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Notes

Visualizing relationships between hydrology, climate, and water level fluctuations on Earth's largest system of lakes

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ABSTRACT

Understanding drivers behind monthly, annual, and decadal water level fluctuations on the North American Great Lakes is a high priority for regional research and water resource management planning. The need for improved understanding of these relationships is underscored by a series of recent unprecedented extreme water level patterns, including (but not limited to) record low water levels on Lakes Michigan and Huron in December 2012 and January 2013. To address this need, we developed the Great Lakes Hydro-Climate Dashboard (GLHCD), a dynamic flash-based web interface that builds upon the previously-released Great Lakes Water Level Dashboard (GLWLD). In addition to including water level data and projections from the GLWLD, the GLHCD presents a range of hydrological and climatological data through an improved graphical user interface specifically designed to manage, and display simultaneously, a variety of data time series from different sources. By serving as a common portal to critical regional hydro-climate and water level data, the GLHCD helps visualize and explain lake level phenomena including water level declines across all of the Great Lakes in the early 1960s and their relationship to changes in regional precipitation, as well as the abrupt water level declines in the late 1990s and their relationship to remarkable changes in over-lake evaporation. By providing insight into these, and other important regional hydro-climate events, the GLHCD helps practitioners, researchers, and the general public improve their understanding of the drivers behind Great Lakes water levels, and to employ that understanding in prudent water resource management planning.

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Introduction

In January 2013, monthly-average water levels on Lake Michigan and Lake Huron dropped to their lowest levels in recorded history. These two lakes, along with the other North American Great Lakes (Lake Superior, Lake Erie, and Lake Ontario) constitute the largest system of lakes and the most expansive surface of fresh water on Earth (Gronewold et al., 2013b). Understanding drivers behind the recent record-low water levels and other historical extreme water level fluctuations on the Great Lakes is a high priority for regional research (Angel and Kunkel, 2010; Lenters, 2001) and water resource management planning (Brown et al., 2011; Clites and Quinn, 2003). To address this need, we implemented a series of improvements to the existing Great Lakes Water Level Dashboard (or GLWLD; a web-based interactive tool for viewing and downloading historical, current, and projected Great Lakes water levels, as described in Gronewold et al., 2013a) resulting in a new on-line tool, the Great Lakes Hydro-Climate Dashboard (GLHCD). The GLHCD promotes understanding not only of how water levels change over different time scales and across different lakes, but also how those changes relate to corresponding changes in regional hydrology and climate variables including over-lake precipitation, over-lake evaporation, runoff, and ice cover.

Here, we describe the new GLHCD, with a particular emphasis on the utility of data sets added following the release of the GLWLD. We begin with an overview of key features of the GLHCD, and then provide two examples of how it can be used to answer pressing research and management-oriented questions about historical and current Great Lakes water levels.

Overview of the Great Lakes Hydro-Climate Dashboard

The GLHCD improves upon the design and content of the GLWLD in two important ways. First, it expands the range of data sets to include new aggregations of historical and current water level measurements, as well as historical Great Lakes water budget and ice cover data. Second, the GLHCD includes a series of design features that accommodate the simultaneous display of this broader range of data sets, and their various units of measurement.

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Availability

Both the GLHCD and GLWLD are freely-available at the following web sites:

- www.glerl.noaa.gov/data/now/wlevels/dbd/GLHCD/ (GLHCD)
- www.glerl.noaa.gov/data/now/wlevels/dbd/ (GLWLD)
- www.glerl.noaa.gov/data/now/wlevels/dbd/portal.html (portal to all dashboard products)

Data

In addition to the data categories included in the original GLWLD (i.e. water level observations, seasonal forecasts, decadal projections, and paleoclimate reconstructions), the GLHCD includes two new categories, identified in the GLHCD legend and menu as 'Hydrological–Climatological' and 'Ice Cover'. The Hydrological–Climatological (hereafter referred to as hydro-climate) data sets are derived primarily from Croley and Hunter (1994) and include monthly and annual over-lake precipitation, over-lake evaporation, and runoff (all expressed in millimeters over the lake surface) for each of the lakes. We also include in this data category the difference between over-lake precipitation and over-lake evaporation, as well as the net basin supply (NBS) to each lake, where NBS is calculated as the sum of over-lake precipitation, over-lake evaporation (expressed as a negative contribution), and runoff.

We note that multiple other sources of regional hydro-climate data are available, including those developed by the US Army Corps of Engineers (USACE). Importantly, the USACE is one of two federal agencies in the region (along with Environment Canada, or EC) with the official responsibility of developing internationally-coordinated Great Lakes regional hydraulic and hydrologic data. As such, the USACE is currently a formal partner in the GLHCD project, and future evolutions of the GLHCD will distinguish between NOAA-GLERL, USACE, and other data sets, with a particular emphasis on identifying those developed for research purposes, and those designated for implementation in a fully operational framework. For additional perspectives on calculating NBS, including those developed by the USACE, EC, and other regional agencies, we direct readers to Hartmann (1990), Noorbakhsh and Wilshaw (1990), and Deacu et al. (2012).

Ice cover data in the GLHCD is adapted from the NOAA Great Lakes Ice Atlas project, and originates as a digital product from the National Ice Center (NIC) and Canadian Ice Service (CIS). These digital images are developed using a combination of satellite imagery, ship reports, and other daily observations to generate estimates of ice concentration, expressed as the percentage of total area of ice coverage across each lake for specific days of the year. For details, and further reading on the evolution of the ice data included in the GLHCD, see Assel and Norton (2001), Assel (2005), Wang et al. (2012b), and Wang et al. (2012a).

Finally, the GLHCD includes daily lake-wide average water levels and the average of daily water levels for the current month, neither of which were in the GLWLD. These new data sets allow users to better understand how recent hydrological and meteorological conditions (such as drought or high over-lake evaporation rates) propagate into water level variability across daily and monthly time scales, and help address frequent questions about the rate at which water levels change from one month to the next.

Design features

One of the more important features of the GLWLD and GLHCD is the ability to overlay time series for multiple data sets. In the GLHCD, this feature allows users to simultaneously view both hydro-climate and water level data to understand interactions between the two, however this visual comparison can be complicated by the fact that the data sets are recorded in different units of measurement. To accommodate the broad range of data sets in the new GLHCD, we implemented dual-axis capability in each data panel along with controls that allow users to independently adjust the range of the two vertical axes in each panel and to synchronize the vertical axis range for all panels. This feature helps overcome a common user tendency to view water level and hydro-climate data at scales that may be suitable for each individual lake, but can obscure the important relationships between relative water level changes across the entire Great Lakes system. For example, news articles, technical reports, and public outreach materials often present regional climate and water level dynamics from the Lake Michigan–Huron system in a way that suggests that Lake Michigan–Huron dynamics are generally representative of the other Great Lakes. The axis control features we have added to the GLHCD are simple and effective approaches to overcoming these types of conventional, yet often misleading, water level communication protocols.

We note that in the current version of the GLHCD, ice cover data sets (when displayed in the data panel for a particular lake) are not associated with a unique vertical axis. Instead, we present the ice cover data with the explicit acknowledgment (as indicated in the 'Legend and Menu' under 'Ice Cover') that the vertical range of each data panel corresponds to an ice cover range from 0% (bottom of each panel) to 100% (top of each panel). We plan to establish a unique and adjustable axis for ice cover data in each lake's data panel in future iterations of the GLHCD.

Finally, based on suggestions from the Great Lakes user community, we have added an option to view hydro-climate data aggregated across the entire Great Lakes basin. This data is viewed through a single stand-alone panel accessed by clicking on the 'All Lakes I/O' button in the top-right of the main GLHCD graphical user interface (see upper-right corner of Figs. 1 and 2).

Understanding hydrological and climatological drivers behind Great Lakes water levels: representative applications

The GLHCD is designed to display Great Lakes water level, hydrological, and climatological data within an interface that allows users to answer their own questions about the relationships between water level dynamics and the water budget. In the following subsections, we demonstrate how the GLHCD can be used to address two common questions asked about Great Lakes water levels. The first, “Why are current water levels on the Great Lakes so low?”, reflects concern over widespread impacts of persistent low water levels on Lakes Superior and Michigan–Huron, but also misconceptions about relative water level conditions across the entire Great Lakes system (see, for example, Buttle et al., 2004; Millerd, 2010; Schwartz et al., 2004). The second question, “Is less ice cover on the lakes leading to higher evaporation and lower water levels?”, also reflects concerns over water levels and their drivers, but the answer is based on a relatively complex set of relationships that can be represented graphically in the GLHCD.

Long-term changes in annual NBS and water levels

Scientists from NOAA's Great Lakes Environmental Research Laboratory (GLERL) and USACE's Detroit District have, for the past thirty years, employed a combination of meteorological and hydrological measurements, along with computer model simulations, to estimate monthly and annual NBS to each of the Great Lakes (for additional background, see Croley, 1989; Croley and Assel, 1994; Croley and Hunter, 1994; Noorbakhsh and Wilshaw, 1990; Quinn and Kelley, 1983; Quinn and Norton, 1982). These historical estimates, while based on relatively conventional computational procedures (see, for example, procedures in Croley and Hartmann, 1985, which are the basis for current NOAA-GLERL basin-scale precipitation estimates), continue to serve as both a benchmark for comparison with more contemporary alternatives to estimating NBS components across the Great Lakes (Deacu et al., 2012; Fry et al., 2013; Holman et al., 2012; Lofgren et al., 2011; Spence et al.,

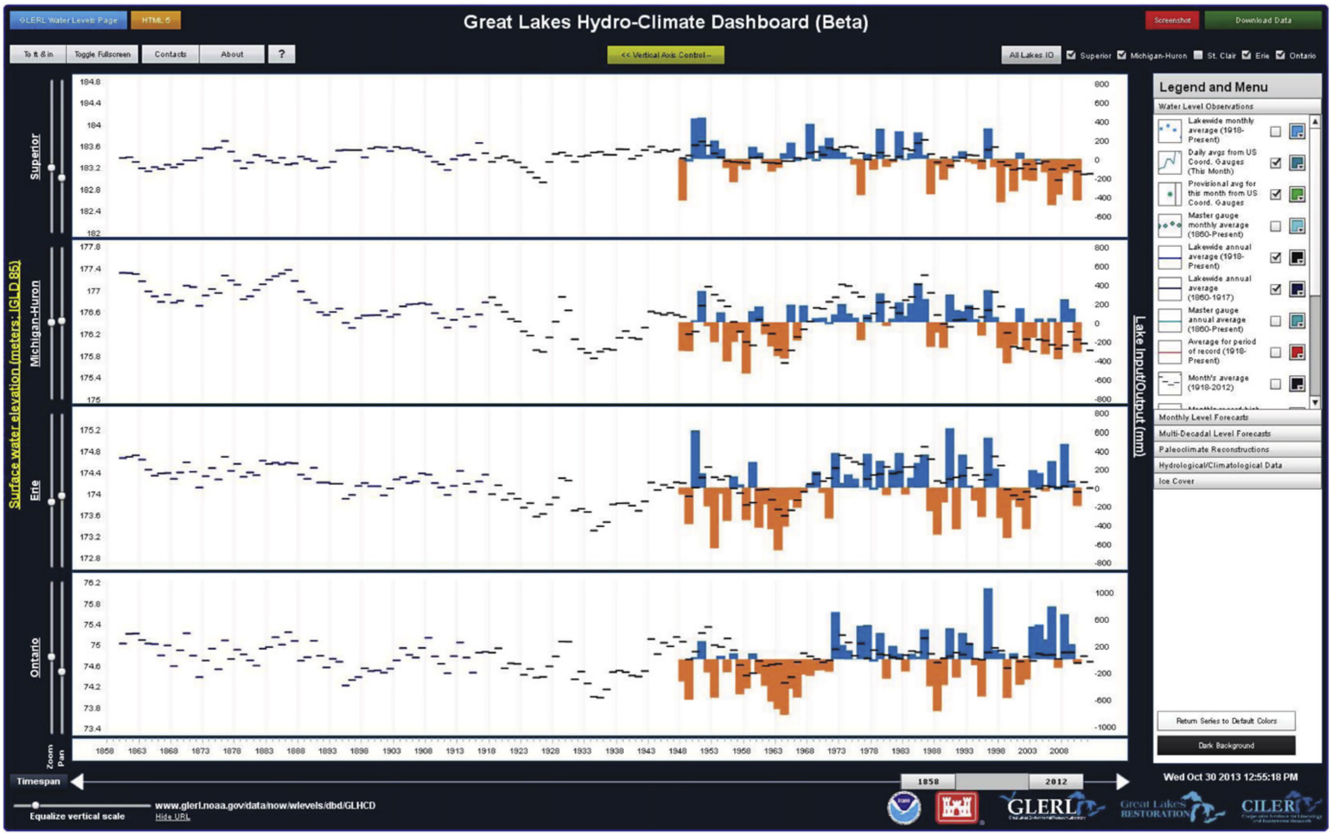

Fig. 1. GLHCD display of historical annual average lake-wide water levels from 1860 to present (dark dashes, expressed as surface water elevations in meters above the 1985 International Great Lakes Datum) and annual NBS values (colored vertical bars, expressed as deviations from the long-term average in units of mm over the surface of each lake) from 1950 to present. Blue vertical bars indicate annual NBS above the long-term average, while tan bars indicate annual NBS below the long-term average. High resolution versions of this image, and step-by-step instructions for reproducing it, are available on the GLHCD web site (see the Availability Section).

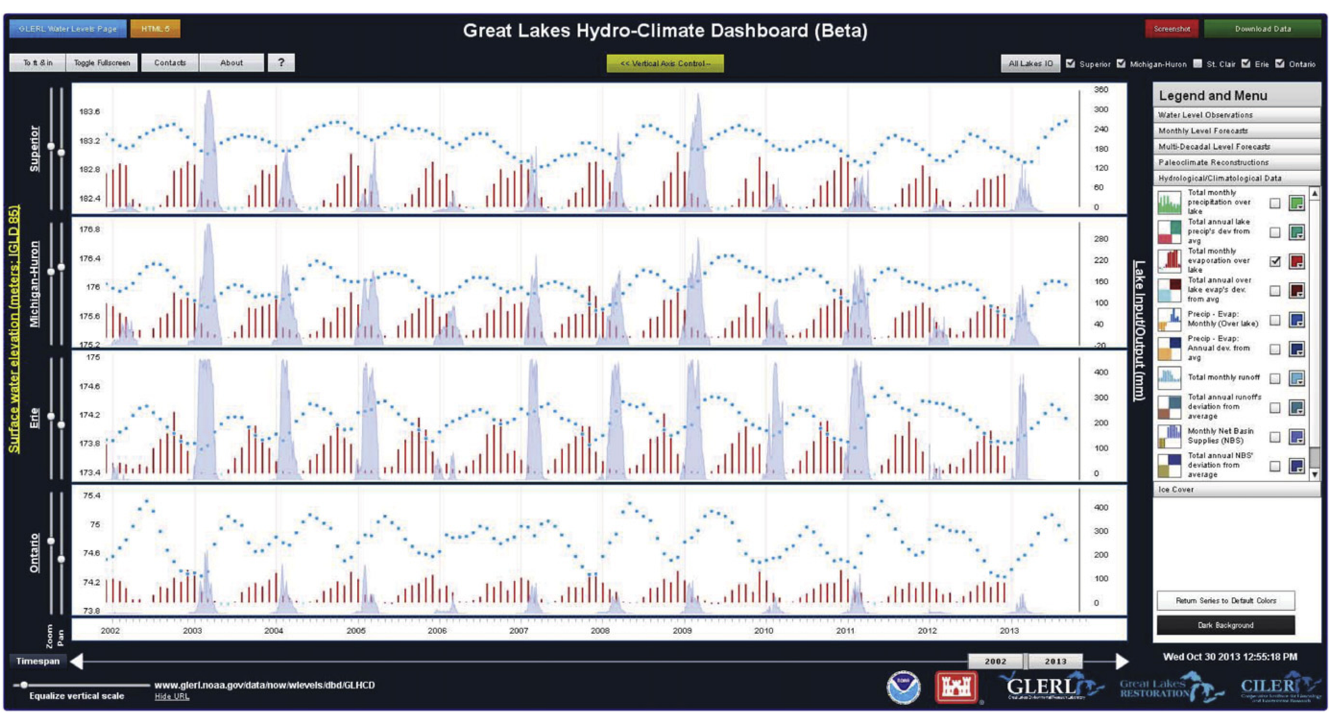

Fig. 2. GLHCD display of monthly total over-lake evaporation (red vertical bars), daily ice cover (gray regions; expressed as percentage of total lake area with each panel's vertical axis spanning a range from 0% to 100%), and internationally-coordinated monthly lake-wide average water levels (blue dots). Year labels along the x-axis are aligned with the beginning (i.e. January) of the corresponding calendar year. High resolution versions of this image, and step-by-step instructions for reproducing it, are available on the GLHCD web site (see the Availability Section).

2011), and as one of the longest continuous data sets of any origin for Great Lakes regional NBS.

While these historical NBS estimates are widely used to support regional water resource planning, they can also be used to provide additional insight when compared directly to corresponding annual average water level measurements in the GLHCD (Fig. 1). Decreasing water levels across all of the Great Lakes in the early 1960s, for example, clearly coincide with decreasing NBS across each of the lakes. Similarly, the period of above-average water levels during the 1970s and 1980s corresponds with a period of predominantly above-average NBS. Importantly, the late 1990s are characterized by a drop in NBS across all of the Great Lakes, while the following decade is characterized by divergent NBS patterns among the lakes. Specifically, we observe NBS values remaining relatively low on Lakes Superior, Michigan, and Huron for the past 15 years, with NBS values rising on Lakes Erie and Ontario. These trends explain much of the recent variability in Great Lakes water levels, including the drop across all of the lakes (in spite of regulation plans on Lakes Superior and Ontario) in the late 1990s. For further reading on the water level drop in the late 1990s, including connections to continental-scale climate patterns, see Assel (1998), McPhaden (1999), Assel et al. (2000), and Assel et al. (2004). These trends in NBS also explain (at least in part) the tendency over the past decade for Lake Superior to continue dropping, for Lake Michigan–Huron to remain low, and for Lake Erie to rise (slowly, if not steadily).

Seasonal changes in ice cover, evaporation, and water levels

Over-lake evaporation and the areal extent of ice cover on the Great Lakes both follow a strong seasonal pattern (Lenters, 2001; Quinn, 2002). Recent research based on a small network of off-shore over-lake eddy-covariance towers (the first of which was installed in 2007 as described in Blanken et al., 2011; Spence et al., 2013) offers valuable insight into the complex relationships between these two variables. This insight, and other important aspects of the ice-evaporation–water level relationship, can be represented visually in the GLHCD by overlaying model-simulated monthly evaporation and monthly ice cover data sets (described in the Data Section) with monthly lake-wide average water levels (Fig. 2). This visual representation indicates that, contrary to what many perceive (but what both historical and recent research have suggested; see, for example Croley, 1989, 1992; Croley and Hunter, 1994; Quinn, 1979; Quinn and Kelley, 1983; Spence et al., 2013), a relatively small proportion of annual over-lake evaporation occurs in the summer months. In fact, more than half of the annual total evaporation for each lake takes place between August and January, a period that typically precedes the onset of significant ice cover. Consequently (as described in further detail in Spence et al., 2013), total annual over-lake evaporation is more closely related to complex inter-seasonal changes in the surface water temperature and energy budget of each lake than to ice cover alone (for further reading, see Austin and Colman, 2007).

Visualizing the relationship between ice cover, evaporation, and water levels through the GLHCD further underscores the importance of linkages between extreme hydroclimate conditions across all of the Great Lakes and seasonal water levels. Extreme low ice cover conditions from January 2012 to March 2012, for example (Fig. 2), combined with a widespread drought and high over-lake evaporation rates through much of the summer and fall of 2012, led to anomalous seasonal water level conditions that included not only the record-low levels on Lakes Michigan and Huron (Gronewold and Stow, 2014b), but also an unprecedented continuous decline in Lake Erie water levels between December 2011 and October 2012 (Gronewold and Stow, 2014a).

Summary and future plans

The GLHCD was developed to serve as a web-based interactive tool for communicating relationships between Great Lakes water levels and regional hydrological and climatological variables while building on the technology and success of its predecessor, the GLWLD (Gronewold et al., 2013a). We intend to continue improving the GLHCD by incorporating user feedback, integrating additional data sets (along with modifications to existing data sets), and broadening the range of contributing partners.

Finally, we recognize that it is informative to acknowledge and consider other factors that impact Great Lakes water levels (though not to the same extent as precipitation and evaporation) including isostatic rebound (Mainville and Craymer, 2005) and the historical (i.e. late 19th and early to mid-20th century) dredging projects along the channels that connect the Great Lakes (for details, see Quinn, 1985). We also recognize that changes in precipitation and over-lake evaporation are related to variability in atmospheric teleconnection patterns (such as ENSO and NAO, as described in Wang et al., 2012b). In light of these considerations, we view the evolution of the GLHCD as an ongoing endeavor aimed at improving understanding of Great Lakes water level dynamics and the range of factors that influence them.

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