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Short communication

# A dynamic graphical interface for visualizing projected, measured, and reconstructed surface water elevations on the earth's largest lakes

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ABSTRACT

There is a growing need within the international water research and water resources management community, and the general public, for easy access to time-series of projected, measured, and reconstructed marine and freshwater coastal surface water elevations. There is also a need for effectively communicating variability among different surface water elevation data sets, as well as the intrinsic uncertainties in surface water elevation forecasts. Here, we introduce an interactive web-based interface, the Great Lakes Water Level Dashboard (GLWLD), designed to address this need for the North American Laurentian Great Lakes, the largest assemblage of unfrozen fresh surface water bodies on planet Earth, and one with a coastline of over 16,000 km (roughly 10,000 miles). The GLWLD is a Flash-based tool that can simultaneously display time-series of measured monthly and annual water level data and seasonal forecasts for each of the Great Lakes, reconstructed lake levels from paleoclimate research, and decadal lake level projections under alternative climate scenarios. By employing a suite of novel data transfer, processing, and visualization tools, the GLWLD allows users to seamlessly transition not only between alternate displays of Great Lakes water levels over different temporal scales, but between different data sets and forecasts as well. Furthermore, the unique GLWLD interface can help users understand the extent to which decisions regarding the use of the lakes depend on an appreciation of uncertainty and variability within, and between, different sources of Great Lakes water level information.

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## Software availability

Name of software: The Great Lakes Water Level Dashboard
Developers: National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, USA and Cooperative Institute for Limnology and Ecosystems Research, University of Michigan, Ann Arbor, Michigan, USA
Hardware required: Adobe Flash Capable Computer with Modern System Specifications, minimum 1 GB RAM
Software required: Internet browser (Mozilla Firefox, Google Chrome, Microsoft Internet Explorer, etc.), Adobe Flash Plugin
Program language: Adobe MXML and ActionScript under the Adobe Flash Builder, HTML, Javascript
Availability: Free at http://www.glerl.noaa.gov/data/now/wlevels/dbd/.

## 1. Introduction

The North American Laurentian Great Lakes collectively constitute the largest surface area and the second largest volume of any unfrozen surface freshwater resource on planet Earth, and are directly and critically linked to the human, environmental, and economic health of central North America (Buttle et al., 2004; Millerd, 2005; Field et al., 2007). As a massive and dynamic inland coastal system, the Great Lakes respond to a combination of intrinsic and extrinsic forces ranging from climate change impacts to anthropogenic controls (Brown et al., 2011). This range of drivers propagates into a variety of large-scale physical and ecological features. Of these, changes in the surface water elevations of the lakes themselves are arguably one of the most important from a regional water resources planning perspective.

Existing web-based outlets for Great Lakes water level information cover a range of spatial and temporal scales. Dynamic displays of hourly and daily-scale data and forecasts, for example, are available from the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Coastal Forecasting System (GLCFS) and the Great Lakes Observing System (Schwab and Bedford, 1994; Read

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et al., 2010). Similarly, static images of both official and experimental monthly-scale water level forecasts are distributed by, respectively, the Detroit District of the United States Army Corps of Engineers (USACE) and the NOAA Great Lakes Environmental Research Laboratory (GLERL). These existing federal institution frameworks underscore the importance of effectively communicating Great Lakes water level information to the general public, policy makers, and regulatory authorities. There is, therefore, a clear need for a single interactive portal through which users can access and analyze time-series data and forecasts of Great Lakes water levels from multiple sources across various temporal scales.

We find, furthermore, that most Great Lakes water level forecasts (and forecasts for a variety of other meteorological, economic, and climate information) are presented to the general public without a basis for assessing their accuracy and the extent to which that accuracy (or model skill) varies over annual and sub-annual time scales (Spiegelhalter et al., 2011). The USACE, for example, routinely publishes operational Great Lakes seasonal water level forecasts in the *Monthly Bulletin of Lake Levels for the Great Lakes* along with summary statistics from the observed water level record. This bulletin provides the general public with a simple, internationally-coordinated forecast and is a readily-available source of accurate and up-to-date information on Great Lakes monthly-average water levels. However, the bulletin (as with most static images) does not give users the option of overlaying archived forecasts and observations so that they get a sense of the forecast model's success rate. This type of retrospective model assessment, when easily accessible, allows researchers to prioritize investments in model improvements while potentially helping the general public understand relationships between risk, forecast-based decision making, and forecasting skill (Murphy, 1993). To address this need, scientists from NOAA-GLERL and the University of Michigan's Cooperative Institute for Limnology and Ecosystems Research (CILER) developed the Great Lakes Water Level Dashboard (GLWLD). This web-based graphical user interface employs state-of-the-art software technology to display and compare Great Lakes monthly and annual lake-wide average water level time-series data, and forecasts, from multiple sources.

## 2. Overview of GLWLD data and forecasts

The GLWLD is a versatile tool designed to communicate monthly, annual, and decadal Great Lakes water level data and forecasts to a broad user community ranging from recreational boaters, marina owners, and hydropower facility managers, to representatives from the Great Lakes shipping industry and coastal infrastructure design teams. As described in the following subsections, the GLWLD organizes this information into four categories.

### *2.1. Lakewide average surface water elevation measurements*

Monthly, seasonal, and decadal-scale Great Lakes regional planning and operational decisions require water level data and forecasts aggregated over both the surface area of each lake and across relatively long time steps. The GLWLD serves as the first-ever dynamic web-based interface to a set of lakewide monthly average water level measurements that address this need, and the procedures for calculating these values are readily accessible through the "Info on surface water elevation data" button in the GLWLD legend and menu. The GLWLD also displays average monthly water level statistics including the average water level for each lake from 1918 to present, as well as record high, mean, and low monthly average water levels. For further reading on the history of the Great Lakes water level monitoring network, see Bunch (1970) and Woodford (1991).

### *2.2. Monthly lakewide average surface water elevation forecasts*

Monthly water level forecasts are used throughout the Great Lakes community to make decisions affecting human and environmental health with significant implications for the region's commercial and economic stability. As with official recorded Great Lakes monthly lakewide data, there are multiple methods that could be used to forecast monthly water levels, each based on a different model or an ensemble of models. In the current version of the GLWLD, we have included one of these forecasts; the "experimental" (i.e. research-oriented) monthly water level forecasts from NOAA-GLERL's Advanced Hydrologic Prediction System (or AHPS, as described in Croley, 1997, 2003; Gronewold et al., 2011). In general, AHPS propagates forecasts of the Great Lakes water budget (including overlake precipitation, overlake evaporation, and runoff) through a "routing" model that simulates the flow of water in the channels that connect each of the Great Lakes (for further reading see Clites and Lee, 1998).

Specifically, the GLWLD includes current monthly lakewide average water level forecasts for ten consecutive months into the future, as well as archived 3- and 6-month water level forecasts for each month dating back to 1997. We expect, in future iterations of the GLWLD, to add archived forecasts from different time periods, as well as both archived and current forecasts from other agencies and research groups.

### *2.3. Multi-decadal surface water elevation forecasts*

There is a large and growing body of research on alternative methods for projecting climate change impacts on future Great Lakes water levels (Lofgren et al., 2011; MacKay and Seglenieks, 2013; Lofgren and Gronewold, 2013). As that body of research expands, so does the potential for both increased variability among different projections, as well as a perception of increasing uncertainty. We believe, however, that much of the confusion regarding future water levels in the Great Lakes arises because projections are rarely displayed within the context of Great Lakes water level measurements, or in comparison to other projections. These comparisons underscore the importance of explicitly acknowledging how different models, and different modeling assumptions, propagate into a potentially broad range of water level projections (see, for example, Hayhoe et al., 2010; Angel and Kunkel, 2010). We address this problem in the GLWLD by allowing users to simultaneously display a variety of Great Lakes water level multi-decadal projections, each based on a different hydrological model and different set of climatological forcings.

### *2.4. Paleoclimate reconstructions*

Over the past two decades, a series of studies has emerged inferring relationships between natural climate proxies (such as tree rings and lake sediments) and surface water elevations to provide a broader perspective on Great Lakes water level changes than that derived from measured lake levels alone. Tree ring-derived estimates of multi-year annual temperature and precipitation, for example, have been used in conjunction with meteorological data to construct approximately 300 years of lake level variation on Lake Michigan–Huron (Quinn and Sellinger, 2006) and Lake Erie (Wiles et al., 2009). Similarly, sedimentary-contact derived estimates within multi-decadal beach ridges (i.e. ancient shorelines) have been used to construct approximately 5000 years of surface water elevation variation on Lake Michigan–Huron

(Baedke and Thompson, 2000) and Lake Superior (Johnston et al., 2012).

Some previous studies indicate significant alterations in the water level regime between the period of record (i.e. with direct water level measurements) and data from the previous centuries and millenia. In this way, paleoclimate reconstructions provide critical insight into large-scale climate teleconnections (such as those related to the Pacific–North American oscillation, as discussed in Wiles et al., 2009), long-term geological processes (see, for example, discussions of glacial isostatic adjustment in Baedke and Thompson, 2000), and the “modern setup” of Lake Superior’s separation from Lake Michigan–Huron roughly a millenium ago (Johnston et al., 2012). These insights support informed and effective decisions about preparing for future change. As additional research investments are made in projecting future climate change scenarios into impacts on coastal water levels, improving understanding of water level dynamics beyond the measurements from the instrumental record will become increasingly important (Curry and Webster, 2011; Sheffield et al., 2012).

## 3. System design

The GLWLD is designed to build on the success of other graphical user interface-based data analysis tools (Hyman et al., 1996; Jeong et al., 2006) while complying with guidance proposed by the environmental data visualization community (Yi et al., 2007; Kelleher and Wagener, 2011). A design attribute of many innovative web-based data access tools is a display that incrementally unveils additional “levels” of information to the user (Spiegelhalter et al., 2011). Implementing this design feature is particularly important to the GLWLD because it contains a broad range of data sets, and because one of the explicit goals of the GLWLD is to allow users to simultaneously display and overlay multiple data sets (such as archived forecasts and measurements) for the same variable and time period. It is also an explicit goal of the GLWLD to expose differences that might arise between multiple versions of the same data set depending on the monitoring network, the model, or the processing algorithm from which they were derived.

To achieve these objectives, we developed the GLWLD interface using the Adobe Systems, Incorporated Flash Builder (San Jose, California) Integrated Developer Environment (IDE) within Adobe’s Flex framework. We then, within the Flash ActionScript language, defined how the interface responds to user interactions. For example, when a user launches the GLWLD (upper-left of Fig. 1), all currently-available GLWLD data sets are transferred from the server to the user’s computer, a process that takes roughly 6–10 s on a standard PC with a 1 megabit per second internet connection. This “front-end” data loading approach (as opposed to a download “on-the-fly” approach) minimizes the number of times a user experiences delays when changing the GLWLD display, and allows users to download all data sets directly through a conventional data download portal (accessed by clicking on a “Download Data” button in the upper right-hand corner of the GLWLD interface).

Subsequent data processing steps, such as aggregating and ordering individual time-series objects, are then executed through a temporary data object (middle of Fig. 1). Only after data processing steps have been implemented within the temporary data object is data then transferred to an active data object, from which it is transferred to the GLWLD display in a single step without a noticeable delay (right-hand side of Fig. 1). These design features ultimately determine how data points appear when overlaid (if and when they are displayed simultaneously) and are critical to achieving a user-friendly display.

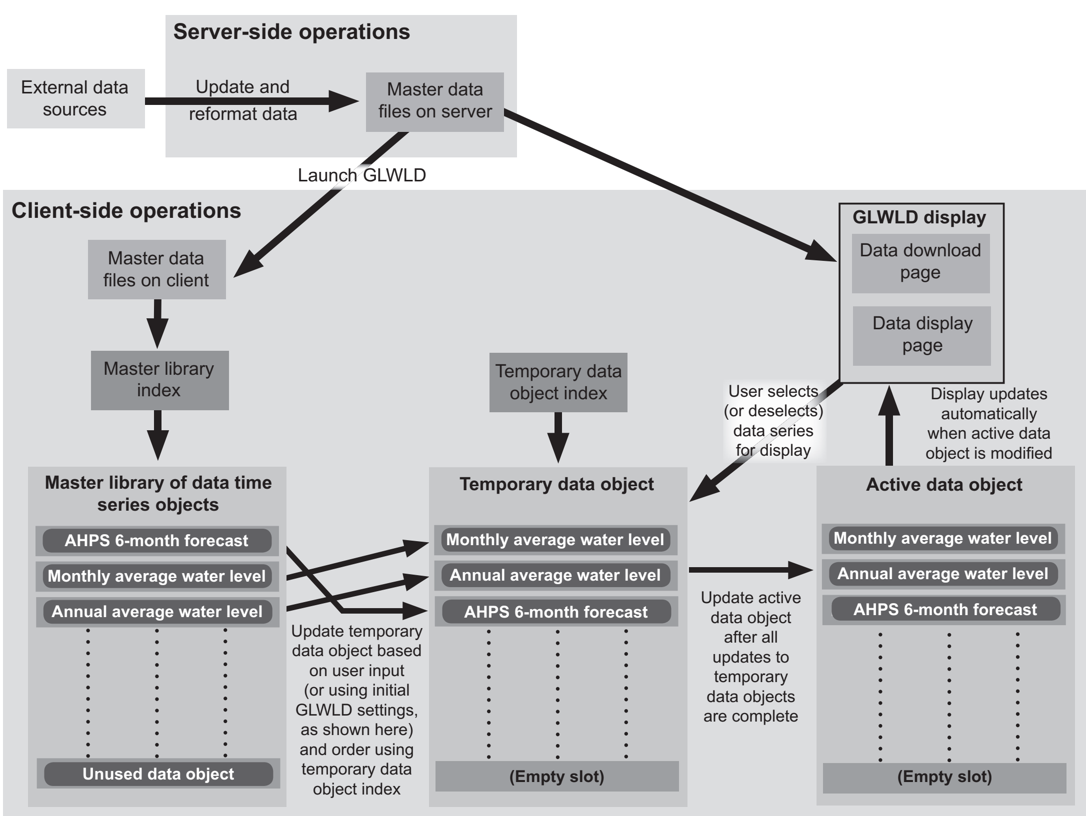


**Fig. 1.** Process diagram indicating the GLWLD data management and display updating scheme.

Finally, our design was implemented with a recognition of evolving HTML and Javascript technologies for use in hand-held devices and tablets. We found that these technologies, however, did not support the full range of capabilities we envisioned for the GLWLD, including (but not limited to) the ability to display and overlay multiple user-selected data sets. We have, however, implemented a preliminary HTML–Javascript version of the GLWLD, accessible by clicking on the "HTML 5" button in the upper-left hand corner of the GLWLD interface (Fig. 2).

## 4. Representative application

The GLWLD was designed to improve how Great Lakes monthly, seasonal, and decadal water level data and forecasts are

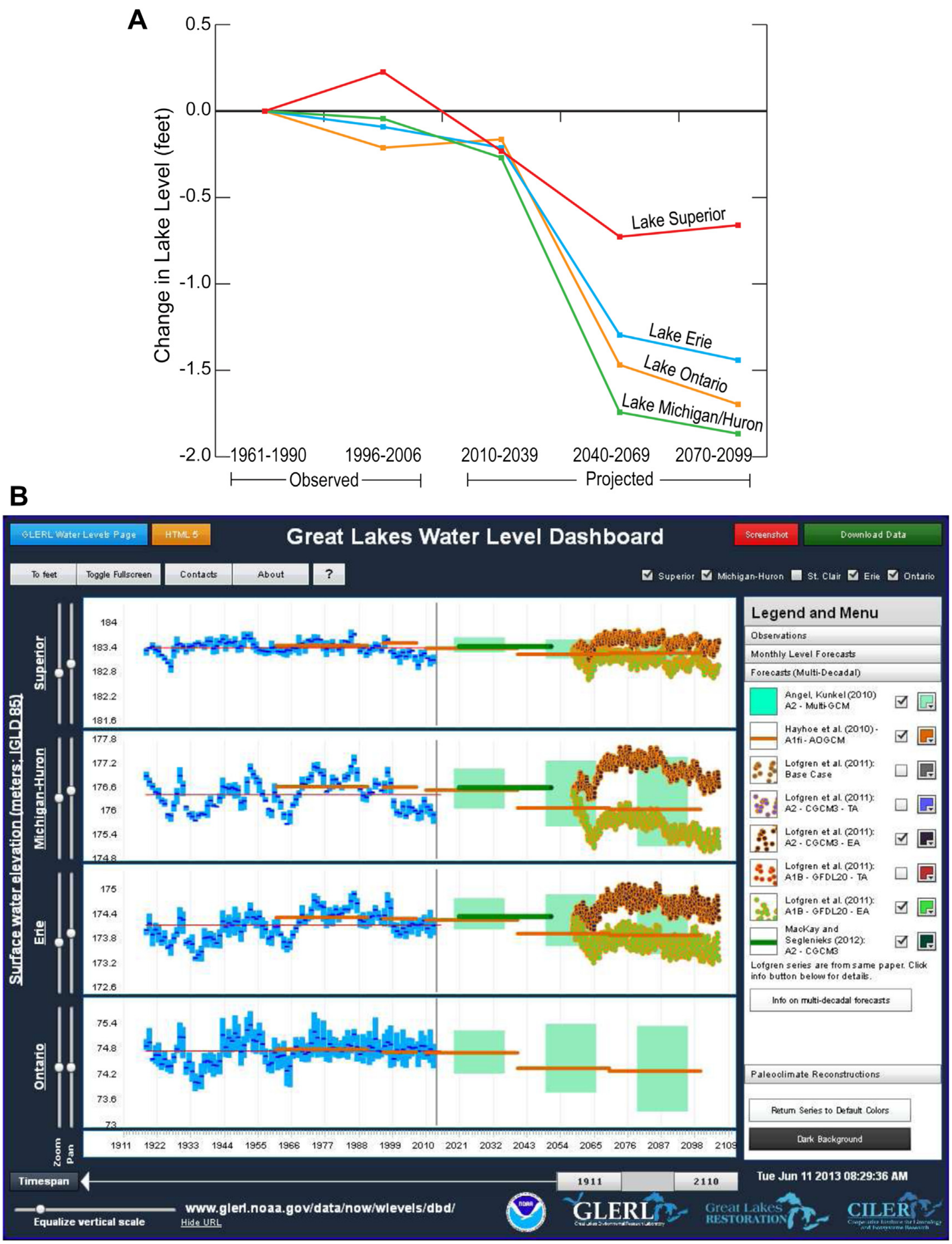


**Fig. 2.** Panel A includes a representative static image of long-term Great Lakes water level projections (reproduced with permission) from Hayhoe et al. (2010). Panel B is the GLWLD-based display of long-term projections including (in left-hand side of panel B) recorded monthly (narrow light-blue vertical bars) and annual (dark-blue thin dashes) average water levels from roughly 1900 to present, and (in right-hand side of panel B) overlayed water level projections from Angel and Kunkel (2010), Hayhoe et al. (2010), Lofgren et al. (2011), and MacKay and Seglenieks (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

communicated to a broad audience, and to move beyond the conventional protocol of disseminating individual "pre-generated" static graphics through multiple web sites. One example of how the GLWLD can be used to achieve this goal is through display of long-term (i.e. multi-decadal) Great Lakes water level projections.

Long-term Great Lakes water level projections have gained significant attention over the past decade, largely because of the critical role water level data and projections play in regional water resources management planning (Brown et al., 2011). In addition, broad distribution of compelling static images (see, for example, top panel of Fig. 2) from studies that project large drops in water levels over the next 30–90 years have given the impression that model projections broadly indicate significant future water level declines (see Angel and Kunkel, 2010; Hayhoe et al., 2010). Long-term Great Lakes water level projections have also received significant attention recently because of climate-related changes to the Great Lakes physical system, including increases in temperature and reductions in Great Lakes ice cover (Wang et al., 2012), and because of revisions to the operations plan for controlling Lake Superior outflows (IJC, 2012). Interestingly, other recent studies on long-term Great Lakes water level projections that utilize alternative models (for examples and further discussion, see Lofgren et al., 2011; MacKay and Seglenieks, 2013) indicate that future long-term average water levels may not differ much from current long-term averages.

Regardless of whether they indicate future increases or decreases in water levels, the full ensemble of currently available long-term Great Lakes water level forecasts (including those referenced above, along with several others) are rarely projected alongside one another (for further discussion, see Gronewold et al., 2013a). The GLWLD facilitates this type of side-by-side comparison (bottom panel Fig. 2), not only for long-term forecasts, but for other data sets as well. It also allows users to understand how different models lead to different forecasts, and how variability within and between those forecasts compares to variability in the record of water level measurements.

## 5. Conclusions and future work

The GLWLD is a novel and freely-available web-based tool that utilizes state-of-the art data visualization and processing schemes to communicate important information about water levels of the North American Laurentian Great Lakes. Many of the data sets in the GLWLD are derived from readily-available web sites and static images that, while informative, do not facilitate a direct comparison between different data sets and forecasts of the same variable across a variety of time scales. The GLWLD was designed to explicitly address this gap in modeling and software-based research.

Great Lakes water level dynamics are linked to changes in the Great Lakes water budget. Comparing Great Lakes water level data and projections to estimates of the major components of the water budget including, for example, the precipitation estimates of Croley and Hartmann (1985), Holman et al. (2012), and Gronewold et al. (2013b), as well as the evaporation estimates of Croley (1992) and Spence et al. (2011), could provide valuable insight into potential driving forces behind water level variability (for further discussion, see Gronewold and Fortin, 2012; Fry et al., 2013). A clearer representation of these relationships could also help practitioners charged with making important water resource management decisions, not only in the Great Lakes, but in similar large freshwater ecosystems as well (Wilson and Carpenter, 1999). We intend to implement these features in future versions of the GLWLD.

The fluctuating levels of the Great Lakes are an example of an environmental variable that impacts multiple sectors of the economy, as well as human and environmental health, in different ways. Although much attention is called to global sea level rise, the Great Lakes represent a massive inland coastal system that continuously experiences interannual water level fluctuations of a greater magnitude than those experienced by marine coastal communities over the past century (Gronewold et al., 2013a). The GLWLD provides important insights into these dynamics, and serves as an example of how coastal water level dynamics could be displayed for other parts of the world, particularly in areas struggling with minimal water budget monitoring infrastructure and limited access to clean drinking water.

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