Great Lakes Water Levels and Temperatures

Identification

1. Indicator Description

This indicator describes how water levels and surface water temperatures in the Great Lakes (Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario) have changed over the last 150 years (water levels) and the last two decades (temperatures). Water levels and surface water temperatures are useful indicators of climate change because they can be affected by air temperatures, precipitation patterns, evaporation rates, and duration of ice cover. In recent years, warmer surface water temperatures in the Great Lakes have contributed to lower water levels by increasing rates of evaporation and causing lake ice to form later than usual, which extends the season for evaporation (Gronewold et al., 2013).

Components of this indicator include:

- Average annual water levels in the Great Lakes since 1860 (Figure 1).
- Average annual surface water temperatures of the Great Lakes since 1995 (Figure 2).
- Comparison of daily surface water temperatures throughout the year, 1995–2004 versus 2011–2020 (Figure 2).

2. Revision History

May 2014:	Indicator published.
June 2015:	Updated indicator with data through 2014.
August 2016:	Updated indicator with data through 2015.
April 2021:	Updated indicator with data through 2020.

Data Sources

3. Data Sources

Water level data were collected by water level gauges and were provided by the National Oceanic and Atmospheric Administration's (NOAA's) National Ocean Service (NOS), Center for Operational Oceanographic Products and Services (CO-OPS) and the Canadian Hydrographic Service (CHS). Water level data are available for the period 1860 to 2020.

The temperature component of this indicator is based on surface water temperature data from satellite imagery analyzed by NOAA's Great Lakes Environmental Research Laboratory's Great Lakes Surface Environmental Analysis (GLSEA). Complete years (all seasons) of satellite data are available from 1995 to 2020.

4. Data Availability

All of the Great Lakes water level and surface temperature observations used for this indicator are publicly available from the following NOAA websites:

- Water level data from the Great Lakes Water Level Dashboard Data Download Portal: www.glerl.noaa.gov/data/dashboard/data. At the time EPA updated this indicator in 2021, the annual high and low water levels for Lake Superior in 1906 were missing from the NOAA repository. As all other pre-1918 data were identical to data previously obtained by EPA from NOAA's website, archived values for those two missing data points were used.

- Water level data documentation: www.glerl.noaa.gov/data/now/wlevels/levels.html.

- Satellite-based temperature data from GLSEA: https://coastwatch.glerl.noaa.gov/statistic.

Methodology

5. Data Collection

Water Levels

NOAA's NOS/CO-OPS and CHS use a set of gauges along the shoreline to measure water levels in each of the five Great Lakes. All five lakes have had one or more gauges in operation since 1860. In 1992, the Coordinating Committee for Great Lakes Basic Hydraulic and Hydrologic Data approved a standard set of gauges suitable for both U.S. and Canadian shores, covering the period from 1918 to present. These gauges were chosen to provide the most accurate measure of each lake's water level when averaged together. The standard set comprises 22 gauges in the five Great Lakes and two in Lake St. Clair (the smaller lake between Lake Huron and Lake Erie). Only the five Great Lakes are included in this indicator. Lakes Michigan and Huron are combined for this analysis because they are hydrologically connected, and thus they are expected to exhibit the same water levels.

The locations of the water level gauges used for this indicator are shown in Table TD-1.

Table TD-1. Water Level Gauge Locations

Lake Superior	Lakes Michigan-Huron	Lake Erie	Lake Ontario
Duluth, MN Marquette C.G., MI Pt Iroquois, MI Michipicoten, ON Thunder Bay, ON	Ludington, MI Mackinaw City, MI Harbor Beach, MI Milwaukee, WI Thessalon, ON Tobermory, ON	Toledo, OH Cleveland, OH Fairport, OH Port Stanley, ON Port Colborne, ON	Rochester, NY Oswego, NY Port Weller, ON Toronto, ON Cobourg, ON Kingston, ON

An interactive map of all NOAA CO-OPS stations and real-time data displays are available online at: https://tidesandcurrents.noaa.gov. For more information about data collection methods and the low water datum that is used as a reference plane for each lake, see: www.glerl.noaa.gov/data/now/wlevels/levels.html.

Surface Water Temperatures

The GLSEA is operated by NOAA's Great Lakes Environmental Research Laboratory through the NOAA CoastWatch program. For general information about this program, see: https://coastwatch.glerl.noaa.gov/glsea/doc. GLSEA uses data from the Polar-Orbiting Operational Environmental Satellites system. Specifically, GLSEA uses data from the Advanced Very High Resolution Radiometer instrument, which can measure surface temperatures. Visit: www.ospo.noaa.gov/Operations/POES/index.html for more information about the satellite missions and: www.avl.class.noaa.gov/release/data_available/avhrr/index.htm for detailed documentation of instrumentation. GLSEA satellite-based data for the Great Lakes are available from 1992 through the present. Data for winter months in 1992 through 1994 are absent, however. Complete years of satellite-based data are available starting in 1995.

6. Indicator Derivation

Water Levels

NOAA provides annual average water level observations in meters, along with the highest and lowest monthly average water levels for each year. As discussed in Section 8, data provided for the period before 1918 represent observations from a single gauge per lake. NOAA corrected pre-1918 data for Lakes Superior and Erie to represent outlet water levels. NOAA averaged observations from multiple gauges per lake in the data from 1918 to present, using the standard set of gauges described in Section 5.

In Figure 1, water level data are presented as trends in anomalies to depict change over time. An anomaly represents the difference between an observed value and the corresponding value from a baseline period. This indicator uses a baseline period of 1981 to 2010, which is consistent with the 30-year climate normal used in many other analyses by NOAA and others in the scientific community. The choice of baseline period will not affect the shape or the statistical significance of the overall trend in anomalies. In this case, a different baseline would only move the time series up or down on the graph in relation to the point defined as zero. Water level anomalies were converted from meters to feet. The lines in Figure 1 show the annual average for each lake, while the shaded bands show the range of monthly values within each year.

Surface Water Temperatures

Surface water temperature observations are provided daily by satellite imagery. The left side of Figure 2 shows annual averages, which were calculated using arithmetic means of the daily satellite data. The right side of Figure 2 shows the pattern of daily average satellite-based temperatures over the course of a year. To examine recent changes, Figure 2 compares average daily conditions from the most recent decade with average daily conditions from the first full decade of data (1995–2004). All temperatures were converted from Celsius to Fahrenheit to make them consistent with all of EPA's other temperature-related indicators.

General Notes

EPA did not attempt to interpolate missing data points. This indicator also does not attempt to portray data beyond the time periods of observation or beyond the five lakes that were selected for the analysis.

7. Quality Assurance and Quality Control

Water Levels

Lake-wide average water levels are calculated using a standard set of gauges established by the Coordinating Committee for Great Lakes Basic Hydraulic and Hydrologic Data in 1992. Data used in this indicator are finalized data, subject to internal quality assurance/quality control (QA/QC) standards within NOAA/NOS and CHS. Each gauge location operated by NOAA houses two water level sensors: a primary sensor and a redundant sensor. If data provided by the primary and redundant sensors differ by more than 0.003 meters, the sensors are manually checked for accuracy. In addition, a three standard deviation outlier rejection test is applied to each measurement, and rejected values are not included in calculated values.

Surface Water Temperatures

NOAA's National Data Buoy Center, which collects the buoy surface temperature observations, follows a comprehensive QA/QC protocol, which can be found in the Handbook of Automated Data Quality Control Checks and Procedures:
www.ndbc.noaa.gov/NDBCHandbookofAutomatedDataQualityControl2009.pdf.

Satellite observations of surface temperature are subject to several QA/QC measures prior to publication. All satellite data are validated by NOAA personnel. Following this step, an automated algorithm flags and excludes temperatures not within the normal range of expected temperatures, correcting for processing errors in the original satellite data. Finally, multiple cloud masks are applied to both day and night satellite imagery so that the final product includes only completely cloud-free data. An additional algorithm is used to correct for missing pixels. Two iterations of this algorithm are described in a presentation entitled "Overview of GLSEA vs. GLSEA2 [ppt]" at: https://coastwatch.glerl.noaa.gov/glsea/doc.

Analysis

8. Comparability Over Time and Space

Water level observations prior to 1918 have been processed differently from those collected from 1918 to present. Prior to 1918, there were fewer water level gauges in the Great Lakes. As such, values from 1860 to 1917 represent one gauge per lake, which may not represent actual lake-wide average water levels. Corrections to data have been made to allow comparability over time. These corrections include adjustments due to the slow but continuing rise of the Earth's crust (including the land surface and lake bottoms) as a result of the retreat of the ice sheets after the last glacial maximum (commonly referred to as the last ice age), as well as adjustments to account for the relocation of gauges. For more discussion about these corrections, see: www.glerl.noaa.gov/data/now/wlevels/levels.html.

Satellite temperature observations have been made systematically since 1992, allowing for comparability over time. This indicator starts in 1995, which was the first year with complete coverage of all months of the year for all lakes.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. Besides climate change, natural year-to-year variability and other factors such as human activity (e.g., land use and development) and contamination can influence water temperatures.

2. Satellite data are only available starting in 1992, and the years 1992–1994 were missing data in winter months. Thus, Figure 2 starts at 1995. Although hourly temperature data have been collected from moored buoys since 1980 in most of the Great Lakes, these data contain wide gaps for a variety of reasons, including scheduled maintenance, sensor malfunctions, and natural elements (e.g., winter conditions). These data gaps prevent reliable and consistent annual averages from being calculated from buoy data.

3. Since the first water level gauges were installed in 1860, several major engineering projects have been undertaken to modify the Great Lakes basin for use by cities and residents in the area. The most prominent of these have been the dredging efforts in the St. Clair River, which connects Lakes Michigan and Huron to Lake St. Clair, to support commercial navigation. At least some of the decrease in water levels in Lake Michigan and Lake Huron has been attributed to this dredging. Specifically, the St. Clair river opening was enlarged in the 1910s, 1930s, and 1960s, contributing to greater outflows from Lakes Michigan and Huron (Quinn, 1985). Similar projects have also occurred in other areas of the Great Lakes basin, although they have not been linked directly to changes in lake water levels.

4. In addition to changes in channel depth, recent studies have found that dredging projects significantly increased the erosion in channel bottoms. The combination of dredging and erosion is estimated to have resulted in a 20-inch decrease in water levels for Lakes Michigan and Huron between 1908 and 2012 (Egan, 2013).

10. Sources of Uncertainty

Individual water level sensors are estimated to be relatively accurate. The gauges have an estimated accuracy of ±0.006 meters for individual measurements, which are conducted every six minutes, and ±0.003 meters for calculated monthly means (NOAA, 2020). In the instance of sensor or other equipment failure, NOAA does not interpolate values to fill in data gaps. Because data gaps are at a small temporal resolution (minutes to hours), however, they have little effect on indicator values, which have a temporal resolution of months to years.

Surface water temperature observations from satellites are subject to navigation, timing, and calibration errors. An automated georeferencing process was used to reduce navigation errors to 2.6 kilometers. When compared with buoy data, for reference, satellite data from the pixel nearest the buoy location differ by less than 0.5°C. The root mean square difference ranges from 1.10 to 1.76°C with correlation coefficients above 0.95 for all buoys (Schwab et al., 1999).

11. Sources of Variability

Water levels are sensitive to changes in climate, notably temperature (affecting evaporation and ice cover) and precipitation. Natural variation in climate of the Great Lakes basin will affect recorded water levels. In addition to climate, water levels are also affected by changing hydrology, including dredging of channels between lakes, the reversal of the Chicago River, changing land-use patterns, and industrial water usage. However, the long time span of this indicator allows for an analysis of trends over more than a century. Water withdrawals could also influence water levels, but arguably are not as influential as climate or dredging because nearly all (95 percent) of the water withdrawn from the Great Lakes is returned via discharge or runoff (Environment Canada and U.S. EPA, 2009).

Surface water temperature is sensitive to many natural environmental factors, including precipitation and water movement. Natural variations in climate of the Great Lakes basin will affect recorded water temperature. In addition to climate, water temperature is also affected by human water use. For example, industries have outflows into several of the Great Lakes, which may affect water temperatures in specific areas of the lake.

12. Statistical/Trend Analysis

Water Levels

Multivariate adaptive regression splines (MARS) (Friedman, 1991; Milborrow, 2012) were used within each lake to model non-linear behavior in water levels through time. The MARS regression technique was used because of its ability to partition the data into separate regions that can be treated independently. MARS regressions were used to identify when the recent period of declining water levels began. For three of the four Great Lakes basins (Michigan-Huron, Erie, and Superior), 1986 marked the beginning of a distinct, statistically significant negative trend in water levels. The MARS analysis suggests that water levels in Lake Ontario have remained relatively constant since the late 1940s.

To characterize the extent to which recent water levels represent deviation from long-term mean values, EPA used t-tests to compare recent average water levels (2011–2020) against long-term averages (1860–2020). None of the lakes had a difference that was statistically significant to a 99 percent level ($p < 0.01$) for a two-tailed t-test, though Lake Erie's recent difference in water levels (higher than the long-term mean) was significant to a 95 percent level.

Surface Water Temperatures

Table TD-2 below shows the slope, p-value, and total change from an ordinary least-squares linear regression of each lake's satellite-based annual average temperature, starting in 1995. The increasing temperature trends for Lake Erie and Lake Ontario are significant to a 95 percent level.

Table TD-2. Linear Regression of Annual Average Temperature Data, 1995–2020

Lake	Slope (°F/year)	P-value	Total change (°F) (slope x 25 years)
Erie	0.064	0.035	1.596
Huron	0.058	0.116	1.451
Michigan	0.048	0.269	1.202
Ontario	0.080	0.042	2.009
Superior	0.044	0.352	1.106

For the daily temperature graphs on the right side of Figure 2, paired t-tests were used to compare the most recent decade of average daily surface water temperature (2011–2020) against the first decade (1995–2004). Significance testing for all five lakes showed highly significant differences between the two time periods ($p < 0.0001$).

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