d) are geopotential numbers divided by a constant gravity value of 9.806199 m/s^2, which is "normal gravity" in the Geodetic Reference System of 1980 (Moritz, 2000) at latitude 45 degrees (γ_{45}): $H^d = C/\gamma_{45}$. It is important to realize that the geopotential number in both systems is the same, but only dynamic heights are expressed in units proportional to the geopotential. Consequently, dynamic heights are especially useful in hydrologic and hydraulic systems like the Great Lakes because only differences in dynamic heights are a direct indication of hydraulic head between locations (see Figures 2 and 3). Knowledge of the hydraulic head in the lakes is critical for water management and power generation. Therefore dynamic heights need to be used on all large bodies of water, their connecting channels, and the St. Lawrence River.

The definition of these attributes for a new geoid-based IGLD are defined in detail in the next section along with outstanding technical issues that still need to be resolved.

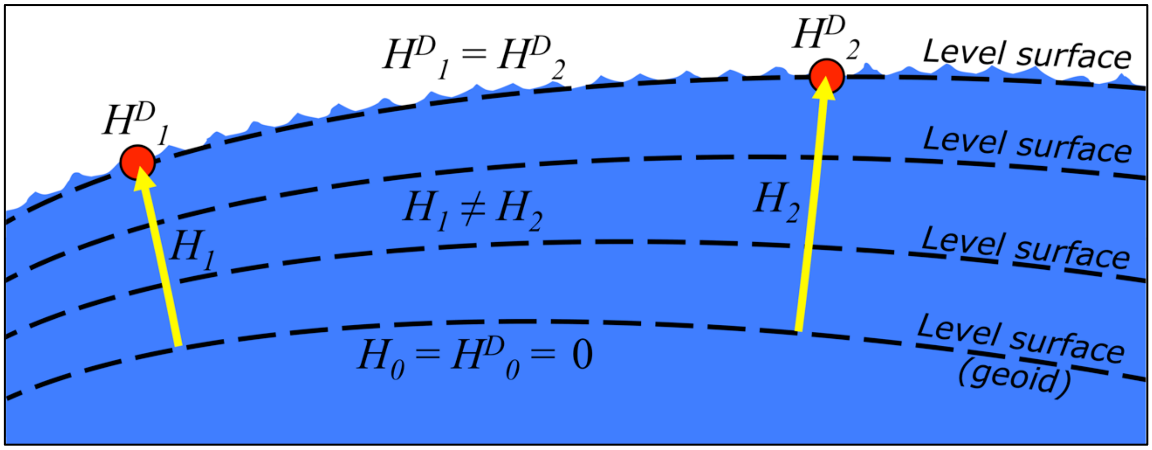

Figure 2. Illustration of dynamic (HD) vs. orthometric heights (H) on an equipotential surface such as an undisturbed lake. Dynamics heights are proportional to the geopotential and thus constant. Orthometric heights represent the physical distance from the reference geoid which changes because of convergence of the equipotential surfaces (and increasing value of gravity) as one proceeds north and closer to the center of mass of the Earth due to the flattening of the shape of the Earth at the poles.

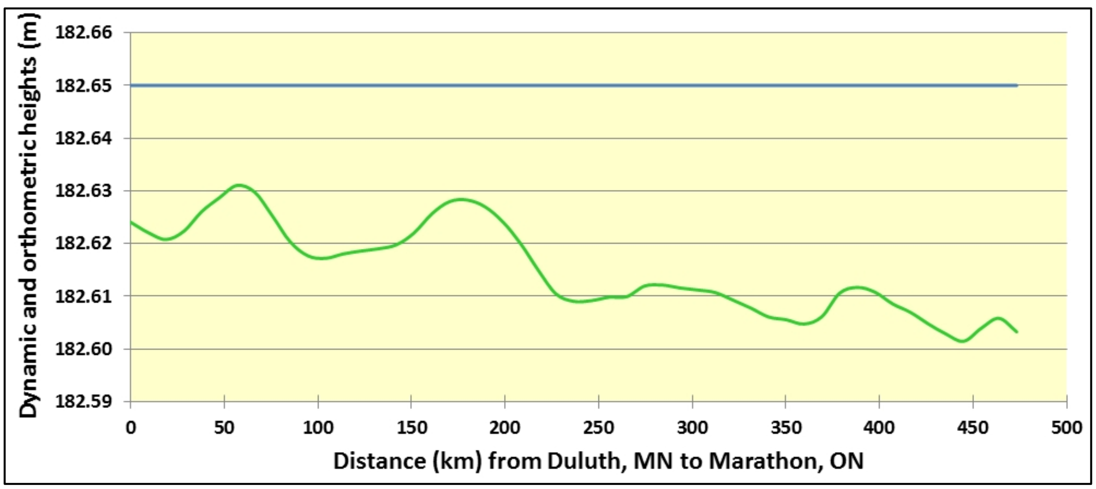

Figure 3. Comparison of orthometric heights (lower green line) and dynamic heights (upper blue line) of Lake Superior water surface along a straight line profile from Duluth, Minnesota to Marathon, Ontario, illustrating that orthometric heights are not constant along a level water surface, while dynamic heights are. Note the downward trend is due to the increasing value of gravity as one proceeds north and is closer to the center of mass of the Earth due to its flattening. The dynamic height of Lake Superior was assumed to be a constant 182.65 m (i.e., the lake is flat). The orthometric heights were obtained by conversion from the dynamic heights.

2. Defining and Implementing a New IGLD

In planning to move forward to IGLD (2020), it has been determined that re-leveling the Great Lakes is cost-prohibitive. A new method of defining a vertical datum and determining heights without re-leveling must be sought through the implementation of a geoid-based vertical datum. Canada has already adopted such a datum. The CGVD2013 is based on the Canadian Gravimetric Geoid of 2013 (CGG2013). Orthometric heights in the datum are determined by subtracting geoid heights from GNSS-determined ellipsoidal heights. The new North American vertical datum expected to be adopted in 2022 will also be based on an adopted geoid and aligned to the same reference zero as CGVD2013.

Implementing a new geoid-based datum requires first defining the following attributes discussed in the previous section:

- A reference zero
- A reference surface (geoid model)
- A reference epoch
- Dynamic heights

In addition, the following issues related to the implementation need to be resolved:

- The need for and determination of hydraulic correctors
- Use of seasonal gauges and identification of their locations
- Crustal motions and their effect on IGLD heights
- Methodologies for determining heights in a geoid-based datum
- Development of tools for transformation between the new datum and older ones

The following sections discuss each attribute and issue in detail and identify outstanding issues that need further investigation before the new datum can be implemented. Each section provides background material, issues requiring further research as well as the required resources for resolving the outstanding issues. These investigations should be refined further in a collaborative manner by the members of the Coordinating Committee and its subcommittees. The results of these investigations and proposed solutions to the issues should be brought to the Coordinating Committee for discussion and agreement for the U.S. and Canada to move forward with the selected methodologies.

2.1 Reference zero for IGLD (2020)

Background

The reference zero is the vertical datum to which IGLD heights are referenced. The previous two datums, IGLD (1955) and IGLD (1985), used the mean sea level at the outlet of the Great Lakes–St. Lawrence River system in the Gulf of St. Lawrence. Pointe-au-Père was chosen as the site for this reference zero because the tide gauge at that location had a long and reliable history, and it had been connected to the rest of the Great Lakes gauges by first-order leveling. In 1984, the tide gauge at Pointe-au-Père was permanently transferred to Rimouski, 5 km upstream. The reference zero was defined by mean sea level averaged over a nineteen-year period from 1970–1988 and was also used for the North American Vertical Datum of 1988 (NAVD 88).

Because of vertical crustal motion and the ongoing global change in sea level, measured local relative sea level will change over time. Global mean sea level rise is currently estimated to be 2.6–2.9 mm/year but has been accelerating in recent years (Watson, 2015). In the vicinity of Pointe-au-Père, absolute sea level rise is almost entirely counteracted by vertical crustal motion, which is estimated from Global Positioning System (GPS) measurements to be about 3-4 mm/year. This gives an apparent or "relative" sea level change of nearly zero.

On the other hand, the new geoid-based datum implemented in Canada (CGVD2013) and the one expected to be adopted by the U.S. in 2022 is or will be referenced to the average of mean sea level at about 200 tide gauges around the coasts of North America and defined by a specific geopotential value ($W_0 = 62,636,856.0\ m^2/s^2$). Canada and the U.S. agreed to adopt this value in 2013 (National Geodetic Survey and Canadian Geodetic Survey, 2012; see Appendix 1), which also corresponds to the current value adopted by the International Earth Rotation and Reference Systems Service (Petit and Luzum, 2010).

The difference between these two definitions of a reference zero (i.e., mean sea level at Rimouski and W_0) is about 31 cm where (IGLD (1985)) is lower than the adopted W_0 surface (see Figure 4). Note that this value of W_0 differs from the value ($62,636,853.4\ m^2/s^2$) adopted by IAG Resolution No. 1 at the General Assembly of the International Union of Geodesy and Geophysics in 2015 as the datum for the International Height Reference System (IHRS). This value comes from a global analysis of satellite altimeters over open-ocean regions rather than one more representative of sea level around North America. The $2.4\ m^2/s^2$ difference implies that the North American value is lower by about 24 cm than the global value. Using the global value of W_0 would result in all coastlines of North America being lower than the vertical reference surface (datum).

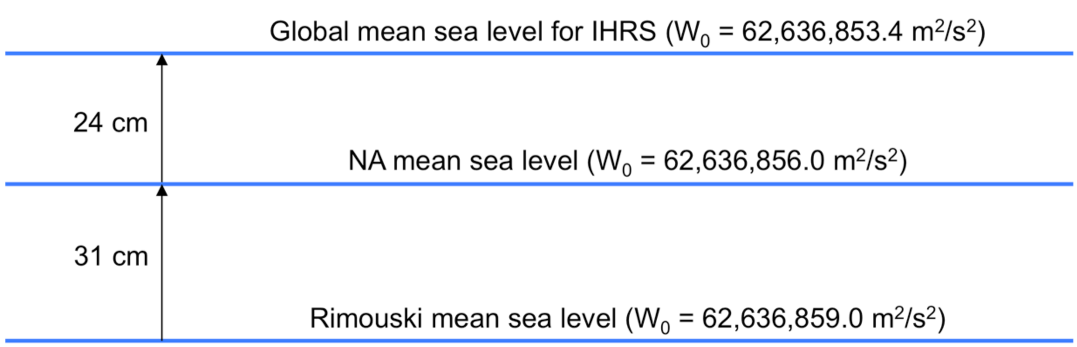

Figure 4. Comparison of different mean sea levels and corresponding W_0's. Global mean sea level is that adopted by the IAG for the International Height Reference System (IHRS). NA mean sea level represents sea level around the coasts of North America that has been adopted for the new N.A. vertical datum in 2022. Rimouski mean sea level was determined from a 19-year period (1970-1988) at Rimouski and Pointe-au-Père for the North American Vertical Datum of 1988 and the International Great Lakes Datum (1985).

Requirements

The reference zero is generally defined as a convention and depends more on impacts to users and compatibility considerations with national vertical datums in the U.S. and Canada than on scientific reasoning. Because Canada and the U.S. have already adopted a W_0 for CGVD2013 and the new geoid-based North American vertical datum to be implemented in 2022 (see Appendix 1), the Coordinating Committee adopted the same W_0 for IGLD (2020) at their 100th meeting in Ottawa in 2016.

Resources

Resources are no longer needed as the Coordinating Committee has adopted the reference zero for the new North American vertical datum.

2.2 Reference surface (geoid model)

Issue

What is required to determine an accurate geoid model over the entire Great Lakes Basin for use as the equipotential reference surface for IGLD (2020)?

Background

Traditional vertical datums were defined by mean sea level as determined by tide gauge measurements at coastal sites. The datum was then propagated inland via leveling networks. As mentioned in Section 1, leveling is too cost prohibitive, time consuming, laborious, and error prone to use for the IGLD update. Both Canada and the U.S. are instead redefining their national vertical reference systems using a high-accuracy geoid model as a reference surface that is both consistent and accurate everywhere across both countries. The U.S. (NGS) and Canada (CGS) have historically always used different methodologies and data for geoid determination (see Wang et al., 2009 and Huang & Véronneau, 2013). Although the agreement of the two approaches is generally quite good overall (about 3 cm), there are some differences where the geoids overlap along the border areas, including the Great Lakes region. Most of these differences can be explained by NGS and CGS using different data sets.

CGS and NGS are collaborating to resolve these differences and are working towards developing a North American geoid model, together with representatives from Mexico, Denmark, and several Central American countries. This collaboration is being done under the auspices of the International Association of Geodesy's Sub-Commission SC 2.4c (Gravity and Geoid in North and Central America). The primary objective of the Sub-Commission is the development of a regional gravity field and geoid model covering the entire North American and Central American regions to achieve a common vertical datum. The intention is to ensure that a suitable North American geoid model is developed to serve as a common datum for everyone in the region.

The achievement of a geoid model for North and Central America will be accomplished by coordinating activities among agencies and universities with interest in geoid theory, gravity,

gravity collection, gravity field change, geophysical modeling, digital elevation models, digital density models, altimetry, dynamic lake topography, leveling, and vertical datums. Of particular interest will be the comparison of geoid models of an equipotential (level) surface to lake topography as determined by satellite altimetry. All necessary data will be collected from all countries involved. However, the determination of a geoid model for North and Central America will not be limited to a single agency. Rather, the Sub-Commission encourages theoretical diversity in the determination of a geoid model among all the agencies. Each agency takes responsibility or works in collaboration with neighboring countries in the development of a geoid model for their respective country with an overlap (as large as possible) over adjacent countries. Each solution will be compared, the discrepancies will be analyzed, and the results used to improve the next geoid model. The Sub-Commission presently meets on a regular basis to discuss overlap regions and to work towards agreements to exchange data to provide a unified geoid model for the entire continent. It is anticipated that one of these geoid models will be chosen for IGLD (2020).

Requirements

Evaluate and select an appropriate methodology and data for the development of an accurate geoid covering the Great Lakes region. This will require collecting a common set of existing gravity data and possibly the collection of new measurements to improve accuracy in targeted areas identified through this work.

Resources

The following skills are required: knowledge of gravity data and geoid modeling. The expected human resources would be experts in geoid modeling from CGS, NGS, and possibly academic researchers.

2.3 Dynamic heights

Issue

How accurately can dynamic heights be determined through use of GNSS, surface and airborne gravity, and a geoid model without the use of leveling?

Background

Dynamic height (H^d) is a function of the geopotential number (C) and normal gravity at 45 degrees latitude (γ_{45}) as described in Section 1. The accuracy of H^d is therefore a function of the accuracy of only C (γ_{45} is a constant value).

In NAVD 88, the geopotential numbers (C) were derived from a mathematical adjustment of leveling observations (measured height differences) that were converted to geopotential number differences using surface gravity measurements. While the mathematically adjusted C's were divided by γ_{45} for IGLD (1985), the same C's were divided by mean gravity along the plumb line ($\bar{g}$) to determine the orthometric heights (H) for the NAVD 88 datum. The mean gravity ($\bar{g}$) is determined from surface gravity (g) using the well-known Helmert height reduction formula $\bar{g} = g + 0.0424\,H$.

In a geoid-based IGLD (2020), C is derived from mean gravity along the plumb line ($\bar{g}$) and the GNSS-derived orthometric height (H), where H is a function of the ellipsoidal height (h) and the geoid height (N); i.e., $C = (h - N)\,\bar{g}$. The accuracy of dynamic height (H^d) in a geoid-based datum is therefore a function of the accuracies of h, N and $\bar{g}$. Again, $\bar{g}$ will be determined from surface gravity. Although the accuracies of both h and N are known to be at the cm level, it will be required to determine how accurately $\bar{g}$ can be determined from the interpolation of existing surface gravity measurements.

The best available geoid models can serve as a preliminary realization and "proof of concept" of a new geoid-based IGLD for evaluating the process of conversion to dynamic heights. It is expected that these geoid models will differ little from the new North American vertical datum adopted in 2022, especially in a relative sense. Results based on such geoid models should therefore be valid for the geoid that is eventually adopted for the IGLD update.

Requirements

The research may require new measurements of gravity, leveling, and GNSS data in addition to existing data sources. It will be required to compare the accuracy of dynamic heights derived from interpolated gravity versus actual gravity measurements. The latest geoid models and GNSS surveys will be required for the analysis. The research plan would need to be developed, all data sources identified and made available, the analysis performed, and findings and recommendations made by 2023.

Resources

The following skills are required: knowledge of GNSS data processing, adjustments, geoid modeling, and understanding of different types of heights (orthometric, ellipsoid, geoid, and dynamic heights). Resources could be various combinations of CGS and NGS staff, interns, contractors, or academic grants.

2.4 Hydraulic correctors

Issue

Will hydraulic correctors be needed for IGLD (2020) and, if so, what do they represent, to what accuracy do they need to be determined, and what interpolation modeling will be necessary for implementing in IGLD (2020)? If required, a new methodology for interpolation of hydraulic correctors would be a primary goal. The methodology could also be applied to interpolation of other data such as vertical land movement rates. Some of the other topics where such interpolation models could provide expertise are:

- Error analysis and appropriate use of water level transfers
- Development of crustal movement models

- Relationship between CGVD2013, NAVD 88, IGLD (1985), IGLD (2020), and the new North American vertical datum in 2022
- Development of hydraulic corrector models
- Other types of interpolation models or GIS layers necessary for implementation of IGLD (2020)?

Background

Neglecting effects other than gravity, the water surfaces of the Great Lakes are considered to be geopotentially equal in which case all mean water level (MWL) values for gauging stations around a lake would be the same. Any deviations from this would be due to errors in the determination of dynamic height or actual variations in lake topography (e.g., hydraulic effects, winds, storm setup, river discharge). To reduce the influence of these effects, the MWL in IGLD (1985) was determined as the average water surface height for the summer months (June–September) for the years 1982–1988 referenced to the dynamic height of the gauging station's primary bench mark. The MWL at each gauging station was treated as a bench mark in the vertical network adjustment to effectively remove errors in the leveling network. Following the adjustment, the MWL values at each gauging station on a lake were found to be slightly different. The differences, referred to as hydraulic correctors, are primarily due to cumulative errors in the spirit (optical) leveling used for determining the base orthometric heights, referencing NAVD 88, and the base for computing "Dynamic Heights" to reference IGLD (1985). To a lesser extent, the hydraulic correctors also account for any smaller residual errors caused by variations in lake topography.

The hydraulic correctors ranged from 0 to +6 cm on Lake Ontario, where accumulated leveling errors were smallest, to -10 to +8 cm on Lake Superior, where accumulated leveling errors were largest (Coordinating Committee, 1995). To correct for these residual leveling errors, the Coordinating Committee applied hydraulic correctors, so that each gauge on a lake would have the same MWL as the master station for the lake. This was accomplished by holding each lake's master station MWL as the controlling value and comparing all other subordinate gauging station MWLs to it over a given period. The hydraulic corrector (HC), being the difference, 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 HC may be positive or negative and is defined algebraically as:

$$HC = MWL_{Sub} - MWL_{Master}$$

A key issue in the analysis of hydraulic correctors is which months to use for the determination of the MWL. In previous IGLD's, only summer months (June–September) were used. A recent study by Bruxer and Southam (2008a, 2008b) of vertical movement rates in the Great Lakes derived from observed water level differences showed that various averaging periods performed similarly overall. However, averaging over the summer months was deemed preferable because (1) it would reduce errors associated with meteorological factors that cause variations in lake topography, (2) it would reduce periods of missing data that may distort results due to seasonal biases in water level differences, (3) MWL differences from seasonal gauges can only be determined during the summer months, and (4) it would retain consistency with past studies.

Whether such hydraulic correctors are still needed in a geoid-based datum, and what their impacts are, will need to be determined. Hydraulic correctors are expected to be smaller because the errors from geoid modeling and GNSS surveys are expected to be much less than errors in spirit leveling incurred during previous IGLD campaigns. Consequently, any residual errors in observed differences in MWL in IGLD (2020) can be expected to be due proportionately more to lake surface topography caused by hydraulic effects than measurement or geoid modeling errors. In this sense, the correctors would be true corrections for hydraulics or lake surface topography. Therefore, the water management implications of whether and how they are applied within the new datum must be carefully considered.

If hydraulic correctors are needed, an interpolation model will be required to predict them between determinations at gauge locations. An existing spatial interpolation model is used for interpolation of hydraulic correctors in the IGLD85 tool within the NGS Geodetic Tool Kit, originally developed by Dennis Milbert. This transformation has also been implemented in the National Oceanic and Atmospheric Administration's (NOAA) VDatum software (NOS, 2012). Figure 5 gives a contour plot of the interpolation model over the Great Lakes. An updated approach using existing expertise and experience with the NOAA spatial interpolation engine called TCARI (Tidal Constituent and Residual Interpolation) developed by the Coast Survey Development Laboratory (CSDL) of the Office of the Coast Survey (OCS) has also been proposed. In addition, consideration should be given to existing interpolation tools used by the Great Lakes Environmental Research Laboratory (GLERL) and in Canada by CGS, CHS and Environment and Climate Change Canada (ECCC).

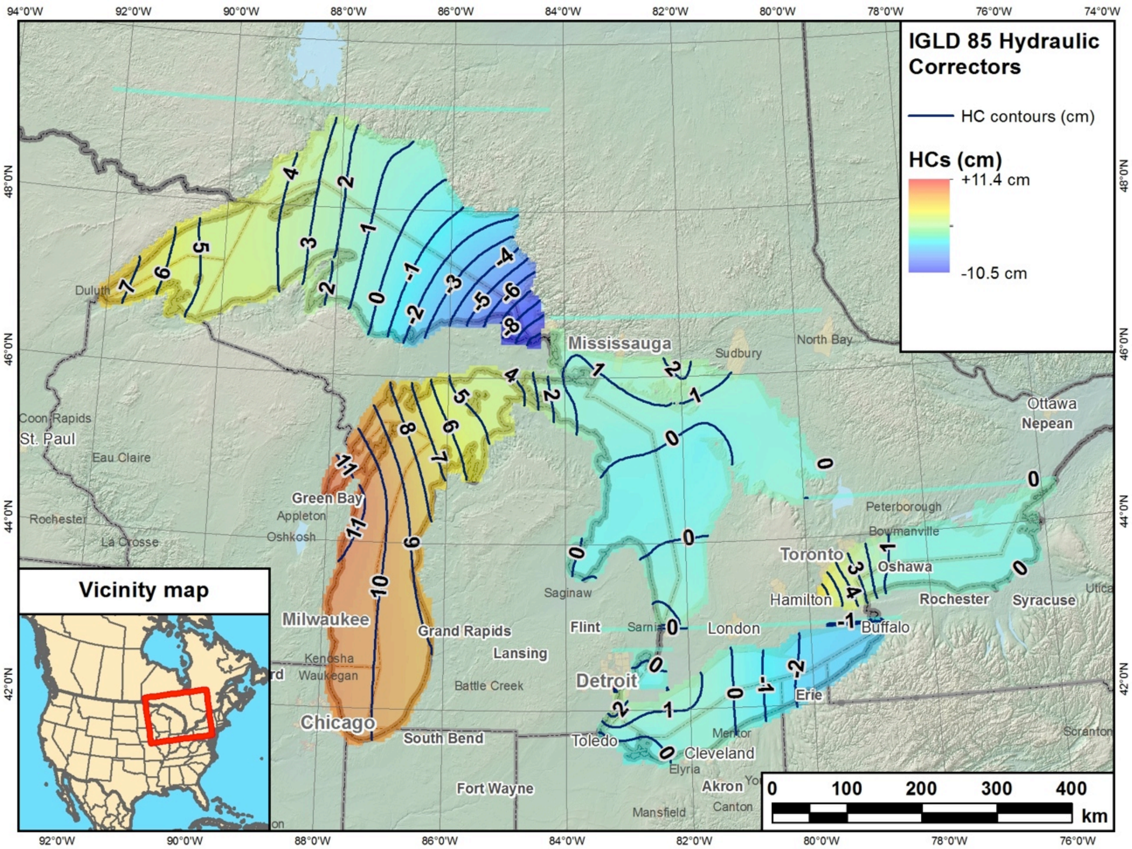

Figure 5. IGLD (1985) hydraulic corrector model developed and implemented in the VDatum transformation tool (NOS, 2012).

Requirements

Develop an adopted, internationally coordinated model and grid for interpolation of desired hydraulic corrector parameters in each of the Great Lakes and compare to results from existing interpolation tools used by Canada and U.S. It is recommended to use the latest geoids developed by CGS and NGS, and mean water levels based on the summer-month period to derive new hydraulic correctors for testing, analysis and comparison with existing models of lake surface topography. Preliminary analyses have already been done and demonstrate the much smaller magnitude of the hydraulic correctors (a few centimeters rather than a decimeter or more). The CSDL has been approached with this requirement but no formal request has been made. Their modelers have significant experience with TCARI and could assist with a new interpolation model.

Resources

The skills needed for this research are related to modeling and spatial interpolation. Resources could come from CGS and NGS geoid development teams, CHS, ECCC, CSDL, NOAA's GLERL, and NOAA's Center for Operational Oceanographic Products and Service (CO-OPS) modeling and hydrometric planning teams, or student intern help.

2.5 Identification of seasonal gauge locations

Issue

Will seasonal gauges be needed for a complete implementation of IGLD (2020) and, if so, how many will be needed, and what criteria will be required for identifying and prioritizing their locations in both countries for installation during the IGLD epoch period?

Background

To obtain a complete picture of the lake levels, water level and GNSS data need to be collected at all ports and harbors of refuge and incorporated into the IGLD update. The GNSS surveys should follow the recommended procedures in Section 2.7. The additional seasonal gauge data will be especially useful for the determination of the hydraulic corrector interpolation model (see previous research topic) and validating the new geoid models. Including these additional ports and harbors will ensure overall minimal cost, more accurate IGLD heights for the seasonal gauges, and the improved modeling of hydraulic correctors for interpolating them to other ports and harbors without seasonal gauges. Otherwise, *ad hoc* determinations of water levels outside the IGLD measurement epoch period would be needed in ports and harbors not included in the IGLD update. However, this would result in hydraulic correctors that are not compatible with those determined during the IGLD update.

The U.S. has identified about 140 possible current and historical seasonal locations in addition to the 53 permanent gauge locations to be used to update IGLD (see Appendix 2 for a list of these gauges). CHS has not yet identified specific locations, but the expectation is 100 seasonal gauging locations in addition to their 34 permanent gauge locations. The following are prioritization criteria that could be used:

- Proximity to international nodal points of seiches
- Residing in an area with relatively large vertical motions
- Residing in an area with large hydraulic correctors as indicated by the Milbert (NGS) model used in VDatum (NOS, 2012)
- Locations identified as high priority commercial ports
- Locations identified as high priority recreational port/harbor of refuge
- Locations identified as other high priority needs (e.g., high population areas, nuclear and hydroelectric power plants, etc.)
- Existing infrastructure (e.g., docks, piers)
- Proximity to CGS/NGS BMs – for ties between the different IGLD datums

Requirements

Perform analyses to determine the criteria for selecting and prioritizing seasonal gauge locations. A research plan would need to be developed, all data sources identified and made available, the analysis performed, and findings and recommendations made during the IGLD measurement epoch period (2017-2023).

Resources

This work will require knowledge of hydrodynamic modeling and vertical reference systems in addition to experience with water resources management. Resources could come from those involved with the measurement of water levels, such as CO-OPS and CHS, and possibly other partners.

2.6 Crustal motions and their effect on IGLD heights

Issue

How accurately can crustal motions be determined in the Great Lakes region, and specifically at water level gauges, using Continuously Operating Reference Stations (CORS), Canadian Active Control System (CACS) stations, and specially designed, high-accuracy campaign-style GNSS surveys?

Background

It is a well-documented fact that the Great Lakes region is affected by crustal movement due to glacial isostatic adjustment (GIA) (Mainville and Craymer, 2005; Henton et al., 2006; Craymer et al, 2011). The process of GIA is illustrated in Figure 6 while Figure 7 illustrates the amount and pattern of movement as determined from water level gauges and more recent GPS data. The northern parts of the Great Lakes Basin are uplifting while the southern parts are subsiding, representing an overall north-south tilting of the entire basin of about 5–7 mm/yr. After a few decades (about 30 years) height differences become out of date by as much as 21 cm over the entire basin, thereby necessitating a redefinition of the heights and IGLD in general.

To determine these movements throughout the Great Lakes region, the hydrographic and geodetic offices of Canada and the U.S. have worked together since 2001, under the auspices of the Coordinating Committee, to install CORS and CACS stations at key permanent water level gauging stations. Realizing that it takes several years to obtain an accurate estimate of the relatively small magnitude of vertical motion throughout the region, it was imperative to install the CORS and CACS stations as soon as possible. Further CORS and CACS stations are still required to improve the modeling of GIA. Such new sites should be installed at the earliest opportunity to obtain accurate velocity estimates as soon as possible.

CORS and CACS stations have been installed at only about a dozen permanent water level gauges in both Canada and the U.S. To determine GIA movements at all of the other permanent water level gauges, specially designed, high-accuracy GPS campaign-style surveys have been performed in 1997, 2005, 2010, and 2015. A new GNSS survey is planned for 2020 to coincide with the middle epoch of the new IGLD. Comparing repeated, high-accuracy, GNSS-derived ellipsoid heights can provide further estimates of crustal movement (velocities) at the reference bench marks.

Using the velocities estimates from the CORS, CACS stations and campaign surveys throughout the Great Lakes Basin, it will be possible to model the crustal motion and propagate heights to an adopted common reference epoch. As crustal motions accumulate over the years, it will also be possible to update the heights as needed by propagating them to future reference epochs to keep pace with the crustal motion.

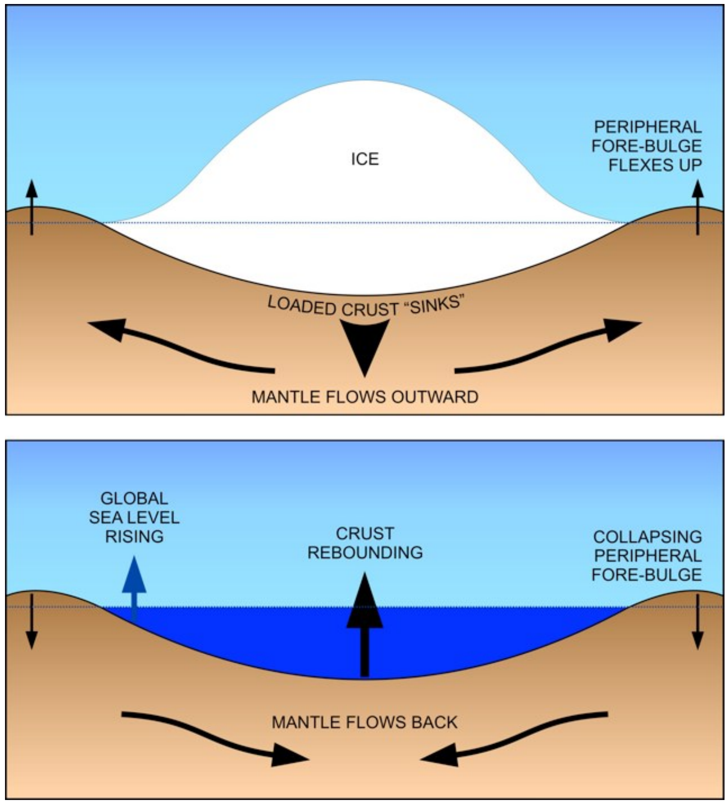

Figure 6. Process of glacial isostatic adjustment (GIA).

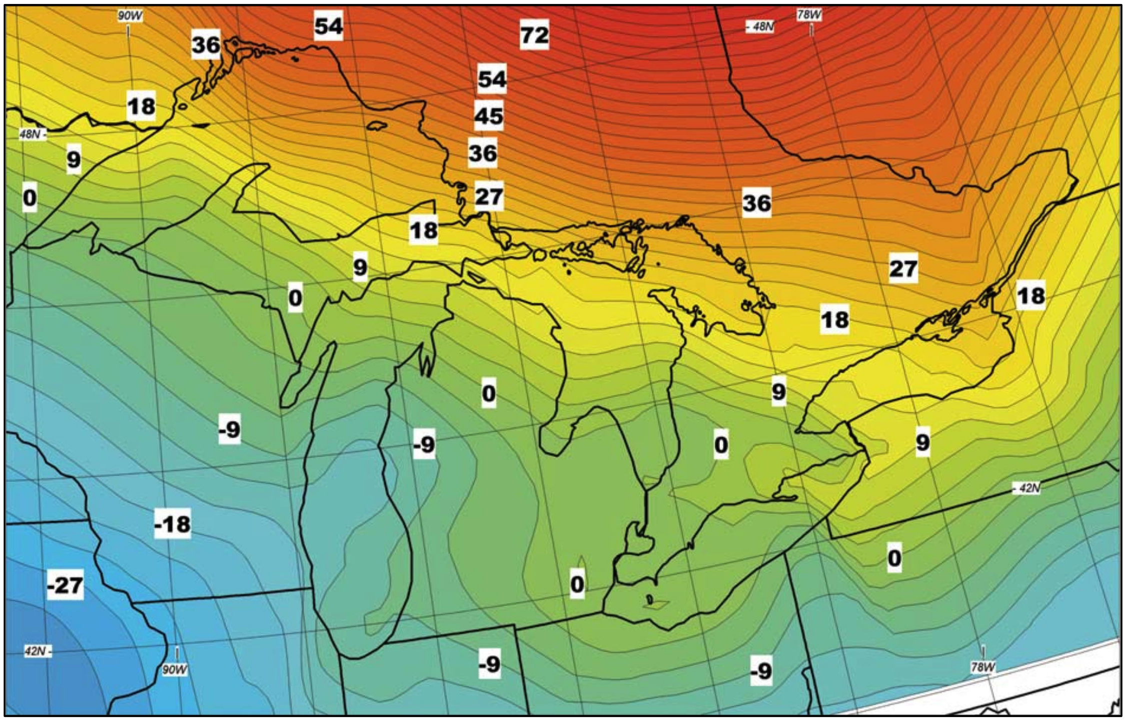

Figure 7. Contour map of vertical velocities in cm/century derived from water level gauges over the Great Lakes with ICE-3G model of velocities in the background (Mainville and Craymer, 2005). Contour interval: 3 cm/century (0.3 mm/year).

Requirements

Determine the rates of movements and their accuracies at water level reference bench marks using CORS and CACS stations together with specially designed, high-accuracy GNSS survey campaigns, and develop procedures and algorithms for using vertical rates of movement for projects that require high-accuracy heights. The research would use existing GPS survey data but will also require the installation of new CORS and CACS stations in targeted locations. In addition, a new GNSS survey campaign in 2020 will ensure that the height of the reference bench marks at all the gauges are accurately estimated at the reference epoch of the new IGLD (the middle epoch of the seven-year water level measurement period). To estimate accurate velocities for all the bench marks, all GNSS data may need to be reprocessed using the latest GNSS processing strategies, software packages, and satellite orbits from the International GNSS Service to ensure consistency among all the solutions at the different epochs.

Resources

The skills needed for this are knowledge of GNSS processing routines, crustal movement modeling, and understanding of different types of heights (orthometric, ellipsoid, geoid, and dynamic heights). Resources could be various combinations of CGS and NGS staff, interns, contractors, or academic grants. As done for the 2015 GPS survey, additional resources from other agencies (e.g., field personnel and their travel expenses) may also be needed for the planned GNSS survey in 2020. CGS has already developed and implemented tools for estimating crustal motions and has adopted a crustal motion model for Canada that includes the Great Lakes region. These tools and knowledge can be applied to the new IGLD.

2.7 Determining heights in a geoid-based datum

Issue

How will heights be determined in a new geoid-based datum using more efficient GNSS techniques as a replacement for leveling for water management of the Great Lakes, their connecting channels and the St Lawrence River?

Background

GNSS-based leveling methodologies using a geoid-based datum (or hybrid geoid-based datum) have been widely used for many years and can provide high accuracy heights and height differences in a more efficient and cost-effective manner than traditional geodetic spirit leveling, yet still as accurate. This is especially true over long distances. The ellipsoidal heights (h) determined from GNSS technologies can be easily converted to orthometric heights (H) through geoid heights (N) by the simple relation $H = h – N$ (see Figure 8). Orthometric heights can then be converted to dynamic heights (see Section 2.3).

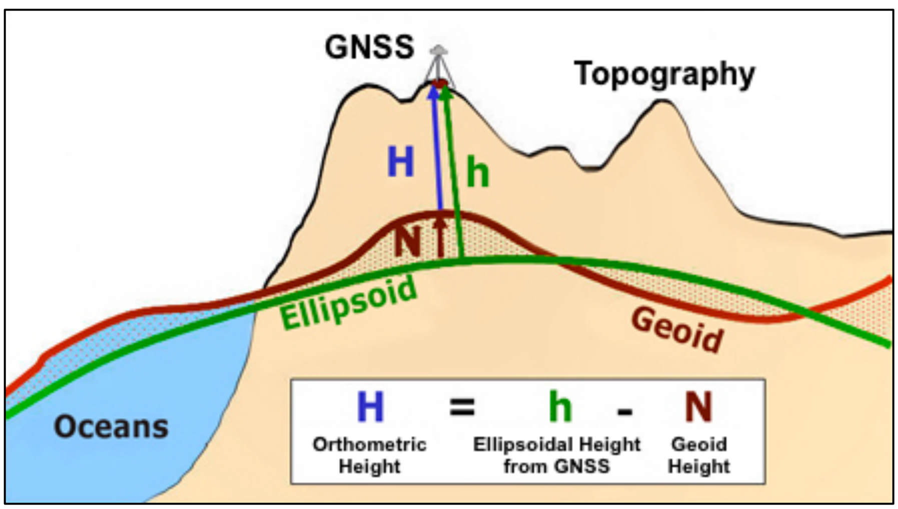

Figure 8. Relation between ellipsoidal height (h), orthometric height (H), and geoid height (N). Orthometric height (also called mean sea level height), from which dynamic heights are derived, can be obtained by subtracting the geoid height from the GNSS-determined ellipsoidal height. A geoid height is positive when the geoid is above the ellipsoid and negative when below.

GNSS-based leveling will allow users to (1) achieve more consistent and accurate heights and height differences on water level gauges and their reference bench marks across the entire Great Lakes region, (2) determine the vertical velocities of water level gauges and improve the determination of a crustal motion model for the Great Lakes region, (3) provide an independent validation of geoid models for the region (together with existing geodetic leveling), and (4) determine geopotential numbers (and dynamic heights) for assessing how level a lake surface is (see Section 2.3).

In addition to GNSS surveys, permanent GNSS stations (CORS or CACS) have been installed at many key water level gauges (see Figure 9). Such stations ensure the highly accurate (millimeter-level) determination of the absolute heights of water levels on a weekly or even daily basis without the adverse effects of any local movements of the reference bench mark network. They also provide more accurate estimates of crustal motion and enable more accurate GNSS surveys at nearby gauges. Although many of the U.S. CORS stations are using outdated GPS-only receivers and are offline for a variety of reasons, efforts are under way to modernize the stations with GNSS receivers. In Canada, most of the CACS stations already have or are being modernized with upgraded GNSS-capable receivers and more reliable cellular-based communications. Although leveling ties between the CORS/CACS monuments and the water level gauge reference point and local bench marks have been made at most gauges during installation, such ties have never been repeated or monitored afterwards.

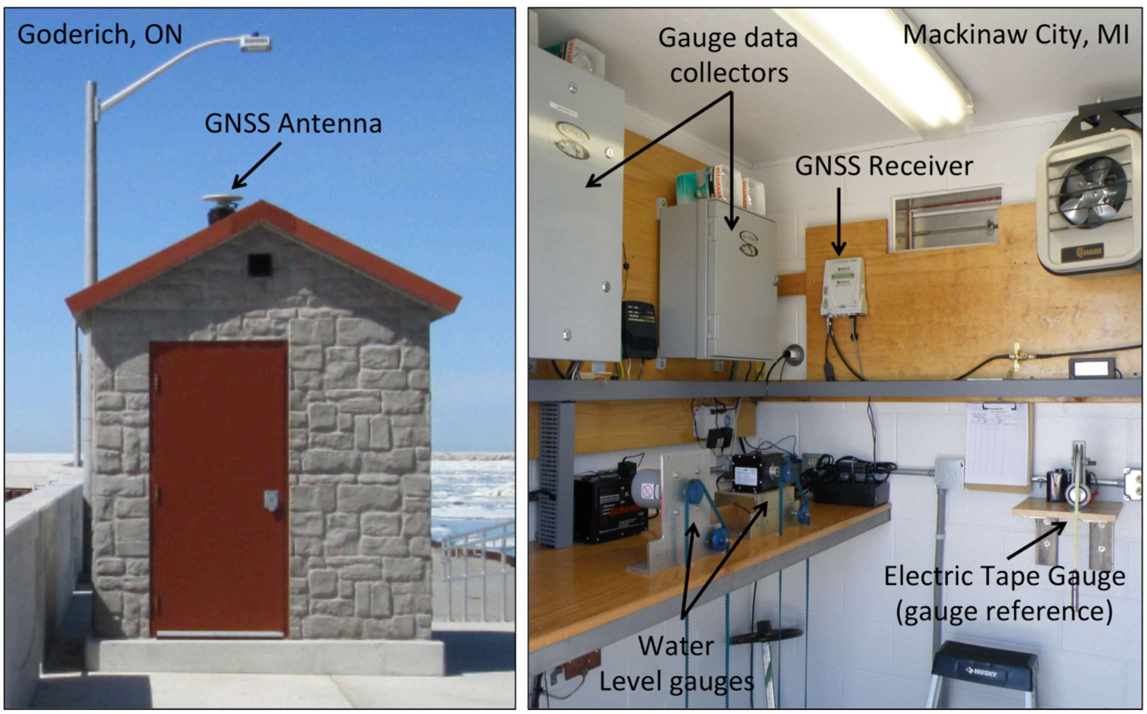

Figure 9. Typical CACS and CORS at water level guage stations in Goderich, ON and Mackinaw City, MI.

In future it is envisaged that all water level and tide gauges will use permanent GNSS installations to determine the height of the gauge reference points (e.g., ETG or gnomon) in near real-time without the need for any reference bench mark network and its regular monitoring. It is expected this would reduce operational costs in the long term while enabling more accurate determinations of water and sea levels, in addition to any crustal motion. This would require close cooperation between the geodetic agencies computing the heights of the GNSS stations and the agencies responsible for the water level and tide gauges such that the entire process of generating absolute heights of water and sea levels can be more or less automated. If the GNSS antenna/monument is attached to the same structure as the gauge, it would only be required to verify the vertical offset between the GNSS antenna and the gauge reference points every few year or so.

Requirements

(1) Develop internationally coordinated methodologies (including observing procedures, guidelines, and any necessary algorithms) for determining heights in a geoid-based datum using GNSS survey techniques and any required local leveling at water level stations. This research would use the latest existing GPS survey data and geoid models to validate the developed procedures, guidelines, and algorithms for determining accurate GNSS-based heights in a geoid-based datum. This task will require determining the positioning and accuracy requirements for water management of the Great Lakes, their connecting channels and the St. Lawrence River, and developing GNSS-based leveling methodologies to meet these requirements.

(2) Develop requirements for upgrading permanent GPS stations at gauges to more modern GNSS-capable receivers and, possibly, antennas. (3) Develop requirements for the operation and maintenance of CORS and CACS at gauge sites, including the optimum frequency for monitoring leveling ties between the GPS/GNSS monuments, gauge reference marks, and local bench marks. (4) Assess the need for and install additional CORS and CACS sites to improve the monitoring of more permanent gauges and regional crustal motion.

Resources

The skills needed for this activity include a knowledge of GNSS processing routines, an understanding of different types of heights (orthometric, ellipsoid, geoid, and dynamic heights), and the ability to translate Great Lakes water level management requirements into geodetic requirements. Resources could be various combinations of CGS and NGS staff, interns, contractors, or academic grants.

2.8 Tools for transforming between datums

Issue

How accurately can transformations be determined between the various vertical datums, including low water (or chart) datums (LWDs) that have previously been used in the Great Lakes region, and how these can be incorporated into existing transformation tools, such as VDatum used in the U.S.

Background

There are many products using the older IGLD datums that need to be updated to the new datum. In many cases, it will not be possible to regenerate such products in the new datum without collecting new data or using a transformation tool. Because it will be difficult or impossible to collect new data, it is expected that such products will need to be updated to the new datum using new transformation tools that can handle thousands of data points.

Requirements

Determine accurate transformation models between a new geoid-based IGLD (2020) datum and previous IGLD datums. In addition, translations (offsets) will be required to convert LWD from one IGLD to another (see Section 3.1 for updating the LWD itself). Develop new tools implementing the transformations or enhance existing software tools such as VDatum and VERTCON in the U.S. This task would require obtaining heights at common points in both the new and old IGLD realizations with which to determine transformations between the datums. It will therefore be required to digitize heights from older datums.

Resources

A wide range of resources and skills will be needed for this activity, including knowledge of data in the old datums, the digitizing of old data, and the ability to determine geodetic transformation models. Resources are expected to be various combinations of CGS and NGS staff, interns, contactors, and academic grants.

3. Impacts of an IGLD Update

The establishment and implementation of a new IGLD will have significant impact on a great many operations, products, and services throughout the Great Lakes region. Section 3.3 provides a list of some of the most important impacts organized by general activity; i.e., navigation, water level regulation, water management, shoreline use planning, and surveying and mapping. These will need to be addressed, and ways to prepare for and mitigate them should be included in the outreach plan proposed in the next section. Two of the most important impacts are the determination of LWD (chart datum) and the updating of heights at the many gauges other than those operated by NOAA and CHS. These two impacts are discussed in Sections 3.1 and 3.2.

The change in heights resulting from a change of datum will also provide an opportunity to re-evaluate the methodologies used to compute some of the products impacted by the change. An example is the method of determining low water datum on each lake as discussed below.

3.1 Low water datum (chart datum)

The LWD (or chart datum) is the geopotential elevation for each of the Great Lakes, their connecting channels, and St. Lawrence River to which the depths shown on navigational charts and the authorized depths for navigation improvements are referred (see Figure 10). By definition, LWD is supposed to identify a surface so low that the water level will seldom fall below it. As part of both the IGLD (1955) and IGLD (1985) updates, the LWD of each lake was updated to the new IGLD by simply shifting the LWD by the difference in IGLD dynamic heights at the master station. The historical record of water levels has not been reviewed in the context of re-evaluating LWD since their original determination in 1933. Since then, the Great Lakes region has experienced historically high and low water levels. Changes to hydraulic and hydrologic conditions, have left in question the suitability of the existing LWD determination for present-day and future use. Although the LWDs can be updated as before (as a shift in height relative to the primary bench mark at each master gauge), re-evaluating the determination of LWD on each lake is recommended.

Unfortunately, there is little source documentation available that provides detailed information on how present values of LWD were determined. Subject-matter experts report that an analysis was performed using historical monthly mean data for the master stations to determine a conservative elevation for navigation purposes. However, during the recent low water stages, the water levels were often below the existing LWD elevations in the upper Great Lakes region (Lakes Superior, Huron and Michigan and the St. Marys River). Consequently, the determination of LWD for the upper lakes region, and possibly other lakes, should be re-examined considering historically observed water levels and potential future conditions.

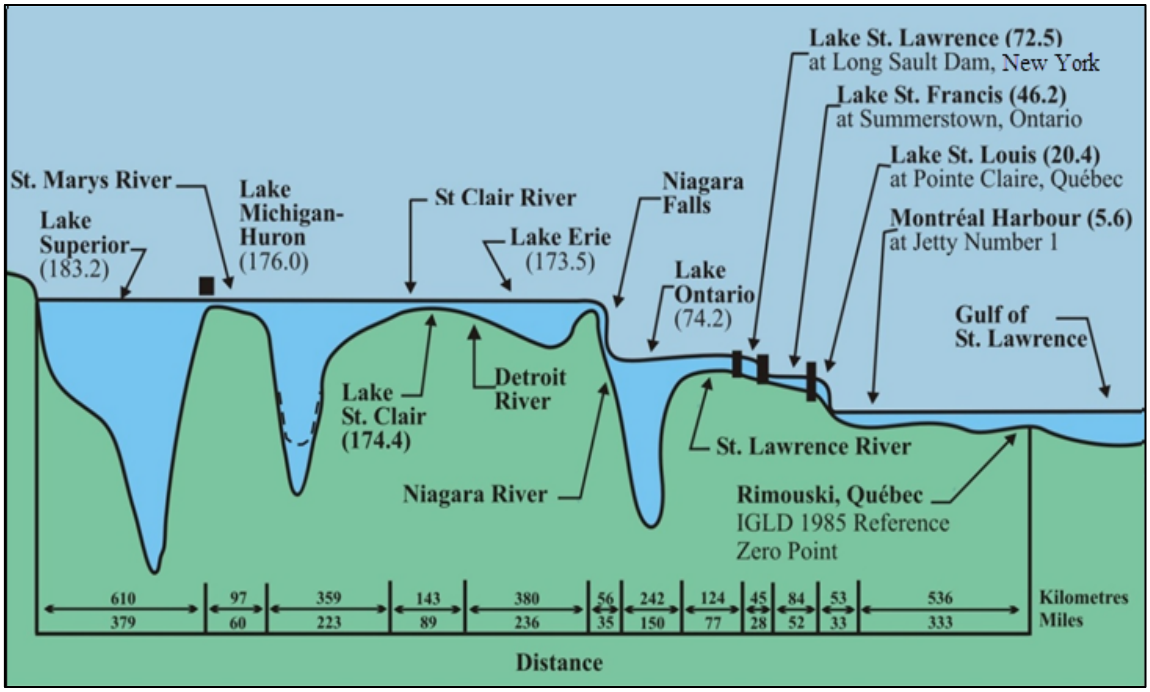

Figure 10. IGLD (1985) low water datums for the Great Lakes and the St. Lawrence River shown in meters and rounded to the decimeter.

LWD within Lake Ontario and the St. Lawrence River must be determined using water level data after the beginning of the regulation of Lake Ontario in 1960 due to construction of the Seaway and Robert Moses-Robert H Saunders Power Dam. The entire international project encompasses over 60 km (37 miles) of the St. Lawrence River Valley and includes three control dams and three huge locks used by ocean-going cargo ships and tankers.

There are two questions related to LWD. First, how will the LWD for nautical charting be determined for each of the Great Lakes, their connecting channels and the St. Lawrence River after the determination of IGLD (2020)? And, second, what water reference surface (usually referenced to LWD) will used to depict the shoreline on nautical charts? To answer these questions, it will be necessary to analyze historical data and decide on a methodology for determining updated values of LWD for the lakes, as well as the LWD steps along interconnecting channels and the St. Lawrence River. This may include determining which master station, if any, is needed for each lake, identifying nodal points to use for each lake, and deciding if separate LWD values should be used for Lakes Huron and Michigan. This work will involve reviewing present-day shoreline determinations for the Great Lakes and determining a methodology and path forward for providing updated shoreline depictions relative to IGLD (2020).

This work will require analyses of historical water level data. New data may not be required. A research plan would need to be developed, all data sources identified and made available, the analyses performed, and findings and recommendations made available by 2023. The analyses will require staff familiar with statistics and analysis of data time-series using tools such as MATLAB and Excel. Knowledge of Great Lakes nautical charts and navigation products is also desired. Resources would come from members of the Vertical Control – Water Level and Hydrology Subcommittees and their agencies.

3.2 Updating heights at other gauges

There are many other water management operations in the Great Lakes region that require monitoring water levels for navigation, dredging, and regulating transboundary water levels and flows. The gauging stations used for these operations will need to be updated to the new IGLD (2020), including:

- International Gauging Stations (IGS)
- Binational Interest Gauging Stations (BIGS)
- Seaway gauging stations (for lock operations and navigation)
- Power entities gauging stations
- Inland river and canal gauging stations within Great Lakes Basin
- Municipality gauging stations (e.g., water intake/outflows)
- Gauging stations used for dredging operations

The water level regulation operations are overseen by various international boards, some of which are discussed below.

The International Joint Commission's (IJC) Boards operate plans under which Lakes Superior and Ontario outflows are regulated. These outflows are regulated to provide a balance of socioeconomic and environmental benefits, subject to physical and operational limits. Lake Superior outflows have been regulated since 1916. Lake Ontario outflows have been regulated since 1960. The boards adhere to Orders of Approval issued by the IJC, and typically prescribe outflows in accordance with a regulation plan. Based on water supplies received by each lake (computed from water level information), each plan specifies outflows based on the water levels of Lakes Superior, Michigan-Huron and Ontario, as well as water levels along their respective outlet channels. The regulation plan used to manage Lake Ontario outflows is administered by the International Lake Ontario - St. Lawrence River Board. Regulation began in 1960, and the current Plan 2014 was implemented in January 2017 to advance regulatory operations and will:

- Provide essentially the same level of benefits to domestic water uses and navigation
- Provide a small increase in hydropower generation at the Moses-Saunders dam and the Hydro-Quebec facilities on the St. Lawrence River
- Provide shoreline property owners on the upper and lower river essentially the same level of protection
- Result in a small reduction of benefits to shoreline property owners on Lake Ontario (in the form of increased costs of maintaining shoreline protection structures)
- Work to restore the natural environment of Lake Ontario and the upper St. Lawrence River that support wetlands, birds, amphibians, fish and mammals
- Have a mixed effect on recreational boaters

- Provide essentially the same benefits downstream of the dam as does the previous regulation regime

The outlet of Lake Ontario is regulated by a series of structures and channel enlargements. The Iroquois Dam, Moses-Saunders Power Dam, Long Sault Spillway Dam and the Eisenhower and Snell Navigation Locks contribute to the regulation of outflows.

The regulation of Lake Superior outflows is administered by the International Lake Superior Board of Control. The outflow from Lake Superior to Lake Michigan - Huron is regulated by varying the amount of water allocated to domestic uses, navigation, and hydropower production, in conjunction with adjustments of the gates in the Compensating Works at the head of the St. Marys Rapids, a world-class fishery.

The International Niagara Board of Control was established by the Commission in 1953 to provide advice on matters related to the Commission's responsibilities for water levels and flows in the Niagara River. The Board's main duties are to oversee water level regulation in the Chippawa – Grass Island Pool and installation of the Lake Erie-Niagara River Ice Boom. The Board also collaborates with the International Niagara Committee, a body created by the 1950 Niagara Treaty to determine the amount of water available for Niagara Falls and power generation.

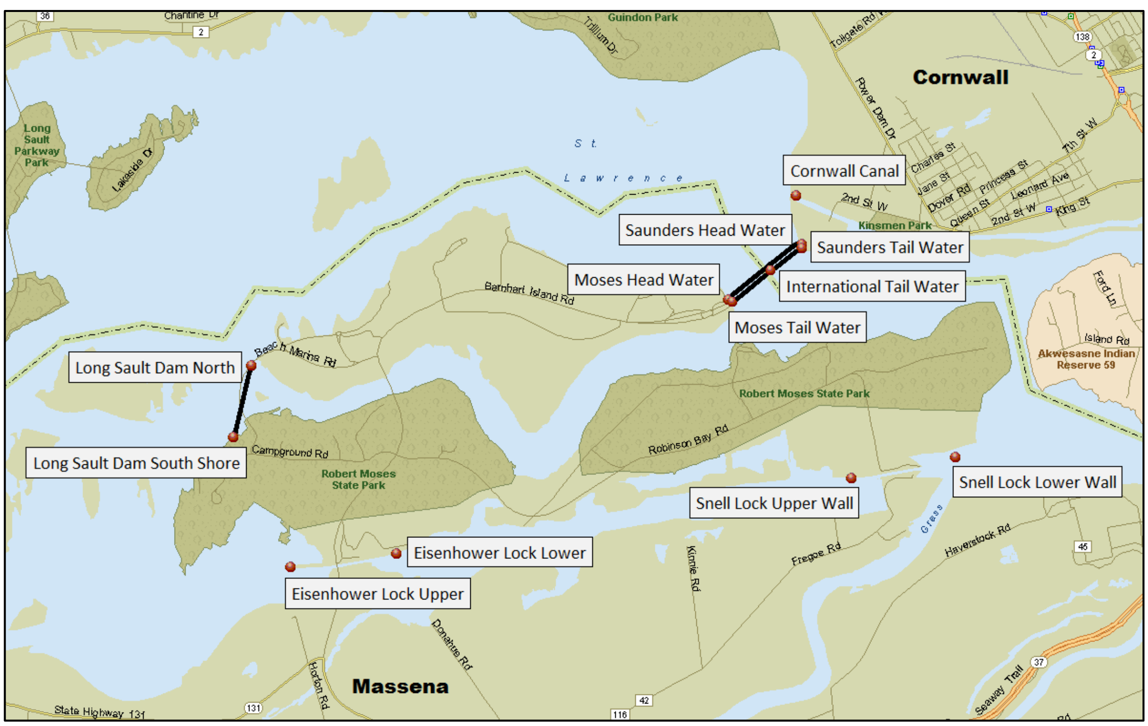

Figure 11. Gauging stations operated by the power and Seaway authorities in the Cornwall-Massena area. This is just one example of many where gauges will need to be updated to IGLD (2020)

In addition, Great Lakes diversions also contribute to lake level fluctuations. There are presently five major diversions of water affecting the Great Lakes system: The Long Lac and Ogoki diversions, the Lake Michigan diversion at Chicago, the Welland Canal diversion, and the New York State Barge Canal diversion. All the above diversions are long-standing ones, each established for a different purpose and possessing a unique set of hydrologic, environmental and economic impacts.

All the above operations fall within the water management perspective of the Great Lakes system. All use operational water level gauges that will require their datums to be updated (see Figure 11 for an example). The gauging stations associated with these operations are included in Appendix 3. It is highly recommended that these gauges be included in the IGLD (2020) (and the 2020 GNSS survey) to avoid any incompatibilities in the heights used for their operations when IGLD (2020) is adopted. Because LWD steps need to be re-determined, many of these stations must be included in IGLD (2020).

3.3 Other impacts

There are many other impacts that need to be considered and addressed in the outreach plan. Some of the most important ones are summarized in the following Table 1.

Table 1. Some potential impacts of an IGLD update.

Activity	Impacts
Navigation	• LWD (or chart datum) will need to be changed on nautical charts from IGLD (1985) to IGLD (2020). • LWD at the connecting channels and St. Lawrence River gauging stations, along with those at locations used for dredging, will need to be re-determined. • The shoreline depicted on nautical charts (high water mark) may change. • Chart depths may need to be changed. • Under-keel clearance may be affected.
Outflow Regulation	• Height references will require adjustment for regulating Lake Superior and Lake Ontario outflows, and the Chippawa – Grass Island Pool in the Niagara River. • Flooding/erosion control heights, trigger heights, and criteria thresholds will change. • Engineering project datums will be affected. • Restoration project datums will be affected. • Models and tools used in adaptive management to evaluate regulation plan performance will be affected.

Activity	Impacts
Water Management	• Update of historical water level records and lake level forecasting products to new datum will be required. • Update of stage-discharge rating equations and other supporting models/data/tools (e.g., bathymetry), used to calculate lake outflows, lake and connecting channel hydrodynamic and routing models, to new datum • Update of hydroelectric rating tables to new datum will be required. • Update of water supply information will be needed. • Effect on infrastructure such as municipal water intakes and nuclear power station water cooling systems must be determined. • Updating of heights of power entities' and Seaway authorities' water level gauges for flow determination and regulation planning are needed. • Updating of water level information in publications and other communications will be required.
Shoreline Use Planning	• Shoreline use permits in the U.S. and Canada will need to reference IGLD (2020) because… • Lake levels, IGLD station bench marks and high water marks will be based on the new datum. • Monthly water level bulletins and weekly water level forecasts published by USACE, ECCC and CHS will be on the new datum.
Surveying and Mapping	• GNSS surveys and the adopted IGLD geoid (datum) will substitute for geodetic leveling between gauges. • Procedures and algorithms for using geoid-based datums to estimate accurate IGLD (2020) GNSS-derived dynamic heights will need to be developed and published. • Crustal movement models will be available. Procedures and tools using movement rates will need to be developed for applications that require high-accuracy coordinates.

4. Agency Roles and Responsibilities

The International Great Lakes Datum is maintained by both Canada and the United States. As such, several government agencies in both countries assume responsibility for the datum and mention the datum in their strategic plans.

4.1 Agency mandates

U.S. Agencies

The U.S. Department of Commerce Strategic Goal on the Environment, Objective 3 (Department of Commerce, 2014) is to advance the understanding and prediction of changes in the environment through world-class science and observations. This is through both the National Institute of Standards and Technology (NIST) and NOAA. Updating a datum that has seen shifts over time due to changes in the environment directly fulfills this objective. The NOAA objective that covers the IGLD is "Resilient Coastal Communities and Economies" and falls under NOAA's National Ocean Service (NOS). Within NOAA/NOS, both CO-OPS and NGS are responsible for the update to the datum.

The CO-OPS 2015-2020 Strategic Plan (Center for Operational Oceanographic Products and Services, 2015) directly cites as an actionable strategy to initiate activities to upgrade the International Great Lake Datum.

The NGS Ten-Year Strategic Plan 2013-2023 (National Geodetic Survey, 2013) states that NGS must develop a comprehensive strategy for incorporating past and future leveling data into a GNSS/geoid-based vertical datum and include a connection between the new geoid-based vertical datum and the updated International Great Lakes Datum.

GLERL's Strategic Plan (Great Lakes Environmental Research Laboratory, 2016) and its companion Implementation Plan, commit to supporting the IGLD by: (1) providing outreach via the NOAA Great Lakes Regional Collaboration Team and its Communications Committee, (2) providing vessel support from the Lake Michigan Field Station as required, (3) supporting water level data analysis and dynamic water level modeling for determination of hydraulic correctors, and (4) participating in the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data.

The U.S. Army Corps of Engineers (USACE) builds and maintains the U.S.'s infrastructure within the Great Lakes region through district offices in Chicago, Detroit, Buffalo, and a division office in Cincinnati. These offices provide information on water levels, outflows and flood monitoring in the Great Lakes region. They also support Great Lakes navigation through dredging of channels and harbors, and construction and maintenance of coastal infrastructure. The U.S. portion of the navigation system includes 140 harbors (60 commercial; 80 recreational), two operational locks, 193 km (104 miles) of breakwaters and jetties, and over 1,100 km (600 miles) of maintained navigation channels. In addition, the Great Lakes Navigation System (GLNS) is connected to several other shallow-draft waterways (Illinois Waterway, New York State Barge Canal, etc.) to form an important waterborne transportation network, reaching deep into the continent. An accurate and up-to-date International Great Lakes Datum is critical to meeting the requirements for the management of water resources and the navigation system in the Great Lakes.

Canadian Agencies

ECCC's National Hydrologic Services (NHS) has a mandate to conduct water science and hydrometric monitoring to provide information on the water cycle (Environment Canada, 2015). ECCC also provides science, engineering and monitoring information to domestic and international water boards (e.g. International Joint Commission) for the regulation of water levels and flows related to domestic and Canada-U.S. transboundary waters. The maintenance of an accurate, up-to-date IGLD is essential for ECCC to deliver on these responsibilities in the Great Lakes – St. Lawrence River Basin.

The CHS of Fisheries and Oceans Canada (DFO) has a mandate to provide timely, accurate, and up-to-date hydrographic products and services, which include operating a water level gauging network to provide water level data for marine navigation, forecasting, and monitoring (Fisheries and Oceans Canada, 2015). For CHS to deliver on its responsibilities in the Great

Lakes and St. Lawrence River, the International Great Lakes Datum must be maintained and updated as required to provide an accurate reference datum for these data and products.

The CGS of Natural Resources Canada (NRCan) has a mandate to define and maintain the geometric and vertical references systems for Canada that are consistent with continental and global reference systems (Geodetic Survey Division, 2009). In support of this, Canada has already implemented and adopted a new geoid-based national vertical datum. Although it does not explicitly mention the IGLD, the plan does mention that CGS needs to focus on providing "reliable geometric reference frames to support high accuracy positioning and geodetic measurements of the Dynamic Earth contributing to Water, Climate Change, Natural Hazards research and other Public Policy issues and priorities." This includes the modernization of vertical datums based on GNSS and a geoid-based vertical datum for monitoring of water levels as well as the GNSS monitoring of crustal dynamics in the Great Lakes – St. Lawrence River Basin.

International Agencies/Committees

The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, formed in 1953, is an *ad hoc* committee of experts from federal agencies of the United States and Canada charged with the responsibility for collecting, compiling, using, or disseminating data related to hydraulics, hydrology, vertical control, and water levels for the Great Lakes – St. Lawrence River System. The Coordinating Committee serves in an advisory capacity and provides international standardization of hydrologic and hydraulic data for the federal agencies involved in monitoring and managing water levels within the Great Lakes, connecting channels and the St. Lawrence River. The IGLD is used as the reference datum for these water levels, and the Coordinating Committee's Vertical Control – Water Levels Subcommittee has the responsibility for reviewing the existing IGLD and revising it as necessary. It also issues informational materials, binational standardization guidance, and reports for establishing bench mark elevations in the current IGLD reference frame.

The IJC is an international organization that prevents and resolves disputes between the United States of America and Canada under the Boundary Waters Treaty and pursues the common good of both countries as an independent and objective advisor to the two governments (International Joint Commission, 2015). The IJC rules upon applications for approval of projects affecting boundary or transboundary waters and may regulate the operation of these projects.

The IJC establishes "boards" of experts from both countries to assist in carrying out its activities. Boards are appointed by the Commission to report on compliance with the orders of approval, while study boards, advisory boards, task forces, and committees assist in references and other matters. These include the following for the Great Lakes Basin:

- International Lake Superior Board of Control
  The board oversees the operation of various control works on the St. Marys River to regulate the outflow of Lake Superior at Sault Ste. Marie.
- International Niagara Board of Control
  The board monitors the operation of the Chippawa – Grass Island Pool control

structure above Niagara Falls and supervises the annual installation and removal of an ice boom at the outlet of Lake Erie.

- International Lake Ontario - St. Lawrence River Board
  The board oversees the operation of various control works on the St. Lawrence River to regulate the outflow of Lake Ontario.
- Great Lakes-St. Lawrence River Adaptive Management Committee
  The Great Lakes-St. Lawrence River Adaptive Management (GLAM) Committee undertakes the monitoring, modeling and assessment needed to support on-going evaluation of the regulation of water levels and flows.

All these boards and committees depend on an accurate and up-to-date IGLD.

The Great Lakes Commission is another public agency established in 1955 to help its member states and provinces speak with a unified voice and collectively fulfill their vision for a healthy, vibrant Great Lakes – St. Lawrence River region (Great Lakes Commission, 2007, 2012). Commission products and services focus on communication and education, information integration and reporting, facilitation and consensus building, and policy coordination and advocacy. Its members include the eight Great Lakes states with associate member status for the Canadian provinces of Ontario and Québec.

The primary purpose of the Great Lakes Commission is to promote the orderly, integrated, and comprehensive development, use, and conservation of the water resources of the Great Lakes Basin. The Commission addresses a range of issues involving environmental protection, resource management, transportation, and economic development. Observer organizations, including U.S. and Canadian federal, regional and tribal governments, participate extensively in Commission activities. The Commission focuses on six program areas: (1) Clean Energy and Climate; (2) Water-dependent Economy and Infrastructure; (3) Invasive Species; (4) Water Resources Management; (5) Water Quality and Ecosystem Health; and (6) Habitat and Coastal Management. These programs depend on an accurately established vertical datum. The Commission has considered this to be such an important requirement that they have adopted a resolution urging Canada and the U.S. to prioritize the updating of the IGLD to ensure that this fundamental vertical datum is maintained to the highest accuracy possible using the best available technologies (see Appendix 1 for the full resolution).

The Great Lakes/St. Lawrence Seaway was built as a binational partnership between the U.S. and Canada and continues to operate as such. Administration of the system is shared by two entities: (1) the Saint Lawrence Seaway Development Corporation (SLSDC) in the U.S., a federal agency within the U.S. Department of Transportation, and (2) The St. Lawrence Seaway Management Corporation in Canada (SLSMC), a not-for-profit corporation (ownership of the Canadian portion of the Seaway remains with the Canadian federal government).

The U.S. SLSDC is a wholly owned government corporation created by statute May 13, 1954 to construct, operate, and maintain that part of the St. Lawrence Seaway between the Port of Montréal and Lake Erie, within the territorial limits of the United States. The SLSDC operates and maintains the U.S. infrastructure and waters of the St. Lawrence Seaway, while performing trade development focused on driving economic activity for the Great Lakes – St. Lawrence Seaway System. Their mission is to serve the marine transportation industries by providing a safe, secure, reliable, efficient, and competitive deep-draft international waterway, in cooperation with the Canadian St. Lawrence Seaway Management Corporation.

The Canadian SLSMC is a not-for-profit corporation responsible for the safe and efficient movement of marine traffic through the Canadian Seaway facilities, which consists of 13 of the 15 locks between Montréal and Lake Erie. The Corporation plays a pivotal role in ensuring that the waterway remains a safe and well-managed system, which it shares with its American SLSDC counterpart.

The two Seaway entities coordinate operational activities, particularly with respect to rules and regulations, overall day-to-day operations, traffic management, navigation aids, safety, environmental programs, operating dates, and trade development programs. The unique binational nature of the system requires 24-hour, year-round coordination between the two Seaway entities. Both Seaway authorities, as well as power entities, operate and maintain water level gauges that should be used to help define the IGLD.

4.2 Roles and responsibilities

The maintenance and updating of the IGLD falls directly under the auspices of the Coordinating Committee. Member agencies responsible for establishing, implementing, and maintaining the IGLD are NGS and CO-OPS in the U.S., and CGS, CHS, and ECCC-NHS in Canada. The work proposed by these agencies to update the datum needs to be coordinated and approved by the Coordinating Committee.

To maintain an accurate datum that represents the entire Great Lakes Basin, careful coordination between Canada and the United States must occur. Accordingly, anytime an agency in one country collects geodetic or water level information associated with the update, it must be done simultaneously with the other country's measurements to eliminate, as much as possible, errors associated with measuring at different times.

In the Great Lakes, CO-OPS maintains 53 water level gauge stations within the U.S., while in Canada CHS and ECCC-NHS maintain 34 gauges. These stations will be the primary reference for the update. Updating the IGLD at these 87 stations represents only the framework for the implementation of IGLD. The ideal implementation of an IGLD update also includes a set of strategically located harbors, ports, locks, and hydro power projects throughout the region, at which either long-term and or new short-term observations are required to establish locally accurate updated IGLD elevations. Because of insufficient funding during the update period for the establishment of IGLD (1985), some 140 seasonal harbors in the U.S. and some 100 harbors in Canada referenced in IGLD (1955) were not included in the 1985 update. Only the permanent Canadian and U.S. long-term network stations were used in the 1985 compilations to determine IGLD (1985). Thus, local datums originally established in IGLD (1955) are severely out-of-date due to GIA movements (estimated to be as much as ±0.2 m over 65 years). The water level agencies should work closely together to identify as many seasonal water level gauge requirements and locations as possible and coordinate collection of data.

In the U.S., NOAA's CO-OPS office performed a gap analysis study of its permanent gauging network for safe and efficient navigation in harbors, better representation of hydraulic corrections, research on coastal resiliency, etc. (Gill, 2014). They identified three potential new gauge locations. Two locations are in Lake Michigan, one in the lower southeast corner, and one in the northeast corner of the lake. The third is in the upper northwest corner of Lake St. Clair. In Canada, CHS plans to perform a similar gap analysis for their gauging network.

Up to 140 gauge locations in local U.S. harbors and ports have been identified for possible seasonal installation using a single, four-month deployment scheme (June through September). These deployments will be prioritized based upon criteria discussed in Section 2.5. Canada is working to identify their gauge locations for seasonal installation. It is expected that up to 100 locations will be identified using similar criteria for prioritization as the U.S.

Both federal geodetic agencies in Canada and the U.S. (CGS and NGS, respectively) will work together to collect GNSS measurements at bench marks at the permanently operating water level gauges in the U.S. and Canada. NGS and CGS completed a fourth GPS campaign survey during August 2015 and plan to do another GNSS campaign in 2020 — the central (reference) epoch of the IGLD update.

Although Canada has already developed and adopted a geoid-based vertical datum, the CGVD2013, as their country's new vertical datum, both NGS and CGS are also working closely on the development of a North American geoid model that will eventually be adopted by both countries' geodetic offices. This model will serve as the foundation for determining dynamic heights in the Great Lakes – St. Lawrence River system. The two organizations meet periodically to discuss and solve technical issues associated with establishing a North American geoid model. NGS and CGS will periodically brief the Coordinating Committee on the status of a North American geoid model.

Finally, CGS is evaluating the requirement for absolute gravity measurements at the IGLD stations and will report back to the Coordinating Committee after collecting and analyzing test data obtained along the northern shores of Lake Superior.

4.3 Recommended agency roles for IGLD (2020)

The Coordinating Committee's Vertical Control – Water Levels Subcommittee has been tasked with the responsibility for coordinating and implementing the IGLD (2020) update plan. The Subcommittee will be represented by CO-OPS and NGS from the U.S. and CHS, ECCC-NHS, and CGS from Canada.

CGS and NGS

CGS and NGS maintain geodetic datums in the Great Lakes – St. Lawrence River system and are integral to determining heights over land as they relate to the IGLD. It is recommended that:

- CGS and NGS collect GNSS observations in FY2020 at identified bench marks associated with the permanent Great Lakes water level gauges. The GNSS measurements will be used to determine the stability and/or movement of the water gauge reference bench marks over time. CGS and NGS have already completed full or partial surveys of the IGLD network in 1997, 2005, 2010 and 2015.

- CGS and NGS continue to generate scientific North American geoid models and evaluate the accuracy of these geoid models comparing ellipsoid heights and leveling-derived heights. NGS has collected airborne gravity data over the Great Lakes as part of its GRAV-D project to incorporate into and improve the geoid models. To evaluate the accuracy of geoids, CGS and NGS are also continuing their analysis of water levels on each lake using geopotential data based on their latest geoid models.
- CGS and NGS determine if it is necessary to collect additional surface gravity data in the Great Lakes region after more analyses of GRAV-D results and testing of updated geoid models. Comparison of actual gravity measurements in northern Lake Superior to interpolated gravity to determine whether gravity measurements will be required at all IGLD stations.
- CGS and NGS collaborate on the generation of crustal movement models and other geodetic activities as they relate to IGLD.
- CGS and NGS provide transformation models and tools between the new IGLD and previous datums as required.
- CGS and NGS provide guidelines and tools for users to obtain accurate IGLD dynamic heights.
- CGS and NGS determine and disseminate a consistent set of heights and velocities for the IGLD (2020) project.

CHS/ECCC-NHS and CO-OPS

CHS and CO-OPS water level monitoring expertise in the Great Lakes is essential to determining the update to the IGLD. It is recommended that:

- CHS and CO-OPS perform annual maintenance at all permanent gauge locations in accordance with standard operating procedures, including leveling ties between the gauge reference and the local bench marks. This is most critical during each year of the seven-year data collection period and in an additional eighth year to ensure the seventh year is still valid.
- CHS and CO-OPS calculate the LWD (chart datum) reference for each of the Great Lakes with respect to the new vertical datum.
- CHS and CO-OPS, once the Lakes LWD references are determined, compute the LWD references for each country’s gauges located in the sloping surfaces of the connecting channels and the St. Lawrence River.
- CHS and CO-OPS determine the best method to archive the backlog of leveling data from Great Lakes gauging stations.
- CHS, ECCC-NHS, and CO-OPS assist CGS and NGS with reconnaissance and GNSS survey campaigns in FY20.
- CHS and CO-OPS collaborate with CGS and NGS to determine whether hydraulic correctors are needed.

- CHS and CO-OPS prioritize the deployment of seasonal gauges and their local leveling ties.
- CHS and CO-OPS collaborate with CHS and NGS to provide transformation models and tools (see CGS and NGS roles above).

4.4 Coordination with Other agencies

In the U.S., in addition to NGS and CO-OPS, there will be coordination with other NOAA offices as the update progresses. Specifically, the Office of Coast Survey (OCS) has nautical charting responsibilities as well as mathematical modeling expertise. These skills will be used as the IGLD is updated. Once the update is completed, OCS will determine if nautical charts need to be updated. For changes of less than half a chart unit (6 inches in Great Lakes), OCS will declare soundings to be on the new datum. If a change is more than the sounding interval, OCS will determine adjustments. Shoreline reference adjustments may also have to be made in conjunction with NGS/ Remote Sensing Division. OCS may also provide support for modeling of the new interpolation model, which in turn will support the update to VDatum models. Additionally, OCS has a Great Lakes navigation manager who will be important to communicating the changes in the datum to the marine navigation community.

GLERL has requirements for water level information to assist with modeling information for real-time operational forecasts but also for understanding meteotsunami (meteorological tsunami) in the lakes. In particular, GLERL is interested in Green Bay and Saginaw Bay, which CO-OPS already acknowledges are special areas of concern in both Lakes Michigan and Huron. Additionally, the newly released Lake Level Viewer from the NOAA's Office of Coastal Management (OCM) will need to be updated once the official datum is accepted and updated. CO-OPS will work closely with OCM on any updates. Also, CO–OPS and NGS will engage with the Great Lakes Observing System Regional Association to discuss collaborations on products or instrumentation.

The National Estuarine Research Reserves and Sea Grant offices will be instrumental in outreach to stakeholders about the updated datum. See Section 5.0 on outreach for more information on collaboration efforts.

As in both the previous IGLD establishments, continued coordination with those agencies responsible for the Great Lakes water level network stations and those agencies responsible for dredging the federal harbors, connecting channels and the St. Lawrence River, is essential. In the U.S. USACE and in Canada the Canadian Coast Guard (CCG) maintain the federal harbors. Both agencies share the dredging responsibilities for the connecting channels. In the St. Lawrence River, the Canadian SLSMC and the U.S. SLSDC jointly share the responsibilities for dredging of the seaway. In all these locations, each country's permanent water level network gauge or gauges determine the LWD reference for a lake. For the sloping surface of a channel or river, each station's LWD reference is based on a regression analysis holding the LWD reference on the lake above and the lake below. Similar determination is used for the LWD steps between the permanent stations for dredging operations.

In the U.S., the USACE is responsible for defining the "ordinary high water mark" (OHWM) adopted around the Great Lakes. In Canada, CHS is responsible for defining a similar point called the "high water line" (HWL).

Also, the adjustments to lake-wide average water levels, net basin supplies, daily/monthly/quarterly mean water level datasets, as well as many other products, will need to be coordinated in conjunction with USACE, ECCC, GLERL and the IJC Boards.

In Canada, CHS will determine if the chart soundings (or water depths) will need adjustments and if charts need updating. This would be communicated through Notice to Mariners, product updates and communication with user groups.

4.5 Required resources

Funding

To obtain a complete representation of the lake levels, water level and GNSS data need to be collected at all ports and harbors of refuge and incorporated into the IGLD update. Although there may not be enough funding for the installation of all seasonal gauges in both countries, Section 2.5 will identify criteria for selecting and prioritizing the "seasonal" gauging.

Additional funding may be required to address the research questions outlined above. There may be opportunities to leverage geodetic research work at universities as well, especially those in the region. There may also be possibilities of leveraging the work and capabilities in provincial and state agencies within the region.

Personnel

Additional personnel resources within both countries' offices will be necessary to complete the analysis and research required to perform the update. Most of the existing U.S. and Canadian Subcommittee members working on IGLD in 2016 will be retired by 2025. It is important to recognize this loss of institutional knowledge and train newer employees on the history and nuances of IGLD, as well as the steps needed to update the datum. Both the U.S. and Canadian offices will need to ensure that research activities that need to be performed in support of IGLD are determined in advance and incorporated into future planning documents.

Personnel will be required to support the GNSS campaigns in FY2020. Additionally, personnel are required to prepare any seasonal gauge requirements that may be deployed in support of the update. Some of this work may also be contracted out to qualified engineering firms.

IT Infrastructure

Both the U.S. and Canadian agencies will need to ensure that any IT infrastructure to load, retrieve, and publish IGLD (2020) results (e.g., databases, websites, user interfaces) is available or developed. Graphical interfaces may also be required for the analysis and distribution of IGLD (2020) results and products. These IT requirements will need to be determined and incorporated into future planning documents. The LWD reference will need to be added as an attribute to be tracked at each station.

External Contributions

CO-OPS, NGS, CHS, and CGS will need to determine whether they will accept external user data, such as GNSS survey data on IGLD bench marks, for incorporation into IGLD (2020). If such data are accepted, how will it be used to support other projects (e.g., geoid modeling and analysis, validation of GNSS-derived orthometric heights, leveling system error studies, development of guidelines)? What standards and criteria would such data need to meet to be useful for these analyses?

5. Outreach and Communication Requirements

A significant amount of outreach in both the U.S. and Canada will be needed in relation to the update. Since the update last occurred 30 years ago, many people do not have the "corporate memory" of the changes that were made or any impacts that were realized from the update.

An outreach and communication strategy is needed to ensure that stakeholder groups are included. The Vertical Control – Water Levels Subcommittee needs to identify partners, customers, users, and stakeholders involved in or affected by an IGLD update. Members will need to prepare publications, convene workshops/webinars, etc. to discuss with stakeholders the IGLD update (e.g., its definition and transformations to/from other datums) and its impact.

Coordinating Committee agencies should identify potential impacts to their products and services and provide outreach to the offices that produce those products to ensure full understanding of the IGLD update (e.g., any products that reference water levels to IGLD should be updated). In the U.S., this would include the Office for Coastal Management's Lake Level Viewer and numerous GLERL products such as the Great Lakes Water Level Dashboard. In Canada, this includes DFO's Marine Environmental Data Service and Environment and Climate Change Canada products such as water level forecasting and the *Level News* publication. As previously mentioned, the nautical charts may need to be updated as well, with implications for the shipping and maritime community. IJC regulation plans would also all require adjustments.

Other federal agencies, whose projects will most likely be affected by the update, should be at the top of the list for an outreach effort. In the U.S., this includes the USACE, USGS, U.S. Coast Guard, and the Federal Emergency Management Agency. In Canada, this includes ECCC, Fisheries and Oceans Canada, and the provincial governments of Ontario and Québec. In addition, the Coordinating Committee should brief the U.S. Federal Geodetic Control Subcommittee of the Federal Geographic Data Committee, the Great Lakes Commission, and the Conference of Great Lakes and St. Lawrence Governors and Premiers.

The IJC and its Great Lakes Boards for Lake Superior, Niagara River, and the Lake Ontario-St. Lawrence River oversee regulation of water levels and flows in the Great Lakes – St. Lawrence River System. The boards are key clients of water level information products and can act as conduits to Great Lakes stakeholders affected by water level regulation. Outreach to the boards and potentially through the boards to the public should be a key outreach activity. Further outreach can be through the GLAM Committee, an IJC committee recently enacted in February 2015. This committee is composed of eighteen members, of which six are presently representatives within the Coordinating Committee. The GLAM committee reports to each of the Great Lakes boards. It will undertake the monitoring, modeling, and assessment needed to support ongoing evaluation of the regulation of water levels and flows and will assess the differences related to the IGLD update. The GLAM committee will inform and keep the Great Lakes boards updated. They will provide ongoing information on the effects of the changing heights related to regulation of water levels and flows, which can affect local, regional, national, and global socioeconomic interests, as well as possible environmental impacts. All are key to keeping the public informed about the IGLD update. For more information about the IJC, the boards and the GLAM Committee, see the following websites:

http://www.ijc.org/en_/
http://www.ijc.org/en_/boards
http://ijc.org/en_/GLAM/About_the_Committee

State and provincial transportation and environmental agencies will benefit from outreach discussions about the upcoming datum shift.

The Coordinating Committee's agencies should also begin to engage with the conservation authorities and other special interest groups in both countries to explain the implications of the update.

The general surveying and mapping community will need to be informed about the changes that will be made to the datum and possible effects it might have on their work.

The navigation community will also benefit from outreach about the IGLD update. NOAA and CHS will ensure that they provide information to the community about the updated navigation products. The Saint Lawrence Seaway corporations in both countries should also be informed of the update and its implications for their products.

Collaboration with the Sea Grant program should be sought by U.S. agencies to help with outreach and communications to state and local stakeholders in the U.S.

If necessary, outreach to potential partners that could collaborate with the installation of seasonal gauges meeting federal standards should take place. These might include local harbor authorities and state agencies with a vested interest in the IGLD update.

Since national vertical datums in both countries are expected to be updated around the same time, it will be a good opportunity to draw attention to and educate others on the importance of vertical datums.

Training Materials & Workshops

While the IGLD update work continues, it would be desirable to develop training materials and guidelines on the use of the IGLD and focus on moving from IGLD (1985) to IGLD (2020).

The Coordinating Committee's agencies involved in the IGLD update should consider preparing workshops to explain what IGLD heights are and how to use them. These workshops could include training on the computation of orthometric heights, dynamic heights, hydraulic correctors, and how gravity is important to the computations. The workshops could be held in conjunction with conferences and as periodic webinars.

Additionally, the Coordinating Committee agencies working on the update will need to document and share their expertise in the analysis of water level data and IGLD adjustments in the presence of crustal motion. This can be accomplished in a variety of ways, including formal publications, internal reports and seminars, workshops, and webinars.

6. Initial Project Timeline

An initial project timeline (Table 2) has been identified for the period of work leading up to the revised datum.

Table 2. IGLD (2020) project activities and milestones.

Activity	Target Date/Period	Recommended Responsible Agencies
Complete binational plan for IGLD (2020) and present to the Coordinating Committee for approval	Completed	Vertical Control – Water Levels Subcommittee
Choose and adopt a W_0 as the new IGLD reference zero (Section 2.1)	Completed	Coordinating Committee
Identify potential IGLD partners and users who can help develop and implement IGLD (2020) (Section 3.4)	2016-2023	Vertical Control – Water Levels Subcommittee
Digitize and archive old leveling information, as required	2016-2023	CO-OPS, NGS CHS, CGS
Perform annual maintenance and leveling ties at permanent water level gauges	2016-2024	CO-OPS, USACE CHS, ECCC & others
Perform analysis of permanent gauging requirements and prioritize new proposed gauges (Section 2.5)	2017	CO-OPS CHS
Adjust and publish 2015 GPS campaign survey results	2017	NGS CGS
Complete preparation of internationally coordinated methodologies for determining heights using GNSS surveys and local leveling ties at gauges (Section 2.7)	2017-2018	NGS, CO-OPS, USGS, USACE CGS, CHS, ECCC
Complete preparation of international outreach and communication plan, and begin implementation (Section 5)	2017-2018	Vertical Control – Water Levels Subcommittee
Review historic water level data for re-evaluation of LWD (Section 3.1)	2017-2018	CO-OPS, USACE CHS, ECCC
Reanalyze and compare all GPS campaign surveys from 1997, 2005, 2010, 2015 to estimate preliminary rates of movement (Section 2.6)	2017-2018	NGS CGS
Perform analysis of seasonal gauge requirements and prioritize locations (Section 2.5)	2017-2023	CO-OPS CHS
Begin annual installations of seasonal water level gauges with GNSS and leveling ties (Section 2.5)	2017-2023	CO-OPS CHS
Perform 2020 GNSS campaign survey in Great Lakes – St. Lawrence River system, including entity gauges (Section 2.6).	Summer 2020	NGS, CO-OPS CGS, CHS and others
Adopt N.A. geoid model for IGLD (2020) (Sections 2.1 and 2.2)	2022	Coordinating Committee with NGS & CGS
Create crustal movement models for the Great Lakes – St. Lawrence River system using all available GNSS campaigns and CORS/CACS data (Section 2.6)	2023	NGS CGS
Complete seasonal water level gauging (Section 2.5)	2023	CO-OPS / CHS
Determine hydraulic correctors (Section 2.4)	2024	NGS, CO-OPS CGS, CHS, ECCC
Determine new LWD on lakes and rivers with respect to IGLD (2020) (Section 3.1)	2024	CO-OPS, USACE CHS, ECCC
Determine and publish transformations between IGLD (2020) and other datums, including IGLD (1985) (Section 2.8)	2024	NGS CGS
Publish new IGLD (2020) datum	2025	Coordinating Committee

7. Reporting Requirements

The Coordinating Committee recommends that agencies involved in the IGLD update follow their own project management processes to plan, execute, track, and report on their activities to their management and the Vertical Control – Water Levels Subcommittee. The Subcommittee should then report on these activities at the biannual meetings of the Coordinating Committee. NOAA has already prepared a detailed plan upon which has contributed greatly to this document.

A Coordinating Committee publication on the establishment and results of the updated IGLD should be prepared and published at the completion of its implementation.

8. Acknowledgements

This binational plan was prepared by the Coordinating Committee and its Vertical Control – Water Levels Subcommittee. The plan has drawn much from the NOAA document "A Plan to Update the International Great Lakes Datum – A Look Ahead: 2015-2020" by the Center for Operational Oceanographic Products and Services and the National Geodetic Survey. That plan has contributed greatly to this Coordinating Committee-focused document. The significant amount of work that went into the preparation of the NOAA document saved the Coordinating Committee much time and effort and was greatly appreciated.

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Appendix 1: Great Lakes Commission Resolution on IGLD Update

Great Lakes Commission des Grands Lacs

RESOLUTION
Adopted Feb. 25, 2015

Updating the accuracy of the International Great Lakes Datum (IGLD)

Whereas, movement of the Earth's crust across the Great Lakes - St. Lawrence River system occurs on a very gradual, continuous and non-uniform basis (in some areas in the magnitude of centimeters per decade), referred to as "glacial isostatic adjustment" or rebounding of the land surface from the weight of glaciers that retreated over 10,000 years ago; and

Whereas, water levels in the Great Lakes-St. Lawrence system fluctuate on a short-term, seasonal and long-term basis, requiring careful and accurate measurements within an accurately established vertical datum; and

Whereas, the safety and economic viability of the Great Lakes commercial navigation industry, the extensive recreational boating community and ports/harbors across the region all rely heavily on accurate water level forecasts and maintenance of congressionally authorized dredging programs to provide depths in the navigation channels including waterways connecting the Great Lakes; and

Whereas, all coastal zone management, including erosion prediction, flood prediction and response, and coastal structure design, construction and maintenance, rely upon an accurate vertical elevation datum; and

Whereas, all coastal habitat restoration, rehabilitation, creation, enhancement, improvement and protection activities currently underway and expected to be implemented under the Great Lakes Restoration Initiative (GLRI) require an accurate vertical datum; and

Whereas, prediction of the magnitude, timing and duration of climate variability as it affects the Great Lakes-St. Lawrence River system, and the development of adaptive management approaches thereto, require accurate water level measurements and forecasts; and

Whereas, 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 35 years to reflect continuous and differential changes in land surface elevations across the region and IGLD (1985) is now due for an update.

Therefore, be it resolved, that the Great Lakes Commission urges the National Oceanic and Atmospheric Administration (NOAA) to prioritize the IGLD update, with anticipated release in 2025, and to coordinate their activities with Canadian federal and provincial partners, to ensure that this foundational vertical datum is maintained to the highest accuracy possible using the best available technologies; and

Be it resolved, that the Great Lakes Commission urges NOAA to partner with states, Canadian provinces and federal entities to extend the accuracy of the new IGLD in all ports and harbors of refuge that were not updated in 1985;

Be it finally resolved, that the Great Lakes Commission urges the U.S. Congress to provide necessary financial resources to complete the IGLD update, and further requests that the Canadian federal government provide a commensurate share to ensure timely completion of this important endeavor.

Adopted at the 2015 Semiannual Meeting of the Great Lakes Commission, February 24-25 in Washington, D.C.

Appendix 2: Agreement on W_0 for a new N.A. Vertical Datum

**Agreement: The U.S. National Geodetic Survey and
The Canadian Geodetic Survey**

March 14, 2012

The U.S. National Geodetic Survey and Natural Resources Canada's Geodetic Survey Division, via conference call held 2012/02/17, **agree**:

- To ***define*** the common (a unique) vertical datum for the United States of America (USA) and Canada (CA) through use of an equipotential surface, realized through one commonly (jointly) computed geoid model, corresponding to the mean coastal sea level for North America by 2022. Adoption is subject to National decisions;
- To ***compute*** the potential W_0 of this equipotential surface using Global Positioning System (GPS) data on tidal benchmarks, by April 1, 2012 and to ***use*** this value, for the realization of geoid models in the USA and CA until 2022;
- To ***maintain*** this equipotential surface as one option to adopt as the vertical datum even if this surface diverges (departs) from the true mean coastal sea level for (around) North America over time;
- To ***monitor*** differences between the above-mentioned equipotential surface and the mean sea level via Global Navigation Satellite Systems (GNSS) on tidal benchmarks, altimetry or other means as required;
- To ***provide*** to the public, deformational velocities (*N-dot*) of the equipotential surface W_0;
- To ***collaborate*** in the realization of geoid models, through the sharing of data and related information:
- To ***compute*** updated geoid models and geoid deformation models with improved realizations as needed;
- To ***inform*** each other when large discrepancies (outside 95% confidence region) are found in overlapping regions; and
- To ***choose*** a threshold value (in alignment with both stakeholder needs and scientific integrity) in 2022, between predicted (modeled) geoid change and true geoid change (including deformation and sea level change) which will warrant new realization of the vertical datum.

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The geopotential for the North American height reference system **16 April 2012**

Canada and the United States are both working towards modernizing their national height reference systems to replace CGVD 28 and NAVD 88, respectively with the objective to create a seamless height reference system across North America. As the new vertical datum will be realized by a geoid model, it is essential that Canada and USA select a common equipotential surface. Both parties have agreed that this surface should be the best fit, in a least squares sense, of the coastal mean sea level around North America.

In order to compute the mean geopotential, GPS heights and water levels at coastal tide gauges were combined with various geoid models. Given the variability of the mean sea level due to Sea Surface Topography (SST), the analysis was affected by tide gauge location and distribution, and geoid model precision and resolution. Based on comparisons at tide gauges around Canada and the United States where SST models were available, the best fit is 62,636,856.0 m^2s^{-2}. By averaging the Arctic gauges that were outside the coverage of the SST models, the geopotential would have been higher, approaching 62,636,858.0 m^2s^{-2}. Although very little data were available around Mexico and in the Caribbean region, including more tropical data would have likely lowered the geopotential to 62,636,854.0 m^2s^{-2}. Thus, the lack of tide gauges in Arctic and tropical regions somewhat compensates itself. Estimates of the North American mean obtained with different datasets, station combinations and weighting scenarios remained within 1 m^2s^{-2} of each other depending on the particular tide gauge distribution and geoid models selected.

Understanding the importance of selecting a conventional value without delay for CGVD2013 realisation, the decision was made to select:

$$\mathbf{W_0 = 62{,}636{,}856.0\ m^2s^{-2}}$$

as the geopotential value for all geoid models in North-America until 2022. This agreed upon value of W_0 was found to be within the uncertainty of the mean estimate that best fits with mean sea level around North America. Although sea level is known to be changing, this W_0 value will be adopted as a fixed reference value until at least 2022 in order to enable consistent height determinations over the coming decade. This value could also be suitable for Mexico, the Caribbean region and Greenland. It also corresponds to the current convention adopted by the International Astronomical Union (IAU) and International Earth Rotation and Reference Systems Service (IERS).

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Director
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Natural Resources Canada Ressources naturelles Canada

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Appendix 3: Permanent and Seasonal Water Level Stations on IGLD

CANADA –ACTIVE PERMANENT GAUGING STATIONS ON IGLD (1985)
(* indicates Reference Zero for IGLD (1985) & NAVD 88)

ST. LAWRENCE RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Pointe-au-Père * (not active)	2980	48.51670	-68.46670
Rimouski *	2985	48.47833	-68.51367
Saint-Joseph-de-la-Rive	3057	47.45000	-70.36670
Saint-François I.O.	3100	47.00000	-70.81670
Vieux-Québec	3248	46.81110	-71.20190
Neuville	3280	46.69650	-71.57283
Portneuf	3300	46.68330	-71.88330
Deschaillons (Cap à la Roche)	3335	46.56100	-72.10583
Batiscan	3345	46.50033	-72.24583
Bécancour	3353	46.40033	-72.37950
Trois-Rivières	3360	46.33330	-72.55000
Port Saint-Francois	3365	46.27250	-72.61933
Sainte-Anne-de-Bellevue	16005	45.40467	-73.95633
Lac Saint-Pierre	15975	46.19483	-72.89550
Sorel	15930	46.04717	-73.11567
Contracoeur	15780	45.83267	-73.28317
Varennes	15660	45.68433	-73.44367
Montréal Rue Frontenac	15540	45.52867	-73.54250
Montréal Jetty No. 1	15520	45.50350	-73.55250
Pointe-Claire	15330	45.42767	-73.82067
Summerstown	14940	45.05995	-74.55410
Cornwall	14870	45.01472	-74.71152
Morrisburg	14660	44.89047	-73.19083
Iroquois Lock Below	14602	44.83457	-75.30872
Above Iroquois Lock	14600	44.82230	-75.32097
Brockville	14400	44.58692	-75.68193

LAKE ONTARIO			
Station Name	**Station ID**	**Latitude**	**Longitude**
Kingston	13988	44.21800	-76.51733
Cobourg	13590	43.95648	-78.16440
Toronto	13320	43.63975	-79.38028
Burlington	13150	43.29943	-79.79343
Port Weller	13030	43.24402	-79.21800

LAKE ERIE			
Station Name	**Station ID**	**Latitude**	**Longitude**
Port Colborne	12865	42.87437	-79.25285
Port Dover	12710	42.78132	-80.20155
Port Stanley	12400	42.65902	-81.21352
Erieau	12250	42.26035	-81.91483
Kingsville	12065	42.02662	-82.73453
Bar Point	12005	45.02662	-83.11498

DETROIT RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Amherstburg	11995	42.14443	-83.11405
Belle River	11965	42.29615	-82.71085
Port Lambton	11950	42.65730	-82.50702
Point Edward	11940	42.99083	-82.42135

LAKE HURON			
Station Name	**Station ID**	**Latitude**	**Longitude**
Goderich	11860	43.74535	-81.72787
Tobermory	11690	45.25682	-81.66285
Collingwood	11500	44.50840	-80.22010
Midland	11445	44.75000	-79.85000
Parry Sound	11375	45.33825	-80.03575
Little Current	11195	45.98132	-81.92610
Thessalon	11070	46.25402	-83.55105

ST. MARYS RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Garden River	02CA003	46.53170	-84.13170
Below Sault Ste Marie	11010	46.51125	-84.34325
Above Sault Ste Marie	10980	46.51228	-84.36722

LAKE SUPERIOR			
Station Name	**Station ID**	**Latitude**	**Longitude**
Gros Cap	10920	46.52910	-84.58630
Michipicoten	10750	47.96167	-84.89975
Rossport	10220	48.83372	-87.51962
Thunder Bay	10050	48.40947	-89.21667

CANADA – PAST & PRESENT SEASONAL GAUGING STATIONS

ST. LAWRENCE RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Île Biquette	3000	48.42000	-68.89000
Ste-Thérèse-de-Gaspé	2285	48.42000	-64.40000
Tadoussac	3425	48.13833	-69.71400
Chenal de l'île Verte	3122	48.01670	-69.40000
Gros Cacouna	3126	47.95000	-69.50000
Riviere-du-Loup	3130	47.84683	-69.57183
Le Petit Pélerin	3145	47.70000	-69.76670
Grande Île	3150	47.61670	-69.86670
St. Jean-Port-Joli	3170	47.21617	-70.27467
L´Islet-sur-Mer	3175	47.13330	-70.36670
Saint-Joachim	3080	47.05000	-70.85000
Québec (Lauzon)	3250	46.83000	-71.16000
Saint-Romuald	3260	46.76670	-71.23330
Pont de Québec	3265	46.74580	-71.28780
Saint-Nicolas	3270	46.71670	-71.38330
Grondines	3325	46.58533	-72.03883
Brickyard	3337	46.54983	-72.13433
Champlain	3350	46.44017	-72.33967
Ilets Perce	15950	46.11717	-72.94900
Lanoraie	15860	45.95950	-73.21467
Lavaltrie	15793	45.88333	-73.27317
Verchères	15720	45.77917	-73.35617
Repentigny	15668	45.74200	-73.43550
Point-Aux-Trembles	15630	45.63267	-73.49050
Longue-Pointe	15590	45.58233	-73.50650
Saint-Lambert Aval	15507	45.50400	-73.52100
Saint-Lambert Amont	15505	45.48567	-73.51533
La Prairie	15470	45.46550	-73.51167
Cote-Ste-Catherine	15450	45.40850	-73.57400
Lachine	15390	45.43050	-73.66950
Pointe-des-Cascades	15220	45.33450	-73.96217
Beauharnois Aval	15262	45.32067	-73.91550
Beauharnois Amont	15260	45.29983	-73.93033
Coteau-du-Lac	15140	45.29667	-74.16800
Coteau-Landing	15110	45.25317	-74.21167
Grenville	16045	45.63033	-74.60883
Pollys Gut	14854	44.99670	-74.76500
Moses Saunders	14835	45.00000	-74.80000

ST. LAWRENCE RIVER (CONT.)			
Station Name	**Station ID**	**Latitude**	**Longitude**
Long Sault	14800	45.03310	-74.89310
Cardinal	14560	44.78000	-75.38000
Johnstown	14530	44.73000	-75.47000
Prescott	14500	44.71310	-75.50810
Rockport	14255	44.37500	-76.94390
Gananoque	14150	44.32500	-76.16110

LAKE ONTARIO			
Station Name	**Station ID**	**Latitude**	**Longitude**
Millhaven	13960	44.19330	-76.74170
Prinyers Cove	13780	44.16670	-76.86670
Napanee River	13772	44.25000	-76.95000
Waupoos	13771	44.00170	-76.99170
Deseronto Harbour	13770	44.19530	-77.04860
Glenora	13765	44.04110	-77.06000
Picton	13760	44.02830	-77.13670
Point Petre	13750	43.84670	-77.16330
Belleville	13740	44.16170	-77.38330
Trenton	13730	44.10310	-77.57500
Brighton	13670	44.02000	-77.72000
Colborne	13640	43.97550	-77.87660
Oshawa	13450	43.89500	-78.86500
Whitby	13425	43.85000	-78.93000
Frenchman Bay	13400	43.80000	-79.08330
Port Credit	13250	43.55000	-79.58000
Oakville	13200	43.44310	-79.67500
Bronte Harbour	13175	43.40000	-79.70000
Fifty Point	13100	43.22000	-79.63000
Port Dalhousie	13040	43.20810	-79.26500

LAKE ERIE			
Station Name	**Station ID**	**Latitude**	**Longitude**
Fort Erie	12950	42.91170	-78.92330
Port Maitland	12800	42.86170	-79.57330
Nanticoke	12719	42.80830	-81.40000
Port Rowan	12615	42.62500	-80.45830
Port Burwell	12500	42.64500	-80.80830
Port Bruce	12450	42.65000	-81.02000
Point Pelee	12120	41.92000	-82.52000

LAKE ST. CLAIR			
Station Name	**Station ID**	**Latitude**	**Longitude**
La Salle*	11985	42.23610	-83.10310
Tecumseh*	11975	42.33810	-82.92110
Mitchell Bay	11958	42.38000	-82.40000
X35 fixed navigational aid	11953	42.52000	-82.67000

LAKE HURON			
Station Name	**Station ID**	**Latitude**	**Longitude**
Sarnia Yacht Club	11938	42.99830	-82.42170
Brights Cove	11930	43.03500	-82.23690
Kincardine	11825	44.17500	-81.64110
Port Elgin	11800	44.44110	-81.40310
Southampton	11798	44.49170	-80.38170
Little Red Bay	11750	44.77170	-81.29000
Stokes Bay	11725	44.95000	-81.40000
Lions Head	11625	45.99110	-81.24890
Wiarton	11565	44.74810	-81.13890
Owen Sound	11550	44.57610	-80.94610
Meaford	11530	44.60960	-80.58950
Thornbury	11520	44.56500	-80.45110
Hope Island	11475	44.91670	-80.16670
Penetang	11450	44.77310	-79.93810
Port McNicoll	11440	44.74670	-79.80330
Port Severn	11430	44.80310	-79.72000
Honey Harbour	11420	44.87080	-79.82330
Nobel	11365	45.40610	-80.08310
Britt	11305	45.77000	-80.55000
Key Harbour	11295	45.88000	-80.72000
Bustard Island	11290	45.90000	-80.90000
French River	11280	45.95000	-80.90000
Beaverstone Bay	11265	46.00000	-81.15000
Killarney	11250	45.97000	-81.52000
Harrison Rock	11220	46.05750	-81.67000
Sheguiandah Bay	11200	45.88000	-81.90000
Sandfield	11192	45.70170	-82.00170
Rockville	11191	45.80330	-82.11500
South Baymouth	11190	45.58330	-82.01170
Ireson Island	11187	46.09330	-81.78170
Barren Island	11185	46.06330	-82.02920
Providence Bay	11180	45.66670	-82.27500
Logan Island	11175	46.03330	-82.19670
Kagawong	11170	45.57100	-82.06260

LAKE HURON (CONT.)			
Station Name	**Station ID**	**Latitude**	**Longitude**
Massey	11161	46.21340	-82.06980
Spanish	11160	45.00000	-82.00000
Gore Bay	11150	45.91830	-82.46330
Cutler	11140	46.20440	-82.40980
Evansville, Manitoulin	11135	45.84500	-82.54670
Spragge	11130	45.00000	-82.00000
Blind River	11110	46.18500	-82.95500
Burnt Island Harbour	11100	45.82170	-82.94500
St. Joseph Island	11041	46.25000	-84.10000
Richards Landing	11040	46.26670	-84.03000

LAKE SUPERIOR			
Station Name	**Station ID**	**Latitude**	**Longitude**
Algoma Steel	10978	46.52310	-84.37810
Ile Parisienne	10910	46.59670	-84.67670
Batchawana River	10860	46.93300	-84.53000
Mamainse Harbour	10850	47.03300	-84.78100
Heron Bay	10310	48.66100	-86.27000
Marathon	10300	48.73800	-86.38600
Jackfish	10240	48.78330	-86.95000

UNITED STATES – ACTIVE PERMANENT GAUGING STATIONS ON IGLD (1985)
(* indicates Master Station)

ST. LAWRENCE RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Ogdensburg	8311030	44.70156	-75.49436
Alexandria Bay C.G.	8311062	44.33170	-75.93500

LAKE ONTARIO			
Station Name	**Station ID**	**Latitude**	**Longitude**
Cape Vincent	9052000	44.13019	-76.33197
Oswego *	9052030	43.46417	-76.51183
Rochester	9052058	43.26903	-77.62575
Olcott	9052076	43.33839	-78.72733

NIAGARA RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Ashland Avenue	9063007	43.10000	-79.06000
American Falls	9063009	43.08170	-79.06170
Niagara Intake	9063012	43.07830	-79.01500

LAKE ERIE			
Station Name	**Station ID**	**Latitude**	**Longitude**
Buffalo	9063020	42.87670	-78.89000
Sturgeon Point	9063028	42.69000	-79.04830
Erie	9063038	42.15330	-80.07500
Fairport *	9063053	41.75000	-81.28330
Cleveland	9063063	41.54000	-81.63500
Marblehead	9063079	41.54500	-82.73170
Toledo	9063085	41.69330	-83.47170
Fermi Power Plant	9063090	41.96000	-83.25830

DETROIT RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Gibraltar	9044020	42.09090	-83.18600
Wyandotte	9044030	42.20240	-83.14750
Fort Wayne	9044036	42.29890	-83.09260
Windmill Point	9044049	42.35780	-82.92990

LAKE ST. CLAIR			
Station Name	**Station ID**	**Latitude**	**Longitude**
St. Clair Shores *	9034052	42.47322	-82.87925

ST. CLAIR RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Algonac	9014070	42.62100	-82.52690
St. Clair State Police	9014080	42.81240	-82.48580
Dry Dock	9014087	42.94530	-82.44350
Mouth of the Black River	9014090	42.97380	-82.42040
Dunn Paper	9014096	43.00250	-82.42240
Fort Gratiot	9014098	43.00690	-82.42250

LAKE HURON			
Station Name	**Station ID**	**Latitude**	**Longitude**
Lakeport	9075002	43.14039	-82.49389
Harbor Beach *	9075014	43.84619	-82.64311
Essexville	9075035	43.64040	-83.84680
Alpena	9075065	45.06300	-83.42860
Mackinaw City	9075080	45.77789	-84.72533
De Tour Village	9075099	45.99250	-83.89820

ST. MARYS RIVER

LAKE HURON			
Station Name	**Station ID**	**Latitude**	**Longitude**
Rock Cut	9076024	46.26500	-84.19170
West Neebish	9076027	46.28330	-84.20500
Little Rapids	9076033	46.48500	-84.30000
US Slip	9076060	46.50000	-84.34000
SW Pier	9076070	46.50170	-84.37330

LAKE MICHIGAN

LAKE HURON			
Station Name	**Station ID**	**Latitude**	**Longitude**
Ludington	9087023	43.94670	-86.44170
Holland	9087031	42.76830	-86.20170
Calumet Harbor	9087044	41.73000	-87.53830
Milwaukee	9087057	43.00170	-87.88670
Kewaunee	9087068	44.46330	-87.50000
Sturgeon Bay Canal	9087072	44.79500	-87.31330
Green Bay	9087079	44.54000	-88.00830
Menominee	9087088	45.09670	-87.59670
Port Inland	9087096	45.97000	-85.87170

LAKE SUPERIOR			
Station Name	**Station ID**	**Latitude**	**Longitude**
Point Iroquois	9099004	46.48500	-84.63170
Marquette C.G. *	9099018	46.54500	-87.37830
Ontonagon	9099044	46.87830	-89.32000
Duluth	9099064	46.77500	-92.09330
Grand Marais	9099090	47.74830	-90.34170

UNITED STATES – PAST & PRESENT SEASONAL GAUGING STATIONS

ST. LAWRENCE RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Louisville Landing	8311013	44.94804	-74.99570
Morristown	8311040	44.58998	-75.65160
Clayton	8311070	44.24170	-76.08670

LAKE ONTARIO			
Station Name	**Station ID**	**Latitude**	**Longitude**
Sackets Harbor	9052012	43.95000	-76.12500
Port Ontario	9052025	43.57138	-76.20209
L. Sodus Bay [Fh]	9052043	43.31833	-76.70333
Sodus Bay	9052048	43.26937	-76.97856
Oak Orchard	9052070	43.36995	-78.19147
Wilson	9052082	43.31676	-78.83443
Fort Niagara	9052090	43.26138	-79.06250

NIAGARA RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Beaver Is. S. P. [GI]	9063015	42.95830	-78.94670
Huntley Station	9063016	42.97120	-78.93000
Black Rock Canal	9063017	42.93340	-78.90750
Tonawanda Island	9063018	43.02830	-78.88670
La Salle Yacht Club	9063013	43.07330	-78.98500

LAKE ERIE			
Station Name	**Station ID**	**Latitude**	**Longitude**
Dunkirk	9063029	42.48812	-79.33541
Barcelona	9063032	42.34437	-79.59666
Conneaut	9063043	41.96395	-80.54748
Ashtabula	9063048	41.89951	-80.79836
Rocky River	9063067	41.49034	-81.83409
Lorain	9063069	41.47039	-82.17649
Vermilion	9063072	41.42332	-82.36517
Huron	9063074	41.39689	-82.55101
Sandusky	9063076	41.45975	-82.71242
Port Clinton	9063083	41.51467	-82.94037
Turtle Creek	9063084	41.61167	-83.12833
Monroe	9063087	41.89784	-83.36034
Cooley Creek	9063091	41.67667	-83.28333
Kelleys Island	9063094	41.60000	-82.70500
Put In Bay	9063097	41.65833	-82.82667

LAKE ST. CLAIR			
Station Name	**Station ID**	**Latitude**	**Longitude**
Minnich Dock	9034058	42.57583	-82.65556
Grosse Point Yacht Club	9034051	42.43500	-82.87170
New Baltimore	9034057	42.67789	-82.73261
St. Clair Flats (CG station)	9034060	42.55000	-82.66167
North Channel	9034160	42.62833	-82.60667

ST. CLAIR RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Marine City	9014078	42.72004	-82.49226
Marysville	9014084	42.90670	-82.46670

LAKE HURON			
Station Name	**Station ID**	**Latitude**	**Longitude**
Forestville	9075009	43.66667	-82.60500
Port Sanilac	9075011	43.43333	-82.53667
Port Austin	9075024	44.05000	-82.99500
Sebewaing	9075031	43.73333	-83.45833
Bay City	9075037	43.56500	-83.90330
Point Lookout	9075045	44.05500	-83.58333
Oscoda	9075056	44.40833	-83.32167
Black River	9075057	44.81333	-83.30500
Harrisville	9075059	44.65944	-83.28639
Presque Isle	9075069	45.34000	-83.48833
Rogers City	9075073	45.42333	-83.81333
Hammond Bay	9075074	45.59000	-84.16000
Cheboygan	9075076	45.64667	-84.47333
Mackinac Island	9075083	45.85000	-84.61500
St Ignace	9075085	45.86667	-84.72333
Cedarville	9075092	45.99667	-84.35833

ST. MARYS RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Cell Dock	9076002	46.32140	-84.15140
Slab Dock	9076004	46.24770	-84.10780
Frechette Point	9076050	46.46110	-84.28610

LAKE MICHIGAN			
Station Name	**Station ID**	**Latitude**	**Longitude**
St James	9087001	45.74333	-85.50833
Cross Village	9087003	45.64667	-85.04167
Petoskey	9087005	45.37500	-84.96000

LAKE MICHIGAN (CONT.)			
Station Name	**Station ID**	**Latitude**	**Longitude**
Charlevoix	9087006	45.32500	-85.26666
Elk Rapids	9087008	44.90000	-85.41667
Traverse City	9087010	44.79133	-85.63720
Suttons Bay	9087011	44.98333	-85.65000
Northport	9087012	45.12500	-85.61667
Leland	9087013	45.02389	-85.76295
South Manitou. Island	9087015	45.01333	-86.10000
Frankfort	9087018	44.63167	-86.24333
Manistee	9087021	44.25000	-86.34167
Pentwater	9087025	43.78000	-86.44167
Muskegon	9087028	43.22833	-86.33833
Grand Haven	9087030	43.06000	-86.23833
South Haven	9087034	42.40000	-86.28330
St Joseph	9087036	42.11667	-86.48333
New Buffalo	9087037	41.80000	-86.71667
Burns Waterway	9087039	41.63167	-87.17667
Indiana Harbor	9087042	41.67333	-87.44333
Chicago Harbor	9087046	41.89167	-87.61000
Waukegan	9087050	42.36666	-87.82500
Kenosha	9087052	42.59167	-87.82500
Port Washington	9087060	43.38333	-87.86667
Cheboygan	9087062	43.75000	-87.70833
Manitowoc	9087064	44.09167	-87.65833
Algoma	9087070	44.60833	-87.43330
Sturgeon Bay Village	9087073	44.83333	-87.38333
Baileys Harbor	9087074	45.06500	-87.09500
Jackson Harbor	9087076	45.40000	-86.85000
Oconto	9087086	44.89500	-87.83333
Cedar River	9087089	45.42500	-87.35000
Escanaba	9087090	45.74333	-87.04667
Manistique	9087094	45.94800	-86.24700
Naubinway	9087097	46.08667	-85.44500

LAKE SUPERIOR			
Station Name	**Station ID**	**Latitude**	**Longitude**
Whitefish Point	9099007	46.75833	-84.96500
Little Lake Harbor	9099008	46.71500	-85.35667
Grand Marais	9099010	46.67500	-85.97333
Munising	9099013	46.41666	-86.65500
Presque Isle [UP]	9099015	46.58000	-87.38333
Big Bay	9099020	46.83333	-87.69167
Keweenaw Lower End	9099025	46.96667	-88.41667

LAKE SUPERIOR (CONT.)			
Station Name	**Station ID**	**Latitude**	**Longitude**
Houghton-Hancock	9099027	47.13333	-88.56667
Lac La Belle	9099035	47.37500	-87.97500
Copper Harbor	9099037	47.47500	-87.85833
Eagle Harbor	9099039	47.45833	-88.16667
Keweenaw Upper End	9099041	47.22500	-88.61667
Black River Harbor	9099047	46.67500	-90.05000
Ashland	9099050	46.57500	-90.90000
Bayfield	9099052	46.81667	-90.81667
Cornucopia	9099055	46.85333	-91.10333
Two Harbors	9099070	47.01670	-91.67500
Beaver Bay	9099075	47.26333	-91.30000
Lutsen	9099085	47.64167	-90.71667
Rock Harbor	9099095	48.08333	-88.58333
Washington Harbor	9099096	47.91667	-89.16667

LAKE WINNEBAGO			
Station Name	**Station ID**	**Latitude**	**Longitude**
Neenah	9020200	44.17000	-88.43670
Oshkosh	9020220	44.02500	-88.52170
Fond Du Lac	9020240	43.79500	-88.44000
Calumet Harbor	9020260	43.91500	-88.33000

LAKE CHAMPLAIN			
Station Name	**Station ID**	**Latitude**	**Longitude**
Rouses Pt.	4295000	44.99611	-73.36028
Burlington	8431740	44.48111	-73.22417
Port Henry	8431720	44.05500	-73.45333
Whitehall	4279085	43.62167	-73.41889

Appendix 4: Entity & Seaway Water Level Stations to be Updated to IGLD (2020)

CANADA

ST. LAWRENCE RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Hydro Québec			
Pointe-Seigneuriale		45.19534	-74.17684
Centrale Beauharnois		45.31367	-73.90868
Écluse Beauharnois		45.26670	-73.93026
Ontario Power Generation			
Cornwall Canal	02MC022	45.01368	-74.79108
International Tail Water	02MC056	45.00669	-74.79448
Saunders Tail Water	02MC054B	45.00875	-74.79033
Saunders Head Water	02MC054A	45.00911	-74.79033
Morrisburg	02MC052	44.89043	-75.19077
Iroquois Tail Water	02MB052B	44.83457	-75.30868
Iroquois Head Water	02MB052A	44.83146	-75.30961
Cardinal	02MB051	44.79538	-75.36983
St. Lawrence Seaway Management Corporation			
St. Lambert Lock Lower Wall	SLBL	45.49668	-73.51836
St. Lambert Lock Upper Wall	SLBU	45.49167	-73.51683
Laprairie	W-LAP	45.41543	-73.49985
Cote Ste. Catherine Lock Lower Wall	CSCL	45.40802	-73.56227
Cote Ste. Catherine Lock Upper Wall	CSCL	45.40799	-73.56958
Water Level South Shore Canal Entrance	W-SSC	45.40972	-73.71111
Lock 3 Beauharnois Lower Wall	BO3L	45.32004	-73.91665
Boh Pool Level	W-BOH	45.31642	-73.91513
Lock 4 Beauharnois Upper Wall	B04U	45.29974	-73.92909
Water Level St. Louis Bridge	W-SLU	45.23056	-74.0008
Valleyfield Level	W-VAL	45.22379	-74.09394
Côteau Landing	CTL	45.25454	-74.20516
Summerstown	CMT	45.0616	-74.54545
Cornwall ON	COW	45.01999	-74.70786
Long Sault Level	W-LGS	45.02371	-74.88827

ST. LAWRENCE RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
St. Lawrence Seaway Management Corporation (cont.)			
Morrisburg ON - Municipal Dock	W-MOR	44.89426	-75.17846
Iroquois Lock Lower Wall	IROL	44.83462	-75.31153
Iroquois Lock Upper Wall	IROU	44.82537	-75.31789
Cardinal ON	CAR	44.78481	-75.37448
Water Survey Canada			
Saint-Laurent à Lanoraie	02OB011	45.95917	-73.21444
Saint-Laurent à LaSalle	02OA016	45.41500	-73.62306
Saint-Louis à Pointe-Claire	02OA039	45.42750	-73.82056
Saint-Laurent à Pointe des Cascades	02MC005	45.33444	-73.96194
Outaouais à Marine Ste-Anne	02OA033	45.40222	-73.94861

LAKE ONTARIO			
Station Name	**Station ID**	**Latitude**	**Longitude**
Ontario Power Generation			
Kingston	02HM008	44.22769	-75.47749
St. Lawrence Seaway Management Corporation			
Kingston	KGN	44.22769	-75.47749

NIAGARA RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Ontario Power Generation			
Black Creek	02HA053	42.98361	-79.02528
Fort Erie	02HA051	42.89000	-78.92333
Frenchman's Creek	02HA052	42.94528	-78.93111
Material Dock	02HA055	43.06111	-79.04278
Ontario Power TW	02HA057B	43.08250	-79.07639
Slater's Point	02HA054	43.05639	-79.02694
Tunnel Intake (1 & 2)	02HA056	43.06667	-79.05306
Crossover	02HA064	43.14000	-79.05806
SAB #2 TW	02HA070	43.14667	-79.04361
SAB #2 HW	02HA068	43.14667	-79.04583
SAB #1 TW	02HA069	43.14917	-79.04417
SAB #1 HW	02HA066	43.14833	-79.04556
SAB PGS TW	02HA065B	43.14417	-79.05972
SAB PGS HW	02HA065A	43.14472	-79.06111
Water Survey Canada			
Niagara River at Fort Erie	02HA013	42.93028	-78.91417

WELLAND CANAL			
Station Name	**Station ID**	**Latitude**	**Longitude**
Ontario Power Generation			
Beaver Dams Pumphouse HW	02HA089A	43.10444	-79.21250
DeCew ND1 HW	02HA095	43.11639	-79.26306
DeCew ND1 TW	02HA095B	43.11861	-79.26472
DeCew NF23 G1 Diff	02HA093	43.11833	-79.26083
DeCew NF23 G2 Diff	02HA094	43.11833	-79.26083
DeCew NF23 HW	02HA092	43.11833	-79.26083
DeCew NF23 TW	02HA092B	43.11889	-79.26222
Lake Gibson	02HA091	43.10000	-79.22806
Welland Ship Canal	02HA080	43.07528	-79.21111
Diverting Weirs	02HA084	43.10222	-79.23778
Montrose Gauge		43.09028	-79.20028
Allanburg Intake #2		43.08889	-79.21556
Allanburg Intake		43.07528	-79.21111
St. Lawrence Seaway Management Corporation			
Port Weller Harbour - Welland Canal	W-PWH	43.22108	-79.21535
Lock 1 Lower Wall	L1N	43.22108	-79.21535
Lock 1 Upper Wall	L1S	43.02125	-79.2124
Reach 1 (20-minute min of L2N)	RCH1	43.19636	-79.20479
Lock 2 Lower Wall	L2N	43.19636	-79.20479
Lock 2 Upper Wall	L2S	43.18678	-79.19924
Reach 2 (40-minute min of L3N)	RCH2	43.15911	-79.19465
Lock 3 Lower Wall	L3N	43.15911	-79.19465
Lock 3 Upper Wall	L3S	43.15144	-79.19363
Reach 3 (20-minute minimum of W-B05)	RCH3	43.14522	-79.19243
Reach 6 (20-minute min of L7NE)	RCH6	43.12589	-79.19304
Lock 7 Lower East Wall	L7NE	43.12589	-79.19304
Lock 7 Upper East Wall	L7SE	43.11908	-79.19485
Long Level (60-minute min of L8NE)	LLVL	42.90416	-79.24485
Lock 8 Lower East Wall	L8NE	42.90416	-79.24485
Lock 8 Upper East Wall	L8SE	42.89214	-79.24774
Port Colborne Harbour, (60-minute min of L8SE)	W-PCH	42.89214	-79.24774
Water Survey Canada			
Welland River Below Caistor Corners	02HA007	43.02167	-79.61778

LAKE ERIE			
Station Name	**Station ID**	**Latitude**	**Longitude**
Ontario Power Generation			
Kingsville	02GH010	42.026620	-82.734530

ST. MARY'S RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
Brookfield Renewable Energy			
Clergue Generating Station		46.51488	-84.34739
Water Survey Canada			
St. Mary's River near Garden River	02CA003	46.53250	-84.13111

LAKE SUPERIOR			
Station Name	**Station ID**	**Latitude**	**Longitude**
Ontario Power Generation			
Longlac at Long Lake	04JD001	49.76944	-86.55139
Water Survey Canada			
Ogoki River above Whiteclay Lake	04GB004	50.86833	-88.93139

UNITED STATES

ST. LAWRENCE RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
New York Power Authority			
Moses Tail Water	MTW	45.00378	-74.79953
Moses Head Water	MHW	45.00394	-74.80009
Long Sault Dam North	LSDN	44.99775	-74.86323
Long Sault Dam South Shore	LSDSS	44.99107	-74.86552
Waddington	W-WAD	44.86475	-75.20850
Ogdensburg	OGD	44.70158	-75.49436
St. Lawrence Seaway Development Corporation			
Snell Lock Lower Wall	SNLL	44.98954	-74.76940
Snell Lock Upper Wall	SNLU	44.98734	-74.78614
Eisenhower Lock Lower	IKEL	44.98020	-74.84399
Eisenhower Lock Upper	IKEU	44.97890	-74.85799

NIAGRA RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
New York Power Authority			
NYPA Tailrace		43.14169	-79.04074
Forebay 1 & 2		43.14142	-79.03850
Reservoir North		43.14300	-79.02109
Reservoir South		43.14152	-79.02114
Huntley	3016	42.96860	-78.93079
Tonawanda	3018	43.02545	-78.88678
LaSalle Yacht Club	3013	43.07379	-78.98618

DETROIT RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
U.S. Army Corps of Engineers			
Belle Isle	BISM4	42.34028	-82.96111

ST. CLAIR RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
U.S. Army Corps of Engineers			
Marine City	1002	42.71440	-82.49220
Middle Channel	MIDM4	42.57560	-82.65640
South Channel	DEAM4	42.57610	-82.57470
North Channel	4160	42.62440	-82.59470

CROOKED LAKE (MICHIGAN INLAND ROUTE)			
Station Name	**Station ID**	**Latitude**	**Longitude**
U.S. Army Corps of Engineers			
Crooked River	CRAM4	45.26080	-84.47220

ST. MARYS RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
U.S. Army Corps of Engineers			
Slab Dock	6063	46.24360	-84.11280
Cell Dock	6052	46.32470	-84.15080
Frechette	FRCM4	46.45810	-84.28920
Lower Rapids	SMLM4	46.30150	-84.20510
Upper Rapids	SMUM4	46.30270	-84.21440

FOX RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
U.S. Army Corps of Engineers & USGS			
Appleton Upper	N/A	44.25370	-88.40811
Appleton Lower	N/A	44.26047	-88.39834
Cedars	N/A	44.27989	-88.33225
Little Chute	N/A	44.27657	-88.31749
Kaukauna	N/A	44.28100	-88.27000
Rapide Croche	N/A	44.31731	-88.19691
Little Kaukauna	N/A	44.37789	-88.12419
DePere	N/A	44.45011	-88.06300
Berlin	BERW3	43.57100	-88.57100
Fritse Park	OSKW3	44.12180	-88.28120

LAKE WINNEBAGO			
Station Name	**Station ID**	**Latitude**	**Longitude**
U.S. Army Corps of Engineers & USGS			
Oshkosh	9020220 & 04082500	44.00360	-88.31380
Fond Du Lac	9020240	43.47420	-88.26130
Menasha	MNSW3	44.12140	-88.25310
Stockbridge	STKW3	44.04160	-88.44250
Poygan	WNCW3	44.09450	-88.28120

WOLF RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
U.S. Army Corps of Engineers & USGS			
Royalton	ROYW3	44.24450	-88.51540
New London	NEWW3	44.23320	-88.44250

WAUPACA RIVER			
Station Name	**Station ID**	**Latitude**	**Longitude**
U.S. Army Corps of Engineers & USGS			
Waupaca	WPCW3	44.32925	-88.99636

Appendix 5: Glossary

Annual variation – Seasonal variation in water level or current, more or less periodic, due chiefly to meteorological causes.

Bench mark (BM) – A fixed physical object or mark having an assigned height at a specific epoch with respect to a vertical datum. A primary bench mark is the principal (or only) mark of a group of bench marks to which an electric tape gauge or staff is referred. The standard bench mark is usually a small diameter brass, bronze, or aluminum alloy disk containing the owner's inscription together with other individual identifying information. A bench mark may have several assigned heights referring to different vertical datums (e.g., IGLD (1985), NAVD 88, CGVD2013), difference types of height (e.g., orthometric, dynamic and geodetic) and different coordinate epochs due to movement of the bench mark caused by uplift or subsidence of the terrain.

Bench mark description – A published, concise description of the location, stamped number or designation, date established and elevation (with respect to a vertical datum and epoch) of a specific bench mark.

Canadian Active Control System (CACS) – The Canadian Active Control System is a network of continuously operated reference stations that provide Global Navigation Satellite System (GNSS) data consisting of carrier phase and code range measurements in support of three-dimensional positioning, meteorology, space weather, and geophysical applications throughout Canada. CACS-based coordinates approach an accuracy of a few centimeters both horizontally and vertically.

Canadian Geodetic Vertical Datum of 1928 (CGVD28) – CGVD28 is the former vertical datum for Canada, replaced in 2013 by CGVD2013. CGVD28 is defined by the mean sea level at five Canadian tide gauges and one American tide gauge. The Canadian gauges include Yarmouth and Halifax on the Atlantic Ocean, Pointe-au-Père on the lower St Lawrence River, and Vancouver and Prince Rupert on the Pacific Ocean. The sixth reference is the height of a benchmark located in Rouses Point, New York. This height (108.15 feet), agreed to by Canada and USA in 1925, was established by leveling with respect to a gauge in New York City. From these six datum points, the vertical datum was propagated inland by leveling observations and heights were established at benchmarks along major roads and railways from a national least-squares adjustment in 1928. Since then, all new leveling observations have been constrained regionally following the same methodology. Heights in CGVD28 are normal-orthometric.

Canadian Geodetic Vertical Datum of 2013 (CGVD2013) – CGVD2013 is the current vertical datum for Canada, replacing CGVD28. CGVD2013 is a geoid-based vertical datum established in November 2013. It is defined by the equipotential surface (or geoid) having a potential (W_0) of 62,636,856 m^2/s^2. This value represents the best fit of the mean sea level for the North American region as measured using GNSS observations at tide gauges across Canada and USA. CGVD2013 is realized by a geoid model that gives the separation between the ellipsoid and geoid, making it compatible with Global Navigation Satellite Systems (GNSS). Heights in CGVD2013 are orthometric in the tide-free system.

Chart datum – The datum to which soundings on a chart are referred. A surface so low that the water level will seldom fall below it. It corresponds to the low water datum (LWD). See low water datum.

Coast and Geodetic Survey – A former name of the National Ocean Survey, now called the National Ocean Service. The organization was variously known as: The Survey of the Coast from its founding in 1807 to 1836, Coast Survey from 1836 to 1878, Coast and Geodetic Survey from 1878 to 1970, National Ocean Survey from 1970 to 1982, and the National Ocean Service from 1982 to present. From 1965 to 1970, the Coast and Geodetic Survey was a component of the Environmental Science Services Administration (ESSA). NOAA became the successor to ESSA in 1970.

Continuously Operating Reference Stations (CORS) – Continuously Operating Reference Stations that provide Global Positioning System (GPS) data consisting of carrier phase and code range measurements in support of three-dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States, its territories, and a few foreign countries. CORS-enhanced coordinates approach an accuracy of a few centimeters both horizontally and vertically.

Control station – See water level station.

Current – Generally, a horizontal movement of water. Currents may be classified as tidal and non-tidal. Tidal current is caused by gravitational interactions between the Sun, Moon and Earth and are part of the same general movement of the sea that is manifested in their vertical rise and fall, called tide. Tidal current is periodic with a net velocity of zero over the particular tidal cycle. See tidal wave. Non-tidal currents include the permanent currents in the general circulatory systems of the sea as well as temporary currents arising from more pronounced meteorological variability. See hydraulic current.

Data collection platform (DCP) – A microprocessor-based system that collects data from sensors, processes the data, stores the data in random access memory (RAM), and can provide communication links for the retrieval or transmission of the data.

Dynamic height (H^d) – Potential difference along the plumb line between the vertical datum and a point of interest divided by a constant value of gravity. In Canada and USA, the constant value of gravity is the "normal gravity" on the ellipsoid at latitude 45° (9.806199 m/s^2). It can be represented mathematically in terms of the geopotential number (C) by: $H^d = C/\gamma_{45}$ where γ_{45} is the normal gravity at latitude 45°. Dynamic heights have no geometric meaning. They are mainly used for the management of water in large lakes, rivers and channels. The surface of a lake has a constant dynamic height if undisturbed by currents, winds, atmospheric pressure, etc. (Unit: m)

Electric tape gauge (ETG) – A gauge consisting of a graduated metal tape on a metal reel (with supporting frame), voltmeter and battery. Heights can be measured directly by unrolling the tape into its stilling well. When contact is made with the water's surface, the circuit is completed and the voltmeter needle moves. At that moment the length of tape is read against an index mark, the mark (known as a gnomon) having a known elevation relative to the local bench mark network.

Equipotential surface (*W*) – A surface having a constant potential and being everywhere perpendicular to the direction of gravity. An equipotential surface is level, i.e., the water is at rest on its surface. There exists an infinite number of equipotential surfaces. These surfaces do not intersect each other but converge towards the poles. Thus, the geometric distance between two equipotential surfaces is less at the poles than at the equator. For example, an equipotential surface which is 1000 m above the geoid at the equator is about 995 m above that same surface at the poles. Note that the mean water level for a large body of water is not an equipotential surface because such bodies of water have a "topography" that is caused by temperature, currents, winds, atmospheric pressure, river discharge, etc. (Unit: m^2/s^2)

Extreme high water – The highest elevation reached by the water as recorded by a water level gauge during a given period.

Extreme low water – The lowest elevation reached by the water as recorded by a water level gauge during a given period.

Float well – See stilling well.

Geodetic heights (*h*) – The distance (height) of a point above (or below) a reference ellipsoid (e.g., GRS80), measured along the normal and defined with respect to a geometric reference frame (e.g., NAD 83, ITRF). The geodetic height is also colloquially known as the ellipsoidal height. (Unit: m)

Geodetic Reference System 1980 (GRS 80) – The following set of values defined on an equipotential ellipsoid of revolution representing the Earth, adopted in 1979 by the International Union of Geodesy and Geophysics:

a	(semi-major axis)	6,378,137 m
GM	(gravitational constant x mass)	398,600.5 x 10^9 m^3/s^2
J_2	(dynamical form factor)	0.001 082 63
ω	(angular velocity)	7,292,115 x 10^{-11} rad/s,

A complete description of Geodetic Reference System 1980 is contained in Bulletin Géodésique, vol. 54, no. 3 (1980), pp. 395-405, in particular the derived values:

f^1	(reciprocal of flattening)	298.257222101
γ_e	(equatorial gravity)	978.03267715 m/s^2

Geoid (W_0) – Specific equipotential (level) surface, which defines best, in a least-squares sense, the global mean sea level. It is the true zero elevation for the world. For practical purpose, the geoid can also be defined as the equipotential surface representing a national vertical datum. The equipotential surface ($W_0 = 62636856$ m^2/s^2) defining CGVD2013 is considered the geoid. (Unit: m^2/s^2)

Geoid height (*N*) – It is the separation between the ellipsoid and geoid, measured along the normal. It allows the relation between the geodetic height (h) and orthometric height (H): $h = H + N$. (Unit: m)

Geopotential (W) – See equipotential surface (W).

Geopotential number (C) – It is the potential difference between a point at an equipotential surface (W_i) and a reference equipotential surface (W_0): $C = -(W_i - W_0)$. The reference geopotential surface is generally the geoid or the vertical datum. The geopotential number can also be expressed as gravity by:

$$C = \int_{P_O}^{P_N} g \, dH$$

where P_O is a point on the geoid, P_N is the point at which the geopotential number is wanted, the integration is carried out along the plumb line (dH) between P_O and P_N, and g is the actual value of gravity along that line. (Unit: m^2/s^2)

Geopotential number difference (ΔC) – It is the potential difference between two equipotential surfaces at two distinct locations at the earth surface: $\Delta C_{ij} = (W_j(\phi_2,\lambda_2,h_2) - W_i(\phi_1,\lambda_1,h_1))$. The geopotential number difference can be determined from leveling: $\Delta C_{ij} = (\Delta H_{ij}+\varepsilon)(g_i+g_j)/2$, where ΔH_{ij} is the instrumental height difference between points j and i, g is the gravity at points i and j, and ε are the systematic corrections applied to the leveling measurement. (Unit: m^2/s^2)

Global Positioning System (GPS) – A space-based radionavigation system owned by the United States government and operated by the United States Air Force. It is a global navigation satellite system that provides locations in space and time using a GPS receiver anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites.

Global Satellite Navigation Systems (GNSS) – Space-based radionavigation systems that include constellations of Earth-orbiting satellites that broadcast their locations in space and time, of networks of ground control stations, and of receivers that calculate ground positions by trilateration. At present GNSS include two fully operational global systems, the United States' Global Positioning System (GPS) and the Russian Federation's GLObal NAvigation Satellite System (GLONASS), as well as the developing global and regional systems, namely Europe's European Satellite Navigation System (GALILEO) and China's COMPASS/BeiDou, India's Regional Navigation Satellite System (IRNSS) and Japan's Quasi-Zenith Satellite System (QZSS).

Gnomon – See electric tape gauge (ETG).

Gradient of gravity – The rate of change of gravity with respect to the horizontal and vertical position. The "standard" vertical gradient of gravity in free-air is 0.3086 mGal/m (or 3.086 µGal/cm). (Unit: mGal/km, mGal/m or µGal/cm)

Gravity (g) – It is the combination of the gravitational (mass) and centrifugal (rotation) forces. It can also be defined as being the vertical gradient of the potential ($g = \delta W/\delta H$), explaining the relation between geopotential, gravity and height. Overall, gravity on the surface of the Earth increases from ~9.78 m/s^2 at the equator to ~9.83 m/s^2 at the poles. The elevation and mass density are components that influenced the local gravity value. (Unit: m/s^2 or Gal; 1 m/s^2 = 100 Gal = 0.1 kGal = 1×10^5 mGal) See gradient of gravity and gravity gradiometer.

Gravity gradiometer – An instrument for measuring the horizontal and vertical gradients of gravity; i.e. the rate of change of gravity with change of horizontal and vertical location. See gradient of gravity.

Height reference frame – The physical manifestation or realization of a height reference system (e.g., heights on benchmarks, geoid models). A height reference system may have several height reference frames (realizations). Geopotential and vertical reference frames are equivalent to height reference frames. For example, CGG2013a is the current height reference frame for CGVD2013.

Height reference system – The abstract collection of principles, fundamental parameters, and specifications for quantitatively describing the reference surface from which heights are referred. A height reference system is considered to be defined "indefinitely". Geopotential and vertical reference systems are equivalent to height reference systems. For example, CGVD2013 is a height reference system.

High water (HW) level – The maximum height reached by a rising water level. The high water is due to the periodic water level forces and the effects of meteorological, hydrologic, and/or lake conditions.

High water line – See high water mark.

High water mark – A line or mark left upon water level flats, beach, or alongshore objects indicating the elevation of the intrusion of high water. The mark may be a line of oil or scum on alongshore objects, or a more or less continuous deposit of fine shell or debris on the foreshore or berm. This mark is physical evidence of the general height reached by wave run up at recent high waters. Also referred to as high water line.

Hydraulic corrector – The difference in the mean water level for an epoch period at a specific water level gauge location with reference to each lake's master station. The Hydraulic Corrector for each gauge is then subtracted from the dynamic water surface elevation at the station to obtain IGLD heights at the subordinate gauge.

Hydraulic current – A current in a channel caused by a difference in the surface elevation at the two ends. The current in the Saint Marys River connecting Lakes Superior and Huron is an example. Such a current may also be expected in a strait connecting two bodies of water, such as the current in the Straits of Mackinac.

Hydrographic datum – A datum used for referencing depths of water and the heights of predicted tides or water level observations. Same as chart datum. See also datum.

International Great Lakes Datum (1985) (IGLD (1985)) – IGLD (1985) is derived from the same continental-wide adjustment as NAVD 88. However, the adjusted geopotential numbers (C) are converted to dynamic heights (H^d) instead of (Helmert) orthometric height (H). See NAVD 88.

Isobaric surface – A surface of constant or uniform pressure.

Latitude – The angle that the normal to the ellipsoid at a point makes with the equatorial plane of the reference ellipsoid and geometric reference frame. Geodetic latitudes depend on the orientation and dimensions of the chosen reference ellipsoid. Latitude is measured north and south of the equator and is usually expressed in degrees.

Level surface – See equipotential surface (Note: Use of "level surface" should be avoided to describe geopotential surface.)

Longitude – The angle between the plane of the local geodetic meridian and the plane of the prime (zero) geodetic meridian (e.g., Greenwich) of the chosen reference ellipsoid and geometric reference frame. A geodetic longitude may be measured by the angle, at one of the poles of the ellipsoid, between the local and initial meridians, or by the arc of the ellipsoid's equator intercepted by these meridians. Longitude is measured east and west of the prime meridian. See also latitude.

Low water datum (LWD) – The surface (represented by a geopotential elevation or geopotential difference) for each of the Great Lakes and the corresponding sloping surfaces of the St. Mary's, St. Clair, Detroit, Niagara, and St. Lawrence Rivers to which are referred the depths shown on the navigational charts and the authorized depths for navigation improvement projects. It is a surface so low that the water level will seldom fall below it. Also known as chart datum. See chart datum.

Low water line – The intersection of the land with the water surface at the elevation of the low water datum (chart datum).

Master station – A water level station in the Great Lakes at which continuous observations of water level heights have been made over a long period of time. Its purpose is to provide the Low Water Datum (LWD) reference zero, also called the chart datum reference. All other continuous water level gauging stations (called subordinate stations) on a given lake are hydraulically adjusted to the same water level height for the datum reference period. The data series from this station also serves as a primary reference for the reduction and comparison of relatively short data series from seasonal water level stations through the method of comparison of water level observations for a given period of time. See water level station and seasonal station.

Mean water level (MWL) – The mean water surface elevation as determined by averaging water levels over specified intervals of time; e.g., 3 minutes, 6 minutes, hourly, daily, quarter-monthly, monthly and annually.

Meteotsunami (meteorological tsunami) – In large lakes, a tsunami-like wave phenomenon of meteorological (atmosphere and air pressure related) origin. Meteotsunami propagate in the water in the same way as other waves, including tsunamis, and have the same coastal dynamics, but unlike tsunamis, they are not caused by geological events in the earth's crust ("plate tectonics") nor by impact events such as landslide and meteor strikes. Instead they are essentially a kind of storm surge - a rising of water level or large amplitude seiche oscillation in the lake, caused by intense low pressure or certain wind conditions associated with tropical storms and hurricanes, in the troposphere. These kinds of waves are called meteotsunami because, for an observer on the coast where it strikes, the two types of tsunamis would look the same. The difference is in their source only.

Microwave radar water level sensor – Non-contact sensor with an unconfined radar beam aimed vertically downward to reference a distance to a water surface.

National Geodetic Vertical Datum of 1929 (NGVD 29) – A fixed reference adopted as a standard geodetic datum for elevations determined by leveling. The datum was derived for surveys from a general adjustment of the first-order leveling networks of both the United States and Canada. In the adjustment, mean sea level was held fixed as observed at 21 tide stations in the United States and 5 in Canada. The year indicates the time of the general adjustment. Sea Level Datum of 1929, USGS Datum, and C&GS Datum are synonyms for NGVD 29. The geodetic datum is fixed and does not take into account the changing stands of sea level. Because there are many variables affecting sea level, and because the geodetic datum represents a best fit over a broad area, the relationship between the geodetic datum and local mean sea level is not consistent from one location to another in either time or space. For this reason, the National Geodetic Vertical Datum should not be confused with mean sea level. NAVD 88 has replaced NGVD 29 as the adopted datum in the U.S.

National Water Level Observation Network (NWLON) – The network of permanent water level and tide stations operated by the National Ocean Service along the Great Lakes and marine coasts and islands of the United States. See also Permanent Water Level Network.

Next Generation Water Level Measurement System (NGWLMS) – A fully integrated system encompassing new technology sensors and recording equipment, multiple data transmission options, and an integrated data processing, analysis, and dissemination subsystem. System developed and used by the United States.

Nodal points – The points about which a standing wave oscillates; i.e., those points of a standing wave with very small or no oscillations.

Normal gravity (γ) – Theoretical value of gravity determined from the parameters defining an equipotential ellipsoid of revolution, e.g., GRS67, GRS80. The normal gravity at latitude 45° (γ_{45}) for GRS80 is 9.806199203 m/s^2. (Unit: m/s^2)

North American Datum of 1983 (NAD 83) – The geometric reference frame for the United States and Canada, based on a nearly geocentric Cartesian coordinate system and the reference ellipsoid defined by the Geodetic Reference System 1980 (GRS 80). This datum was implemented in 1986 and is still the current geodetic reference system. It is planned to replace NAD 1983 with a truly geocentric Cartesian coordinate system in 2022.

North American Vertical Datum of 1988 (NAVD 88) – NAVD 88 was affirmed as the official vertical datum for the conterminous United States and Alaska in 1993. NAVD 88 is defined by the mean sea level (1970-1988) at the tide gauge in Rimouski, Québec, Canada on the lower St Lawrence River. The vertical datum is propagated in land by applying a continent-wide least-squares adjustment (minimum constraint) of leveling observations in geopotential numbers (C). NAVD 88 heights are corrected for actual gravity, making them orthometric (H).

Ordinary high water mark (OHWM) – Term used for the high water limits as defined in Section 10 of the Rivers and Harbors Act for projects in the U.S.

Orthometric height (*H*) – It is the distance of a point above (or below) the geoid (vertical datum), measured along the plumb line, i.e., perpendicular to the equipotential surfaces. It can be represented mathematically in terms of the geopotential number (C) by: $H = C/\bar{g}$ where $\bar{g}$ is the mean gravity along the plumb line. (Unit: m)

Permanent Water Level Network (PWLN) – The network of water level and tide stations operated by the Canadian Hydrographic Service along the Great Lakes, St. Lawrence River and marine coasts and islands of Canada. See also National Water Level Observation Network.

Pressure gauge – A water level gauge that is operated by the change in pressure at the bottom of a body of water due to the rise and fall of the water level.

Seasonal station – Temporary water level stations used to collect water level lake data for the summer month period (June – September).

Seiche – A stationary wave usually caused by strong winds and/or changes in barometric pressure. It is found in lakes, semi-enclosed bodies of water, and in areas of the open ocean. The period (T) of a seiche in an enclosed rectangular body of water is usually represented by the formula:

$$T = 2L \,/\, g\, d$$

in which L is the length of the body of water, d the average depth, and g the acceleration of gravity.

Shaft angle encoder (SAE) – A component of a water level gauge for converting a shaft angle on a rotating disk to length. The position of the rotating disk is determined by single or dual optical or magnetic sensors to provide an electrical output. No electro-mechanical components or gears are used, so extremely low torque is required to move the float wheel, wire, and float mechanism.

Shoreline – The intersection of the land with the water surface. The shoreline shown on charts for the Great Lakes represents the line of contact between the land and the high water level (ordinary high water mark in the U.S. and high water level in Canada).

Staff gauge – A water level gauge consisting of a vertical graduated staff from which the height of the water level can be read directly. It is called a fixed staff when secured in place so that is cannot be easily removed. A portable staff is one that is designed for removal from the water when not in use. For such a staff a fixed support is provided. The support has a metal stop secured to it so that the staff will always have the same elevation when installed for use. See electric tape gauge.

Stilling well – A vertical pipe with a relatively small opening (intake) in the bottom that extends into the adjacent lake or river at a depth that should never become dry. It is used in a gauge installation to dampen short-period surface waves while freely admitting the long-period waves, which can then be measured by a water level gauge sensor inside. Sometimes referred to as a float well.

Storm surge – A departure from a normal elevation of a lake or sea due to the piling up of water against a coast by strong winds such as those accompanying a hurricane or other intense storm. Reduced atmospheric pressure often contributes to the departure in height during hurricanes. It is potentially catastrophic, especially in deltaic regions with onshore winds at the time of high water level and extreme wind wave heights.

Subordinate Station – See master station.

Sump - See stilling well.

Tape gauge – See electric tape gauge.

Telemetry – The transmission or retrieval of data over long distance communication links, such as satellite or telephone.

Thermistor – Temperature sensor.

Tsunami – With reference to the Great Lakes see Meteotsunami

Universal time, coordinated (UTC) – The time kept by a clock controlled by atomic clocks and running at the correct rate (zero offset in frequency) but changed by the infrequent addition or deletion of 1 second "leap seconds" to keep the time within 0.7 seconds of actual rotation of the Earth as defined by UT1.

Vertical datum – A vertical datum is the reference surface for elevations, i.e., the zero elevation. It is also the components that define the vertical reference surface. For example, the mean sea level (1970-1988) at the water gauge in Rimouski, Québec is the vertical datum for the USA. The North American Vertical Datum of 1988 (NAVD 88) is the representation of this vertical datum across the USA. A vertical datum is accessible through benchmarks or, nowadays, a geoid model. A vertical datum includes the definition (height reference system) and realization (height reference frame).

Water level elevation – The elevation of a particular point or small patch on the surface of a body of water above a specific reference point or surface, averaged over a period of time sufficiently long to remove the effects of short-period fluctuations in the water level.

Water level gauge – An instrument for measuring the rise and fall of the water level. See automatic water level gauge, Next Generation Water Level Measurement System, electric tape gauge, pressure gauge, shaft angle encoder, and staff gauge.

Water level station – The geographic location at which water level observations are conducted. Also, the facilities used to make water level observations. These may include a gauge house, water level gauge, and bench marks. See master station. Such stations provide water levels relative to the International Great Lakes Datum in support of safe navigation, regulation, lake level forecasting, international cooperative treaties and agreements, riparian interest, hydroelectric power generation, construction, dredging, litigation, and other water resources management and development activities

Water level transfer – The extension of leveling across a lake or between large bodies of water by assuming that the average position of the surface of each body of water, averaged over a suitable length of time, is a level surface.

Zero Electric Tape Gauge (ZETG) – A specific reference elevation at each Great Lake – St. Lawrence River water level station to ensure correct water level measurements.