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Wireframing for interactive & web-based geographic visualization: designing the NOAA Lake Level Viewer

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ABSTRACT

In this article, we explore the potential of wireframe design and evaluation for interactive and web-based mapping through a case study on water level visualization. Specifically, our research informed design and development of the National Oceanic & Atmospheric Administration's (NOAA) Lake Level Viewer (http://coast.noaa.gov/llv/), an interactive and web-based geovisualization application for the Great Lakes region of North America. As part of our overall user-centered design process, we created two sets of wireframes to evaluate two aspects of the user experience: *high-fidelity* wireframes to illustrate the proposed *representation* solution using real data and *low-fidelity* wireframes to provide a rough sketch of the proposed *interaction* solution. Eighteen target users completed cognitive walkthroughs of the wireframes, with the sessions audio-recorded for subsequent transcription and qualitative data analysis. The wireframe evaluations led to a series of revisions to the functional scope and visual design of the Lake Level Viewer. The process also generated recommendations for designing water level visualizations supporting adaptive management in response to climate change as well as for leveraging wireframes in support of large-scale mapping and GIS projects.

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User-centered design; user-experience design (UX design); wireframes; prototypes; cognitive walkthrough; water level visualization; uncertainty visualization; adaptive management; climate change

1. Introduction

In this article, we explore the potential of wireframing for Cartography and GIScience. A *wireframe* is a rough visual outline of a proposed application (Lloyd 2009), and is a specific kind of prototype generated during the user-centered design process to collect input and feedback from target users before designs are finalized. Prototyping has been identified as essential for incremental improvement to the *utility* (i.e. usefulness) and *usability* (i.e. ease-of-use) of an application, both broadly in Usability Engineering (e.g. Nielsen 1992, 1993) and specifically in Cartography and GIScience (e.g. Slocum et al. 2003; Robinson et al. 2005). While there is a growing volume of scholarship on the user-centered design process for interactive and web-based mapping (e.g. Gabbard, Hix, and Swan 1999; Haklay and Tobón 2003; Fuhrmann and Pike 2005; Nivala, Sarjakoski, and Sarjakoski 2007; Kramers 2008; Koh et al. 2011; Tsou 2011; Roth, Ross, and MacEachren 2015; Delikostidis, van Elzakker, and Kraak 2016), relatively little attention has been given to the design and evaluation of prototypes, and particularly wireframes, during this process (see Lloyd and Dykes 2011 for a notable exception).

Prototypes come in multiple forms, varying by the amount of time and resources required to generate them and the kind of input and feedback garnered by them during the user-centered design process (Roth and Harrower 2008). For instance, hand-drawn sketches can be generated quickly and are excellent for supporting brainstorming and for acquiring early, formative feedback (i.e. "how should this be designed?"). In contrast, rapidly developed *alpha* (partially functional) and *beta* (fully functional, unstable) prototypes require considerably more resources to develop, and although are essential checkpoints toward a final release, only may generate summative feedback from users (i.e. "did the design work?"). Wireframes differ from these kinds of prototypes in that they typically are produced in a digital environment (i.e. are one step beyond early, hand-drawn sketches), but have limited interactive functionality (compared to alpha and beta releases). Wireframes are useful for presenting the functional scope of the proposed application to target users, for structuring the procedure by which target users will work through the application, and for troubleshooting potential issues target users may have in interpreting the information and controls presented to them (Tullis 1998).

We demonstrate the relevance and value of wireframing for Cartography and GIScience through an in-

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depth case study on water level visualization. Specifically, we report on the user-centered design of the National Oceanic & Atmospheric Administration's (NOAA) *Lake Level Viewer* (http://coast.noaa.gov/llv/), an interactive and web-based geovisualization application for the Great Lakes region of North America supporting adaptive management of coastal hazards related to future water levels in response to climate change. We argue that cartographers are well-positioned to take on the role of *user experience* (UX) designers on such large-scale mapping and GIS projects. In addition to contributing to the *development* (coding) of these applications, cartographers should be enrolled in the user-centered *design* and *evaluation* of prototypes for streamlining the development workflow, ultimately promoting a positive user experience with the application. As part of our overall user-centered design process, we generated two sets of wireframes based on a fundamental distinction in user experience design (Roth 2013): (1) *high-fidelity* wireframes to illustrate the proposed *representation* solution using real data, and (2) *low-fidelity* wireframes to provide a rough sketch of the proposed *interaction* solution. Figure 1 presents a comparison of the final release of the Lake Level Viewer to a low-fidelity interaction wireframe.

This paper proceeds with four sections. In the following section, the case study is introduced, including background on adaptive management for the Great Lakes and prior user-centered design steps leading to the Lake Level Viewer wireframes. The third section details our method for evaluating the wireframe designs. Eighteen target users completed a *cognitive walkthrough* of the wireframes, discussing the hypothetical use of the Lake Level Viewer while leveraging the wireframes as visual prompts. The fourth section reports on the feedback from the cognitive walkthroughs, and discusses key revisions following the wireframe evaluation. The fifth and final section provides a summary of Lake Level Viewer revisions based on wireframe feedback, outlines a set of design challenges, and provides concluding remarks on the value of wireframing in Cartography and GIScience.

2. Background: the Lake Level Viewer case study

2.1 Water level visualization to support adaptive management on the Great Lakes

The Great Lakes are a chain of interconnected freshwater lakes (from west-to-east: Lakes Superior, Michigan, Huron, Erie, and Ontario) along the international border between Canada and the USA. The NOAA Lake Level Viewer covers all eight USA states bordering the Great Lakes; integration with Canadian coastlines is a longer-term goal. The Lake Level Viewer is a sibling application to the NOAA Sea Level Rise and Coastal Impacts Viewer, a geovisualization application supporting adaptive management in response to climate change along the Atlantic, Gulf, and Pacific coasts of the USA (http://coast.noaa.gov/slr/). *Adaptive management* describes the application of a structured, iterative process of decision making under high levels of information uncertainty, allowing for incremental action to be taken as new information is generated (Holling 1978; Lee 1982; Walters 1986). The sibling applications are designed to support adaptive management of hazards related to climate change such as coastal erosion, habitat destruction, storm flooding, and water quality degradation (Moy et al. 2011).

Effective adaptive management of coastal areas in response to climate change relies upon the availability and accessibility of *water level visualizations*, or interactive and web-based mapping applications depicting the exposure or inundation of land as a result of historic and current storm events or future climate change predictions (Kostelnick, McDermott, and Rowley 2009; Roth, Quinn, and Hart 2015; Neset et al. 2016). Kostelnick et al. (2013) organize design challenges for water level visualizations supporting adaptive management into three components: (1) hazard and risk characteristics, (2) user and task characteristics, and (3) cartographic considerations. First, the adaptive management context determines the predicted water levels for a specific geographic region, the uncertainties inherent to these predictions, and the consequences that water level changes may have on the built and natural environments, and the people and things within them (Retchless 2014). Next, communication with target users enables definition of user profiles and use case scenarios that outline expected user expertise and primary user tasks (Roth 2009). The combination of the hazard/risk and user/task context then leads to appropriate cartographic design, regarding both the representation solution and interaction solution (Monmonier 2008).

The Sea Level Rise and Coastal Impacts Viewer enables users to explore up to 6 feet (~1.8 meters). Water levels are provided in USA standard units of measurement given the specific USA user/task context; we also provide approximate metric conversions in the following discussion. A fundamental rethinking of the Sea Level Rise and Coastal Impacts Viewer concept was necessary for the Lake Level Viewer due to the unique hazard/risk context of the Great Lakes. Recent

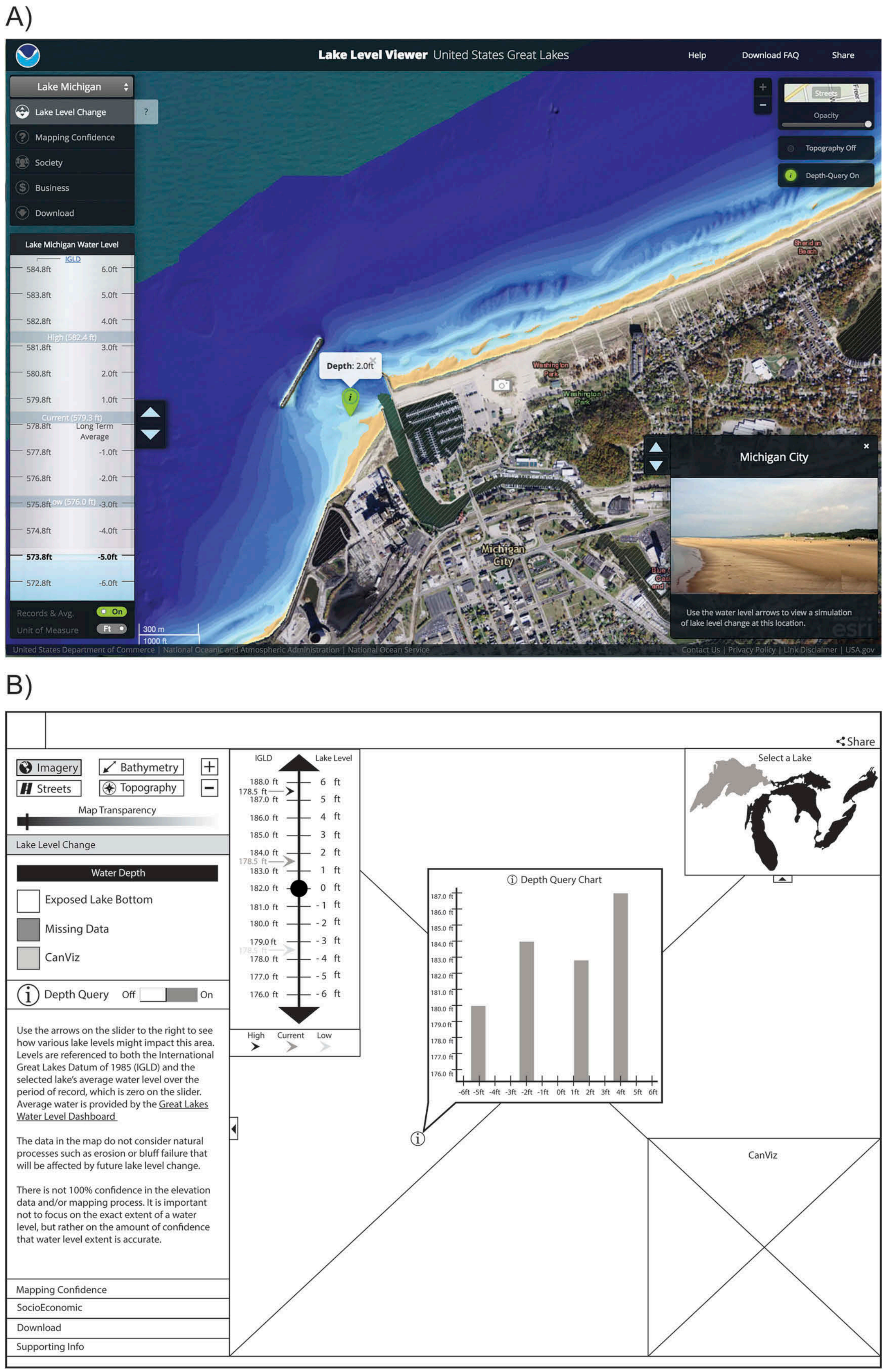

Figure 1. Wireframing the National Oceanic & Atmospheric Administration's (NOAA) Lake Level Viewer. The NOAA Lake Level Viewer is an interactive and web-based geovisualization application for the Great Lakes supporting adaptive management of coastal hazards related to future water levels in response to climate change. (a) The final release of the Lake Level Viewer, configured to show an expanded beachline near a marina in Michigan City, Indiana. (b) A low-fidelity interaction wireframe created during user-centered design of the Lake Level Viewer. The Lake Level Viewer is available for public use at: http://webqa.csc.noaa.gov/llv.

modeling of climate-related changes to the Great Lakes suggests a possible decrease in lake levels, accompanying an increase in the annual variation of water levels (Angel and Kunkel 2010; Hayhoe et al. 2010). Prevailing opinion in the scientific community is that warmer temperatures and decreased ice cover will drive a trend toward lower water levels, although the overall effect of climate change on lake levels remains unclear (Croley 2008; Lofgren and Hunter 2010; DiMarchi and Dai 2011). The water levels across the Great Lakes already set or approached record lows in 2012–2013. Such significant and unprecedented lower lake levels require new forms of water level visualizations, making the Lake Level Viewer a useful case study for exploring the role of wireframing for user-centered prototyping in Cartography and GIScience.

2.2 Target users and functional requirements for the Lake Level Viewer

The wireframe evaluation that we report in this paper was part of a larger user-centered design process for the Lake Level Viewer, completed in partnership by the NOAA Coastal Services Center, the University of Wisconsin Cartography Laboratory, and the University of Wisconsin Sea Grant Institute. User-centered design is a multi-stage, highly iterative process, which typically includes an initial needs assessment study, development of functional requirements and prototyping of the visual layout and design, and implementation and evaluation pairings leading to final debugging and release (e.g. Slocum et al. 2003; Robinson et al. 2005). Prior stages of the Lake Level Viewer user-centered design process included a pair of needs assessment focus groups with target users and a competitive analysis of 25 existing water level visualization tools found online (see Roth, Quinn, and Hart 2015).

Feedback from the focus groups allowed us to formalize target user profiles and use case scenarios for the Lake Level Viewer concept, defining the user and task characteristics emphasized by Kostelnick et al. (2013). The target user group for the Lake Level Viewer was diverse, and included managers and decision makers along the Great Lakes working in all levels of government, academic researchers studying regional climate change on the Great Lakes, and industries whose essential infrastructure and operations may be impacted by changing water levels on the Great Lakes. From this diverse target user group, we identified nine user profiles and associated use case scenarios guiding the design and evaluation of the Lake Level Viewer wireframes (Table 1).

Next, insights from the focus groups and competitive analysis allowed us to establish a set of functional requirements to support the user experience with the Lake Level Viewer, organized by *representation requirements* (i.e. data and services needed to render the visualization onscreen) and *interaction requirements* (i.e. the interface controls for manipulating the resulting visualization) (Roth 2013). Table 2 provides a summary of these functional requirements. First, the Lake Level Viewer required a high-quality digital elevation model (DEM) with detail on both sides of the coastline

Table 1. Target user profiles and use case scenarios for the Lake Level Viewer.

#	Target user profile	Hypothetical organization	Hypothetical sector	Hypothetical use case scenario
1	Community Planner	City Public Works Department	Government, Municipal	I need the Lake Level Viewer to track changes in lake levels, illustrate impacts of these changes to our city's infrastructure, and encourage coastal sustainability
2	Grant Officer	County Planning Commission	Government, County	I need the Lake Level Viewer to help me review grant applications and supervise funded programs designed to promote resilient and sustainable use of our coasts
3	Program Manager	State Coastal Mgmt. Program	Government, State	I need the Lake Level Viewer to select land conservation and restoration locations that could increase in size or richness of habitat
3	Nat. Resource Manager	State Department of Natural Resources	Government, State	I need the Lake Level Viewer to identify locations that may become susceptible to invasive species as water levels change
4	Engineer	US Army Corps of Engineers	Government, Federal	I need the Lake Level Viewer to study and model hydrological processes and hazards across the Great Lakes
5	Director	International Joint Commission	Government, International	I need the Lake Level Viewer to inform our adaptive management strategy for regulating coastal activities across the Great Lakes
6	Outreach Specialist	Sea Grant Institute	University	I need the Lake Level Viewer to disseminate the state of climate change science on the Great Lakes to the community through public workshops
7	Researcher	Research University	University	I need the Lake Level Viewer to collect geospatial data on water levels under different climate change scenarios to inform my research on resiliency and sustainability
8	Engineer	Power Company	Industry	I need the Lake Level Viewer to develop low water scenarios for determining impacts to underwater infrastructure (e.g. water intake pipes) used in our business operations
9	Owner	Marina	Industry	I need the Lake Level Viewer to understand impacts of changing water levels on dredging and infrastructure at and around my marina

These user profiles and use case scenarios were developed through early stages in the user-centered design process and were used to inform design and evaluation of the Lake Level Viewer wireframes (see Roth, Ross, and MacEachren 2015 for additional details).

Table 2. The functional requirements of the Lake Level Viewer.

#	Requirement	Description
1	DEM	Derived from Army Corps topobathy lidar
2	Water depth	Depicted with a blue color ramp; registered to the International Great Lakes Datum (1985)
3	Exposed lake bottom	Depicted with a brown color ramp; registered to the International Great Lakes Datum (1985)
4	Confidence	Depicted with orange; registered to the International Great Lakes Datum (1985)
5	No data	Depicted with a hatched texture
6	Basemaps	Four multiscale basemap tilesets: Imagery, Streets, Bathymetry, and Topography
7	Context layers	Population Density (Census Bureau) and Business Density (Bureau of Labor)
8	Legend	Visual examples of water depth, exposed lake bottom, confidence, no data, and context layers
9	Supporting information	Documentation on the project assumptions, data lineage, and visualization techniques
1	Lake level slider	Change water level, with a range of +/− 6 ft
2	Lake level benchmarks	Change the water level to past benchmarks, including Historic High, Low, and Average
3	Lake selection	Switch lake views using an inset map
4	Accordion panel	Organize functionality, legends, and supporting information by overlay
5	Depth query tool	Activate a histogram of water level scenarios for that location
6	CanVis Overlay	Overlay photo simulations of exposure or inundation at specific sites (created using NOAA CanVis software)
7	Map transparency tool	Adjust transparency of the water depth, exposed lake bottom, and confidence
8	Basemap toggle	Switch basemaps
9	Map browsing	Pan and zoom through direct manipulation of the map and buttons
10	Share	Create a RESTful hyperlink to share the current configuration
11	Download	Download the DEM dataset
12	Minimize	Collapse the interface panels to dedicate more screen real estate to the map

Earlier stages in the user-centered design process were used to establish a core set of functional requirements for the Lake Level Viewer, which then informed design and evaluation of the wireframes (see Roth, Ross, and MacEachren 2015 for additional details).

to account for possible increases or decreases in lake levels, a requirement not needed for the flood-centric Sea Level Rise and Coastal Impacts Viewer. We built a seamless DEM from the US Army Corps of Engineers topobathy LIDAR dataset, although issues with water turbidity limited the completeness of the surface-penetrating topobathy LIDAR dataset across the five lakes, particularly for high traffic areas such as marinas and ports. We therefore designed the visualization architecture as a series of preprocessed web map services, enabling straightforward update as improvements are made to the topobathy dataset.

We then conceived the map visualization as a series of user-selected overlays atop a slippy (i.e. browsable) raster tileset (Muehlenhaus 2013). Interestingly, none of the 25 water level visualizations surveyed in the competitive analysis supported both a positive and negative change in water levels, and therefore represented the "flood extent" rather than the "water level" (Roth, Quinn, and Hart 2015). Accordingly, we proposed a novel representation solution not used by any of the surveyed visualizations for the default map overlay that uses a diverging color scheme, with blue representing "water depth" and brown representing "exposed lake bottom". Based on feedback from the focus groups, we planned on a water level range of 6 feet (~1.8 meters) above and below the International Great Lakes Datum (IGLD) baseline. Following the Sea Level Rise and Coastal Impacts Viewer, we included an optional uncertainty overlay using a simple, intrinsic representation solution (i.e. based on the visual variables), indicating areas with an 80% confidence of being inundated in blue and areas beneath this threshold, but above 50% confidence, in orange (Kinkeldey, MacEachren, and Schiewe 2014). We also included a second, extrinsic uncertainty representation to depict LIDAR completeness, using an overlaid texture fill to represent incomplete data coverage (i.e. "no data"). Following conventions of the other reviewed water level visualizations, we included four basemap tileset options ("imagery," "streets," "topography," and an additional "bathymetry" for decreased water levels), two context overlays ("population density" and "business density," based on readily available information sets), map legends, and supporting information about background assumptions, data lineage, and our visualization techniques.

The primary interface control for the Lake Level Viewer was a persistent "lake level slider," allowing the user to change the depicted water level on the map as well as select key benchmarks, such as the historic "high," "low," and "long-term average" (Harrower 2002). Each of the Great Lakes has its own baseline water level. To account for this variation, we proposed inclusion of a "lake selection" inset map, with selection of a new lake updating both map centering and the baseline value used in the lake level slider. In order to organize interface functionality and supporting information by map overlay, we planned on using an accordion interface panel with five expandable options: "lake level change," "mapping confidence," "socioeconomic," "download," and "supporting info." Additional interaction functionality specific to the "lake level change" option included a "depth query" tool presenting a bar chart of water depths for a selected location and a "CanVis" feature presenting a photo simulation of exposure or inundation at specific locations, created using NOAA CanVis software (http://coast.noaa.gov/digitalcoast/tools/canvis).

Interface controls for manipulating the basemap remained persistent at the top of this accordion panel, which included the ability to toggle the different basemap options, tools for zooming, and a "map transparency" tool for adjusting the opacity of the overlay layers. Additional interaction requirements included the ability to "share" the current map configuration using a RESTful hyperlink and the ability to minimize the accordion panel and lake selection inset to dedicate a larger portion of the screen real-estate to the map.

3. Methods

The Lake Level Viewer wireframes were evaluated using the *cognitive walkthrough* method. In this type of evaluation, target users "walk through" a prototype—in this case the wireframe designs—from the perspective of their user profiles to achieve the cognitive goals associated with their use case scenarios (Allendoerfer et al. 2005; Blackmon et al. 2002). Cognitive walkthroughs provide a useful proxy for first-time use of a proposed application, giving designers insight into the likely entry point of the application (i.e. the first click), the subsequent sequence in which interface controls are used, bottlenecks or breakdowns in this interaction workflow, potentially confusing or misleading controls, and significant gaps in functionality (Polson et al. 1992; Riemen, Franzke, and Redmiles 1995). Unlike many other evaluation methods, the cognitive walkthrough is suitable for evaluating rough wireframes outlining proposed functionality, assuming sufficient explanation of the wireframes is provided for the participant to envision how the application will work—even if this vision is incorrect, which may reveal design issues—and can respond to prompts accordingly.

3.1 Participants

Eighteen target users participated in the cognitive walkthrough of the Lake Level Viewer wireframes. Participants were purposefully recruited to represent the target user profiles and use case scenarios described in Table 1 and were selected from different geographic locations across the Great Lakes region. All 18 participants had earned a Bachelor's degree or higher, with 10 holding a Master's degree. Participants held degrees in a wide range of disciplines—a reflection of the diverse user profiles and use case scenarios—including Atmospheric Science, Aquaculture, Civil and/or Environmental Engineering, Economics, Environmental Studies, Forestry, Geography, Geology, Historic Preservation, Journalism & Mass Communication, Marine Science, and Water Resource Management. The average amount of work experience within the domain was approximately 11 years, with a range of 1–33 years.

3.2 Materials

Design of the Lake Level Viewer wireframes was informed by the user profiles, use case scenarios, and functional requirements formalized in prior stages of the user-centered design process. In practice, two forms of wireframes exist: low-fidelity and high-fidelity. *Fidelity* refers to the degree to which a prototype, wireframe or otherwise, accurately represents the functional scope and visual design of the proposed application (Tullis 1990). Rudd, Stern, and Isensee (1996) provide a summary of the various considerations for using low-fidelity versus high-fidelity prototypes in user-centered design. Low-fidelity prototypes have the advantage of a lower development cost, allowing them to be used earlier in the user-centered design process. Cost considerations also allow for creation of multiple prototypes, enabling evaluation of responsive design across display devices. However, low-fidelity prototypes cannot be evaluated in a controlled study using benchmark tasks, as they do not include actual text and multimedia. This latter issue is particularly a concern when wireframing interactive and web-based map applications, as the inclusion of real data and map representations is essential for understanding how the proposed design matches the needs of target users (Lloyd and Dykes 2011). Roth and Harrower (2008) describe placeholder representations included in low-fidelity wireframes as *lorem ipsum maps*, and warn about the negative implications this design practice can have on the look and feel as well as the usability of the mapping application. In contrast, high-fidelity prototypes make use of real data and representations—allowing for simulated use of the prototype in controlled evaluations—but are expensive to develop and time consuming to create. A high-fidelity prototype often is referred to as a *mockup*.

We designed two sets of wireframes to separately address the representation and interaction components of the user experience (Table 2). For the representation requirements, we designed a set of non-interactive high-fidelity wireframes (Figure 2) that used a small strip of the processed topobathy DEM and showed the proposed representation solution for seven different visual states of the Lake Level Viewer. We then designed a set of six low-fidelity wireframes showing the Lake Level Viewer interaction requirements based on the proposed organization of the accordion panel (Figure 3). The low-fidelity interaction wireframes did not include an example map representation, but did include placeholder informational text. Inclusion of both high- and low-fidelity wireframes in the subsequent evaluation allowed target users to gain an understanding of the types of datasets and map representations that would be included in the Lake Level Viewer through the high-fidelity representation wireframes, but did not require our team to have operational web map services for the entire Great Lakes coast at the time of wireframe evaluation, nor require us to have complete, high-fidelity wireframes for the interface controls.

3.3 Procedure

The wireframe evaluation procedure was divided into four stages. In the initial stage, we collected background information and discussed the participant's professional interests and responsibilities in order to contextualize the subsequent cognitive walkthroughs with his or her real world cognitive goals and work tasks. The middle stages comprised the cognitive walkthroughs, first with the high-fidelity representation wireframes and then with the low-fidelity interaction wireframes. Before the cognitive walkthrough stages, we played a two-minute video demonstration of the sibling Sea Level Rise and Coastal Impacts Viewer to help the participant envision how the subsequent Lake Level Viewer wireframes could work. We concluded the wireframe evaluation with a debriefing discussion.

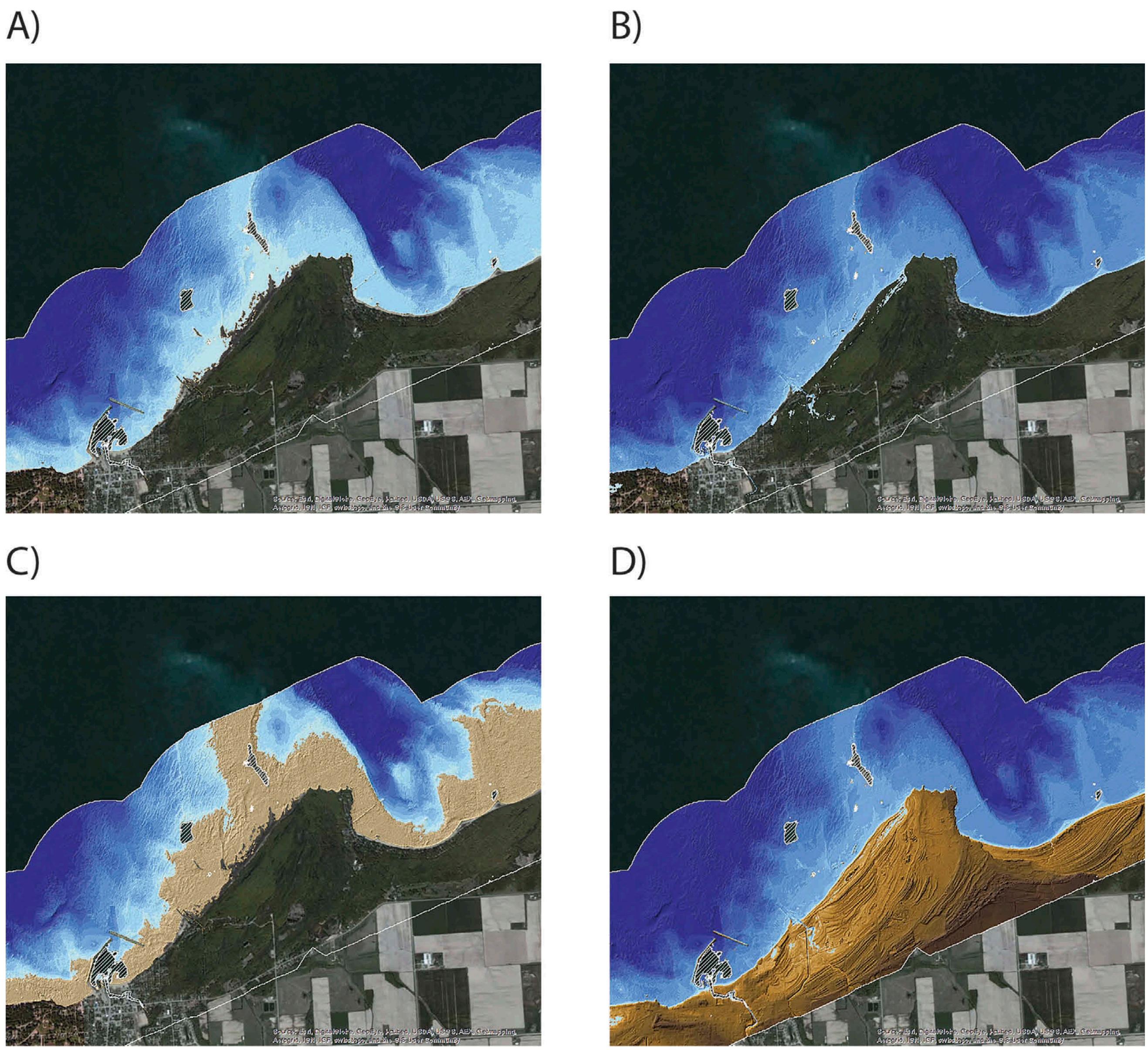

Figure 2. High-fidelity representation wireframes for the Lake Level Viewer. We created seven high-fidelity wireframes using a small strip of processed DEM data to illustrate several visual states of the proposed Lake Level Viewer. (a) water depth at baseline atop satellite basemap, (b) water depth at +6 ft/+1.8 m atop satellite basemap, (c) water depth + exposed lake bottom at −6 ft/−1.8 m satellite basemap, (d) water depth at baseline atop topography basemap, (e) confidence at baseline atop satellite basemap, (f) confidence at +6 ft/+1.8 m atop satellite basemap, and (g) confidence + exposed lake bottom at −6 ft/−1.8 m atop satellite basemap. (Continued on following page).

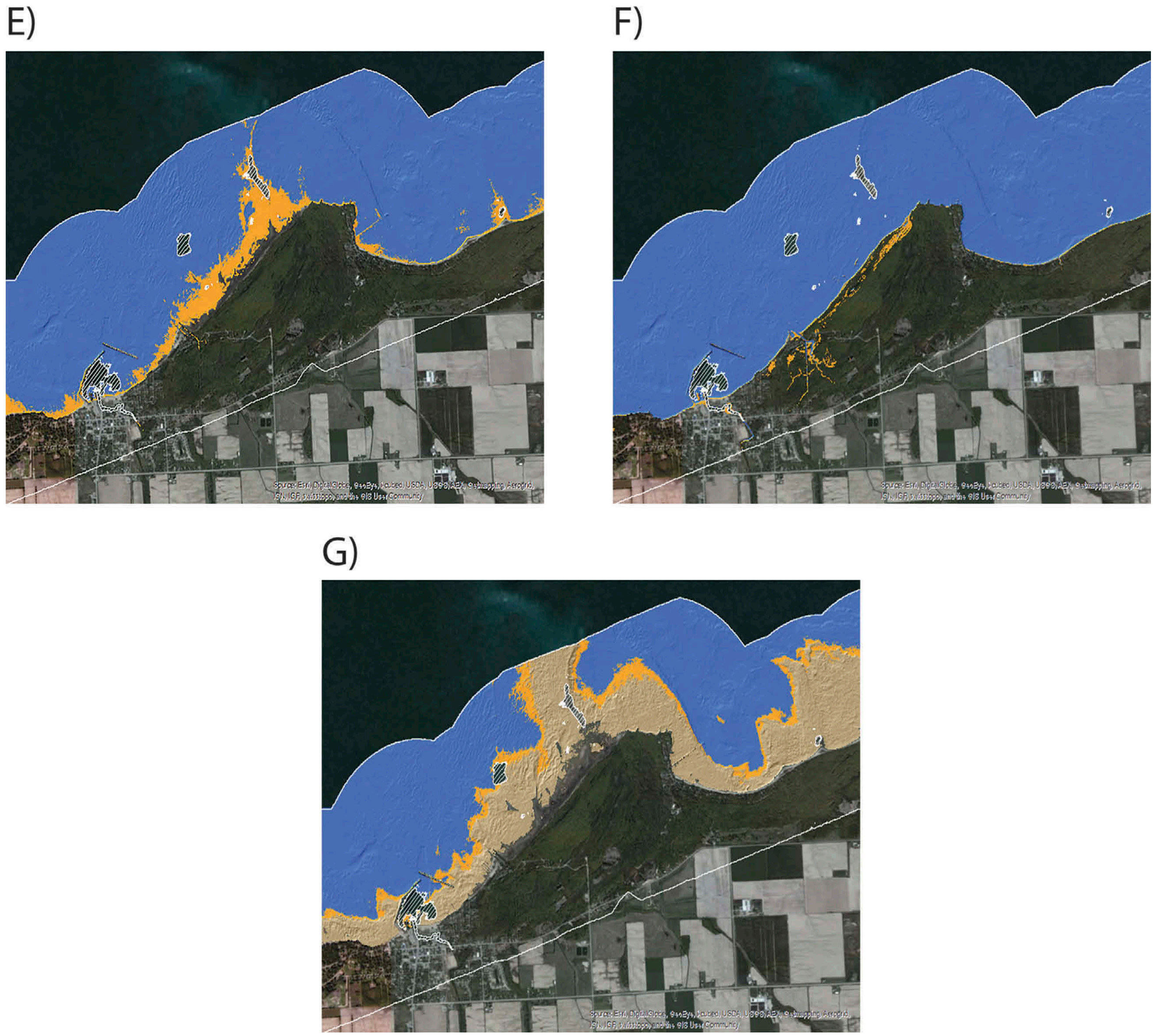

Figure 2. (Continued).

A procedural modification of the cognitive walkthrough method was required for the middle stages of the wireframe evaluation, as the use of interactive and web-based mapping applications for critical thinking and decision making often is unstructured, exploratory, and open-ended (MacEachren 1994). Rather than imposing a set of simplified benchmark tasks, we first allowed each participant to openly explore individual wireframes and then discuss how the functionality could support his or her cognitive goals and work tasks. Following this open-ended discussion, we then asked follow-up probes in order to interrogate specific functionality outlined in the wireframe and to drill deeper into the potential for the Lake Level Viewer to support the participant's goals and tasks. This modification was required since the low-fidelity wireframes provide insufficient detail to complete benchmark tasks (a limitation of low-fidelity wireframes introduced above).

We conducted the walkthroughs in person, at the participant's work location, using full color prints of the high-fidelity representation wireframes and black-and-white prints of the low-fidelity interaction wireframes. We designed the wireframe evaluation to last no longer than 60 minutes, completing the 18 evaluations in February and March of 2014. Finally, we

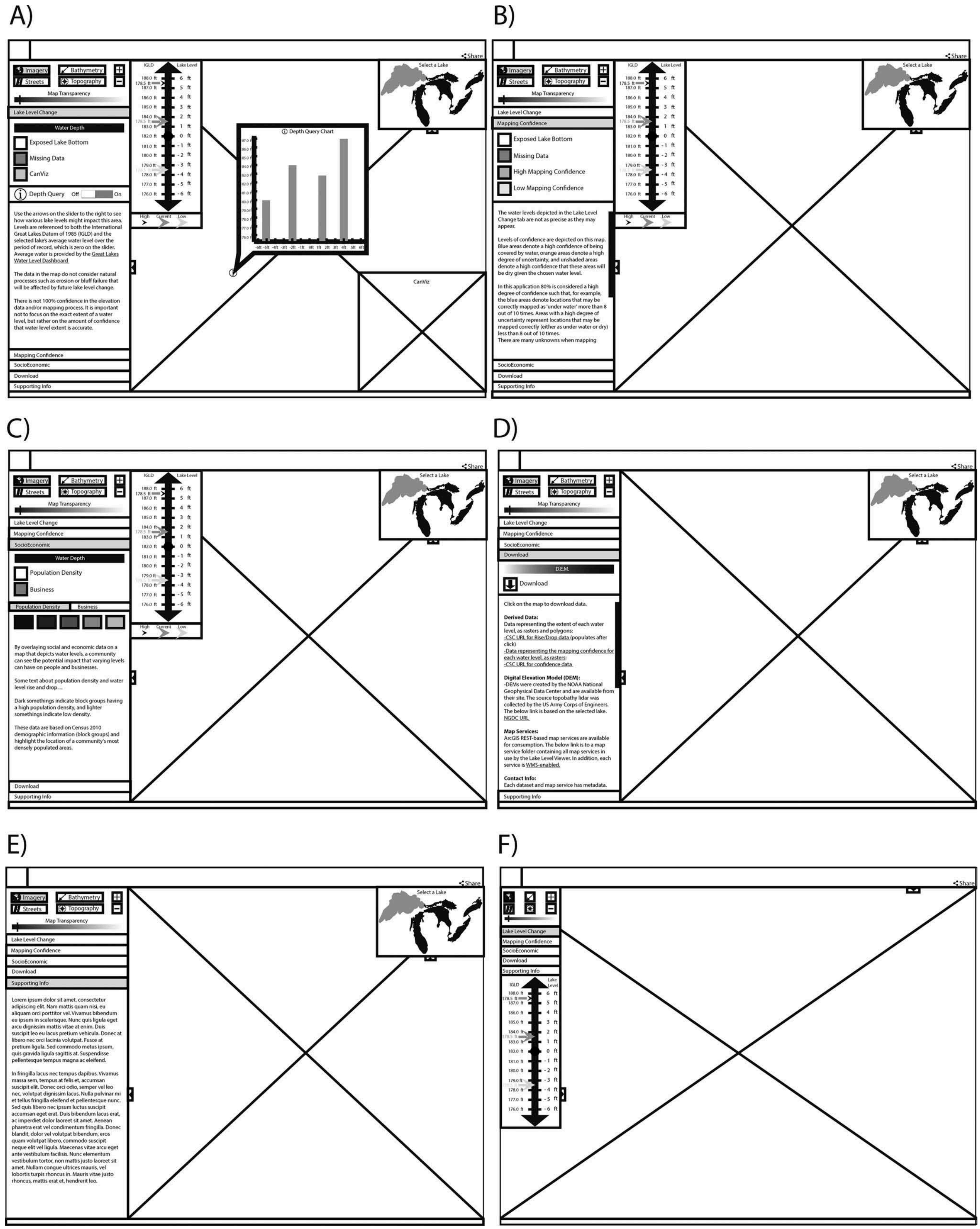

Figure 3. Low-fidelity interaction wireframes for the Lake Level Viewer. We created six low-fidelity wireframes based on the five menu options in the proposed accordion interface panel and a sixth to show the minimized view. (a) lake level change menu activated, (b) mapping confidence menu activated, (c) socioeconomic menu activated, (d) download menu activated, (e) supporting info menu activated, and (f) minimized view.

Table 3. Coding results of the wireframe evaluation of the Lake Level Viewer.

		Positive		Negative		Difference		Overall	
ID	Code	Total	Avg	Total	Avg	Total	Avg	Total	Avg
Representation									
Water levels		*91*	*5.06*	*86*	*4.78*	*5*	*0.28*	*177*	*9.83*
W1	Water depth symbolization	22	1.22	2	0.11	20	1.11	24	1.33
W2	Exposed lake bottom symbolization	23	1.28	11	0.61	12	0.67	34	1.89
W3	Shoreline symbolization	11	0.61	13	0.72	−2	−0.11	24	1.33
W4	Datum choice	17	0.94	36	2.00	−19	−1.06	53	2.94
W5	Legend design	3	0.17	1	0.06	2	0.11	4	0.22
W6	Lake level range	15	0.83	23	1.28	−8	−0.44	38	2.11
Uncertainty		*29*	*1.61*	*91*	*5.06*	*−62*	*−3.44*	*120*	*6.67*
C1	Confidence symbolization	2	0.11	34	1.89	−32	−1.78	36	2.00
C2	No data symbolization	1	0.06	34	1.89	−33	−1.83	35	1.94
C3	Uncertainty comprehension	26	1.44	23	1.28	3	0.17	49	2.72
Basemaps/Overlays		*76*	*4.22*	*81*	*4.50*	*−5*	*−0.28*	*157*	*8.72*
B1	Imagery tileset	19	1.06	0	0.00	19	1.06	19	1.06
B2	Topography tileset	28	1.56	13	0.72	15	0.83	41	2.28
B3	Context layers	20	1.11	54	3.00	−34	−1.89	74	4.11
B4	Supporting information	9	0.50	14	0.78	−5	−0.28	23	1.28
Interaction									
Interface functionality (Utility)		*227*	*12.61*	*126*	*7.00*	*101*	*5.61*	*353*	*19.61*
I1	Lake selection	33	1.83	4	0.22	29	1.61	37	2.06
I2	Lake level slider	30	1.67	11	0.61	19	1.06	41	2.28
I3	Lake level benchmarks	15	0.83	27	1.50	−12	−0.67	42	2.33
I4	Depth query tool	30	1.67	28	1.56	2	0.11	58	3.22
I5	CanVis overlay	50	2.78	14	0.78	36	2.00	64	3.56
I6	Map transparency tool	7	0.39	13	0.72	−6	−0.33	20	1.11
I7	Basemap toggle	16	0.89	7	0.39	9	0.50	23	1.28
I8	Map browsing	21	1.17	5	0.28	16	0.89	26	1.44
I9	Share	12	0.67	7	0.39	5	0.28	19	1.06
I10	Download	13	0.72	10	0.56	3	0.17	23	1.28
Interface design (Usability)		*72*	*4*	*32*	*1.78*	*40*	*2.22*	*104*	*5.78*
U1	Layout design	17	0.94	11	0.61	6	0.33	28	1.56
U2	Minimized layout design	11	0.61	1	0.06	10	0.56	12	0.67
U3	Interface aesthetics	1	0.06	4	0.22	−3	−0.17	5	0.28
U4	Learnability	2	0.11	7	0.39	−5	−0.28	9	0.50
U5	Subjective satisfaction	41	2.28	8	0.44	33	1.83	49	2.72

A 28 part coding scheme was applied to analyze and interpret the transcripts, following tenets of qualitative data analysis (QDA). This table summarizes the total and average (out of 18 participants) frequencies of both positive and negative statements regarding the given code, as well as the difference between positive and negative frequencies and the overall frequency of each code.

audio-recorded the wireframe evaluations for subsequent transcription and analysis.

3.4 Analysis

Our analysis of the wireframe evaluation followed tenets of *qualitative data analysis*, or the systematic interpretation of non-numerical information such as text, images, and maps (Dey 1993; Miles and Huberman 1994). The audio recordings were transcribed by our university transcription service and segmented at the statement level for subsequent coding (Bertrand, Brown, and Ward 1992). We developed a coding scheme based on the functional requirements outline in Table 2, as well as several of our general questions or concerns about the UX design that were unresolved in earlier stages of the user-centered design process. A total of 28 codes were identified, organized by five broader themes: (1) statements about the representation of inundated versus exposed areas, (2) statements about the representation of uncertainty, (3) statements about the basemap or context overlay representations, (4) statements about the interface utility (i.e. usefulness of proposed interactive functionality), and (5) statements about the interface usability (i.e. issues with the overall interaction design). For reliability, two coders applied the 28 part coding scheme to the 18 transcripts, with discrepancies resolved by a third member of the project team (Robinson 2008). Table 3 lists the 28 codes and summarizes the frequencies of participant statements by code.

A total of 910 codes were applied across the 18 transcripts, an average of 50.6 codes per transcript. Participant reaction was slightly more positive than negative, with 495 positively coded statements (average of 27.5; 54.4% of total) and 415 negatively coded statements (average = 23.1; 45.6% of total). Participants discussed the representation and interaction functionality almost evenly, with 454 statements about the representation wireframes (average = 25.2) and 456 statements about the interaction wireframes (average = 25.3). Discussion of the high-fidelity representation wireframes was overall negative, while discussion of the low-fidelity interaction wireframes was overall positive.

4. Results and discussion

4.1 Representing water levels

The first three categories of codes primarily related to the high-fidelity representation requirements (Figure 2), this discussion did spark redesigns to the interface controls in several important ways. The first category of codes indicated statements about our solution for depicting the changing water levels (Table 3). The overall valence of this discussion was nearly neutral. The greatest amount of discussion about the water level representation was generated about the appropriate datum choice (W4), followed by the included lake level range (W6) and exposed lake bottom symbolization (W2). Participants discussed the water depth symbolization (W1) and shoreline symbolization (W3) evenly. Minimal feedback was offered on the legend design (W5).

Reaction to the water depth symbolization (W1) and exposed lake bottom symbolization (W2) overall was positive. All participants correctly interpreted the meaning of the blue color ramp during the cognitive walkthrough without a legend, while exactly half of the participants correctly interpreted the meaning of the brown color ramp without a legend. Upon walkthrough of representation wireframes #1–3, one participant stated "It looks very straightforward actually … It's easy to pick up on," and a second stating that "The [color] ramp is appropriate, I think." The most common misinterpretation of the brown color ramp was shallow water, such as an "inundated sandbar" or a "mudflat." Nearly all participants (17/18) agreed that the representation would be improved by depicting a shoreline benchmark (W3) to aid interpretation of exposed versus inundated areas, as well as to aid comparison across all water level scenarios. One participant stated "If you wanted to really make it clear, you may be able to outline [the shoreline] with some sort of line symbol," while a second stated "Personally, I think illustrating the original shoreline would be useful because you can always use that as a perimeter of what people are familiar with presently."

The one participant stating that the base shoreline should not be included in the visualization was concerned about the dynamic nature of the shore, stating "If you put in a vector shoreline, it's got to be based on one snapshot at a time, and that shoreline, any shoreline, it's going to change … because every body of water is going to change." This concern directly relates to our choice of IGLD as the datum line (W4), a topic that elicited the most negative discussion regarding water level representation. Participants discussed the tendency to think of the baseline as the "current level" or how the lakes "look now," rather than the 25–30 year long-term average on which the IGLD is based. One participant stated "The zero being current … I would think of that as the most recent gauge water level," while a second stated "Is that supposed to be right now, present day based on some kind of data that's taken frequently?" Only half of the participants knew what the IGLD acronym meant, with participants agreeing that it would be clearer to describe the baseline as the "long term average" in the lake level slider rather than, or in addition to, the IGLD acronym.

This discussion about the datum choice (W4) also highlighted the potential utility of converting the baseline datum for different regulatory and management use case scenarios; recommended alternatives included: the "current" or "real-time" shoreline ($n = 7$), the ordinary high water mark ($n = 6$), the ordinary low water mark ($n = 3$), the North American Vertical Datum (NAVD88; $n = 3$), seasonal averages ($n = 2$), the 100-year floodplain ($n = 2$), future projections based on climate change scenarios ($n = 1$), the IGLD55 precursor ($n = 1$), and the vegetation line ($n = 1$). One participant noted that industrial firms along the lake were likely to make use of a "local datum" based on their own surveys, which are unlikely to align with authoritative, government datum definitions. Flexible conversion of the baseline datum was outside of the project scope for the initial Lake Level Viewer release given the technical solution of preprocessing each increment as a different overlay layer. However, we did modify the design of the lake level slider to indicate both water level change relative to the long-term average (i.e. the IGLD baseline) as well as elevation above sea level (supporting simpler conversion to alternatives), and included supporting information about the IGLD (Figure 4). Two participants also noted the importance of converting between USA standard and metric units of measurement for international and research use, an interface control we added subsequently to the Lake Level Viewer functional requirements.

Opinion about our suggested water level range (W6) was divided evenly between participants suggesting that the range should be constrained by actual historic observations and those wanting as wide a range as possible. Representing the former perspective, one participant stated "I mean what's the likelihood of a minus six and how does that happen? Has it ever happened?" While envisioning how a citizen may react to a wider range, a second participant stated "[he or she] would think, oh my God, we're going to see a rise of 20 feet!" This first group of participants therefore was concerned with public reaction to the Lake Level Viewer,

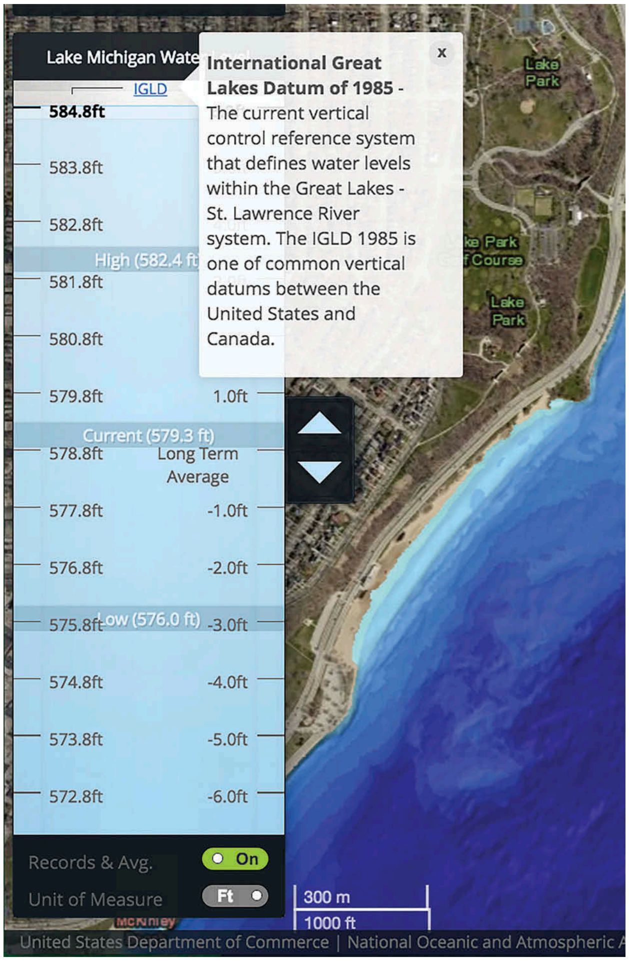

Figure 4. The redesigned lake level slider. Based on feedback on the wireframes, we redesigned the lake level slider to include indications of both elevation above sea level and departure from the "long term average." We also provided supporting information about the meaning of the IGLD as an information window and an interface control to change between standard and metric units of measurement. Finally, to avoid confusion with a zoom slider and to evoke a metaphor of exposure and inundation, we refined the visual design of the lake level slider to appear as a vessel that can be filled or drained.

recommending the depicted range be reduced in half. Representing the latter perspective, one participant stated that when "forecasting or simulating longer-term scenarios, I would say a doubling of the natural range might be a good start," and a second stating that if "the ultimate objective is to visualize the changing sea level or water levels down the road, I wonder if [the current range] is going to be enough." This second group of participants saw the ±6 ft (+/−1.8 m) range as appropriate, with three participants recommending up to +/−10 ft (+/−3 m) to explore longer-term climate change scenarios (e.g. Kopp et al. 2014) .

Discussion around the appropriate water level range also revealed the importance of considering the specific adaptive management context for each of the five Great Lakes. The constraint of +/−6 ft (+/−1.8 m) was seen as most problematic for Lake Erie, where storm-related seiches can cause fluctuations in water levels up to +/−8 ft (+/−2.4 m) from the long-term average. The constraint was seen as least problematic on Lake Superior, which does not see fluctuation beyond +/−3 ft (+/−0.9 m) from the long-term average. However, because Lake Superior is used to moderate the water levels of the lower lakes, having a broader range on Lake Superior allows for exploration of different adaptive management solutions across the five lakes. Ultimately, we decided to maintain the +/−6 ft (+/−1.8 m) range across lakes given our target user profiles comprising educated and experienced professionals (Table 1), but not to extend beyond this range to allay concerns about public misinterpretation. We also decided to maintain the same range across lakes – despite different adaptive management contexts – to improve navigation between lakes in the Lake Level Viewer (see additional details below).

4.2 Representing uncertainty

The second category of codes indicated statements about representing uncertainty in the Lake Level Viewer (Table 3). Overall, discussion regarding uncertainty symbolization and comprehension explained the largely negative opinion toward the representation wireframes, as the proposed uncertainty solutions garnered 91 negative statements but only 29 positive statements. Issues related to uncertainty comprehension (C3) yielded the most discussion, followed by the confidence symbolization (C1) and the no data symbolization (C2).

Participants were not as successful walking through Figure 2e–g depicting confidence (C1) as they were with Figure 2a–c showing the water depth and exposed lake bottom. A major point of confusion was with the orange and blue confidence symbolization. Many participants misinterpreted "confidence" as "risk," and thus interpreted the orange color to have the highest risk of flooding, even though the blue color denoted the areas most likely to become inundated. As one participant explained, "I see warm colors as being, you know, high risk … to me, it's like flip-flopped. You're having low confidence but it's in orange, which is kind of, I wouldn't see it that way." Two participants were wise to note that there are risks with both exposure and inundation, and that the use of orange as a warning of low confidence in the delineation between land and water is appropriate.

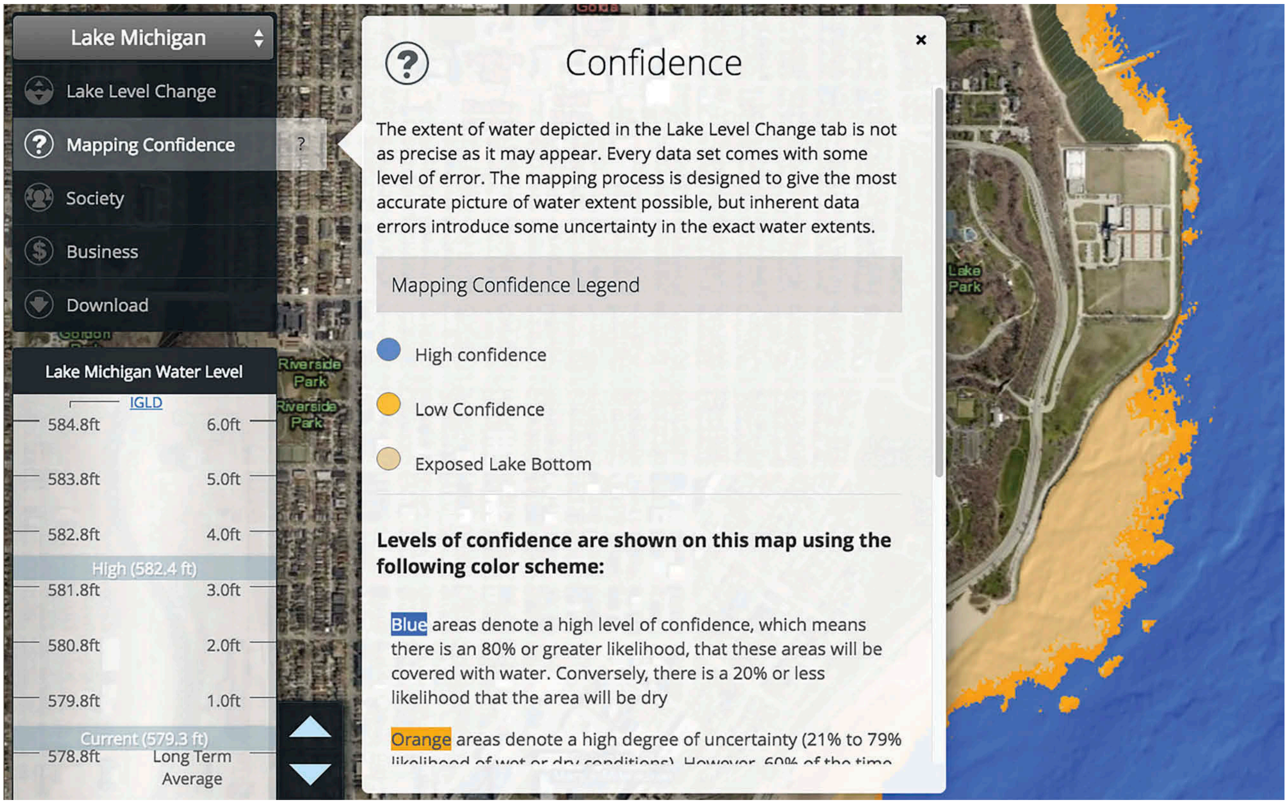

Figure 5. The redesigned lake selection and overlay menu of the Lake Level Viewer. The original lake selection inset map and accordion panel design in the interaction wireframes was replaced with a set of persistent menu options. Further, each overlay option has a "help" button providing comprehensive textual and visual supporting information about the given overlay, rather than providing this information as a single menu item. The figure shows the redesign of the mapping confidence overlay based on recommendations from the wireframe evaluation.

Both of these participants went on to note that the confusion between confidence and risk can be alleviated through proper messaging in the legend and supporting information. As one participant stated, "Going back to the risk versus confidence thing, I think it would be very important to clearly delineate what these colors generally mean, and then have an option, again, to click on to see, okay what does this really get at?" Fourteen of the participants indicated that the confidence legend needed to be accompanied with clear, well-written supporting information (B4) explaining the meaning of confidence. Further, 13 participants stated that the confidence explanation explicitly should use the term "likelihood" and included information about the 80% and 50% likelihood thresholds to communicate what actually is meant by confidence to improve comprehension. As a result of this feedback, we redesigned the accordion panel to consist of a series of menu items, removing the supporting info panel as a menu option. Instead, each of the overlay options includes an associated "help" button that, when clicked, activates an information panel providing comprehensive textual and visual supporting information based on the above recommendations (Figure 5).

Interpretation of the no data texture fill (C2) was problematic across all seven representation wireframes, garnering 34 negative statements but only 1 positive statement. None of the participants correctly interpreted the meaning of the texture fill without use of a legend, with the no data symbolization most commonly confused as offshore islands. One participant offered insight as to why the texture appeared to represent islands, indicating that the white hatching "contrasts with the orthoimage," causing the texture fill to stand out against the dark water surface in the imagery tileset. Because of this contrast, areas with no data rose to the figure in the visual hierarchy, and thus led participants to interpret these areas as important features in the map (i.e. high on the intellectual hierarchy) rather than gaps in the dataset. As a result, we made the no data symbolization partially transparent in the final release of the Lake Level Viewer, suppressing these areas to ground in the visual hierarchy so that they can be read more easily as data gaps.

4.3 Basemap/overlay representations

The third category of codes addressed the various basemap tilesets and context layers viewed in concert with the water level and confidence visualizations (Table 3). Interestingly, context layers (B3) were the most frequently discussed topic across the transcripts. Discussion of context layers was followed by feedback on the topography tileset (B2), supporting information (B4), and the imagery tileset (B1).

Participant reaction to the imagery (B1) and topography (B2) tilesets was largely positive. When probed, nine participants preferred the imagery tileset, while nine participants preferred the topography tileset (shown in representation wireframe #4). Participant discussion indicated different use case scenarios for the imagery versus topography tilesets: Those preferring the imagery tileset needed to interpret land use in the context of the exposed or inundated land, while those preferring the topography tileset primarily needed to interpret landforms when viewing exposed or flooded land. When prompted about all four proposed tilesets, all participants agreed that the imagery tileset was the best default for initial exploration of the Lake Level Viewer. Notably, six participants were confused about the meaning of the white line showing the extent of the LIDAR data when using the imagery tileset. The most common misinterpretations were administrative boundaries or roads. As a result, this boundary line was replaced by an opacity mask over areas not included in the LIDAR swath, a third form of uncertainty representation included in the final Lake Level Viewer.

The discussion about context layers (B3) was largely negative, and primarily constituted requests for additional context layers beyond the proposed population and business layers. Context layer requests primarily were divided between aspects of the built environment and aspects of the natural environment. Requested built environment context layers included: parcels (n = 7), critical infrastructure (n = 5), breakwalls/seawalls (n = 4), marinas/ports (n = 4), public access (n = 4), land use (n = 3), bridges (n = 2), parks (n = 2), permitted structures (n = 2), slip layouts (n = 2), zoning (n = 2), hazardous facilities (n = 1), navigation channels (n = 1), poverty rates/socioeconomic status (n = 1), reservations (n = 1), and water uses (n = 1). This feedback prompted replacement of the simple socioeconomic panel with a pair of menu options indicating the vulnerability of the built environment: "society" (including the Hazards & Vulnerability Research Institute's (HVRI) social vulnerability index for 2006–2010: http://webra.cas.sc.edu/hvri/products/sovi.aspx) and "business" (showing the originally planned density of employees along the lakes). Requested natural environment context layers included wetlands/marshes (n = 9), erosion rates (n = 6), floodplain maps (n = 6), sedimentation/sandbars (n = 5), habitat types (n = 4), flood frequency (n = 3), flood hazards (n = 3), lake bottom (n = 3), rivers/stream (n = 3), fisheries (n = 2), ice cover (n = 2), land cover (n = 2), soil type (n = 2), wind direction/speed (n = 2), beaches (n = 1), currents (n = 1), evaporation scenarios (n = 1), and weather conditions (n = 1). Other requested context layers included historic water level gauges (n = 3), historic imagery (n = 1), locator maps (n = 1), oblique photos (n = 1), and offshore surveys (n = 1). While we were unable to accommodate all requests in the initial release of the Lake Level Viewer, we anticipate integrating a subset of these context layers into future generations of both the Lake Level Viewer and the Sea Level Rise and Coastal Impacts Viewer.

4.4 Interface utility

The fourth and fifth categories of codes primarily related to the low-fidelity interaction requirements (Table 3). The fourth category of codes marked statements about the interface functionality included in the Lake Level Viewer, directly addressing its perceived utility for the use case scenarios outlined in Table 1. The interface functionality proposed in the low-fidelity wireframes by far garnered the most discussion during the cognitive walkthroughs, but also included the largest number of unique codes (see Table 3). The CanVis overlays (I5) received the most discussion, followed by the depth query tool (I4), the lake level benchmarks (I3), the lake level slider (I2), and the lake selection inset map (I1). This discussion was overwhelmingly positive, with only the lake level benchmarks (I3) and map transparency tool (I6) having a slightly negative valence.

The cognitive walkthrough of interaction wireframes required participants to indicate where they would click first, and then how they would continue to navigate the system. Ten participants indicated they first would use the lake selection inset map (I1)—the intended entry point in the interaction wireframes—with five participants first using the lake level slider (I2), two the map browsing tools (I8), and one reviewing the supporting info panel (B4). This initial prompt in the cognitive walkthrough generated discussion about how the Lake Level Viewer should look upon first entry, as the baseline in the lake level slider is relative to a particular

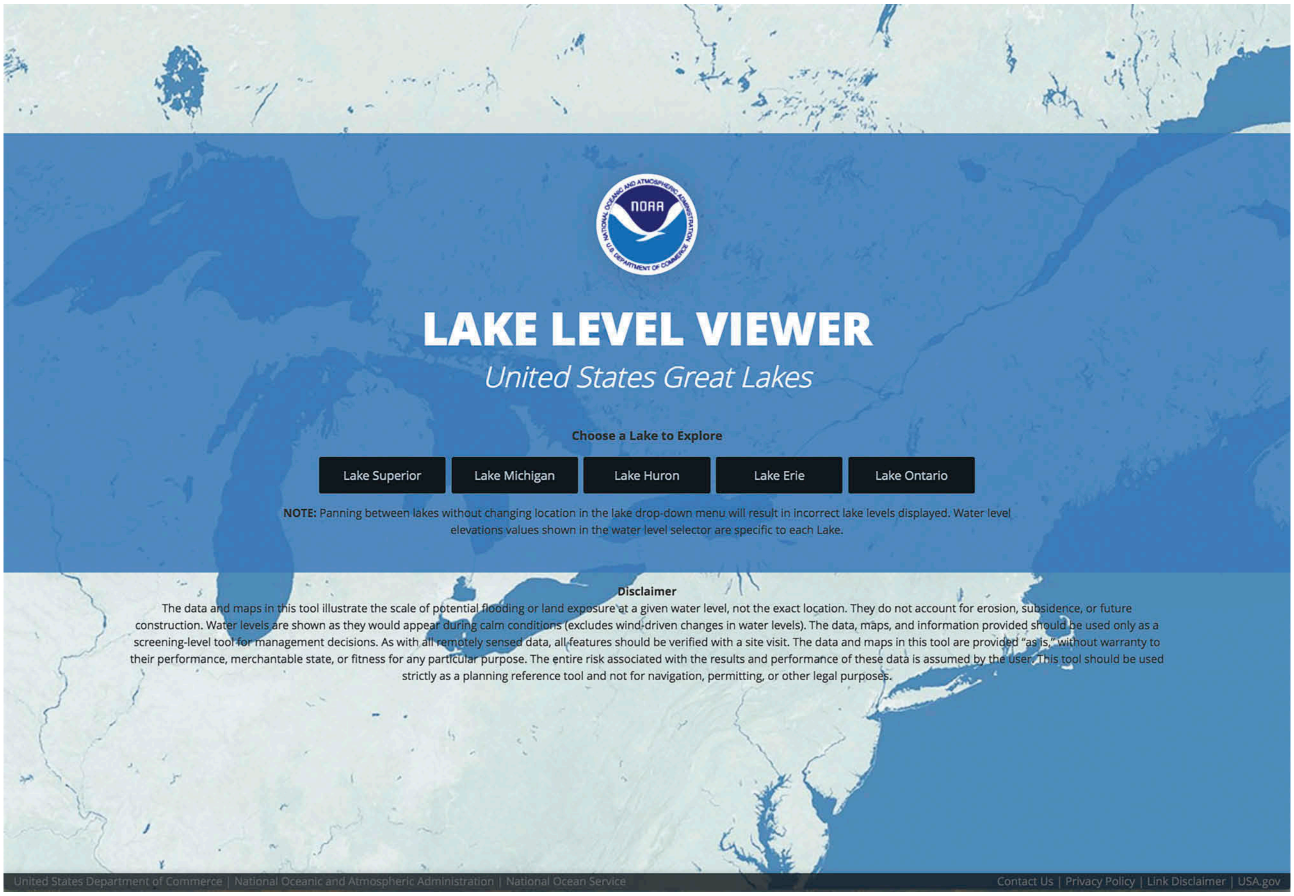

Figure 6. The splash page of the Lake Level Viewer. The cognitive walkthrough of the low-fidelity interaction wireframes generated discussion about the entry point of the Lake Level Viewer. Because the baseline of the lake level slider must be relative to one of the Great Lakes, it was unclear how the application would look upon first loading of the page. Based on participant feedback, we added a splash page requiring users to choose a lake, which then configured the map and the lake level slider.

Great Lake. Several participants suggested having a splash page for the Lake Level Viewer that requires users to first select one of the five lakes. As one participant stated, "It could even be like the first dialogue box that you see when you open up the viewer, select the lake, and then once you select the lake, that dialogue box goes away [and] it zooms in to your lake ... almost as if like the select a lake is, you know, the ignition key." As a result, we added a splash page requiring users to select one of the five Great Lakes (Figure 6), with the map then opening to an overview of the selected lake and the lake level slider adjusting the long-term average baseline accordingly. We then replaced the lake selection inset map with a simple drop down menu for toggling between the lakes (Figure 5). Overall, this discussion and subsequent revisions demonstrated one of the primary advantages of using low-fidelity wireframes: critical evaluation of the entry point of a proposed application.

The majority of participants (17/18) considered the vertical design of the lake level slider to be intuitive. The one dissenting participant was concerned that the lake level slider might be confused as a zoom slider due to the vertical orientation and its position in the top-left corner of the application, an interesting example of how interactive map design conventions impact user expectations. Explaining this concern, the participant stated "I kind of like it in the left panel area only because I think so many people are familiar with this being your zoom level tool ... without really reading the content, that's kind of what I assumed also." As a result, we repositioned the lake level slider in the bottom-left corner of the application and refined its designed to appear as a vessel that can be filled or drained—thus evoking a visual metaphor of water inundation and land exposure—rather than a common slider bar widget (Figure 4). All participants interpreted the lake level benchmarks correctly during the cognitive walkthroughs (I3).

The initial reaction to the CanVis photo simulations was overwhelming positive (I5). Twelve of the participants expressed positive body language or offered encouraging exclamations during demonstration of the CanVis photo simulations in the opening video of the Sea Level Rise and Coastal Impacts Viewer, a reaction not observed with any other functionality shown in the video. Participants thought the photo simulations would be particularly useful for public outreach, with one participant stating "for presentations … I think that's really useful, especially for presenting it to more of a general public … I think that really brings it to light, and like, holy cow, that's what it would look like!" During the cognitive walkthroughs, participants helped us to brainstorm the kinds of locations appropriate for depicting decreasing rather than increasing water levels in the photo simulations, identifying lighthouses, marinas, mud flats, and sea walls as viable landmarks.

Overall, participants were content with the map transparency tool (I6), map browsing tools (I8), the share function (I9), and the download function (I10), having no noteworthy suggestions for improving their position or design. There were minor confusions regarding the depth query (I4) and basemap toggle (I7) functionality. First, participants were confused by the bar chart included in the information window activated when using the depth query tool, correctly identifying that the chart always would display an incremental increase and thus not provide interesting or unexpected information. Several participants continued to critique the bar chart even after we noted to ignore it during the cognitive walkthroughs. Upon probing, all participants indicated they only wanted to retrieve the water depth upon use of the depth query tool, and the majority of participants (12/18) wanted the depth query tool to be deactivated when first entering the map to avoid initial issues with panning. As a result, we restrict details included in the information window to the water depth at the selected location and set the depth query tool to "off" by default.

Second, participants were confused with the topography and bathymetry basemap options in the basemap toggle interface. Seven of the participants were unsure how the map would update when toggling the topography and bathymetry layers. Because all four options were given as radio buttons, participants expected all tilesets to span the entire map extent. However, the LIDAR topobathy dataset only covered a small swath along the coast, meaning that the topography and bathymetry layers actually were overlays placed above the imagery or streets tilesets. Further, six of the participants stated that the bathymetry overlay should remain on at all times, given the purpose of the Lake Level Viewer, and noted that this toggle essentially was redundant with the map transparency tool. As a result of the above feedback on the depth

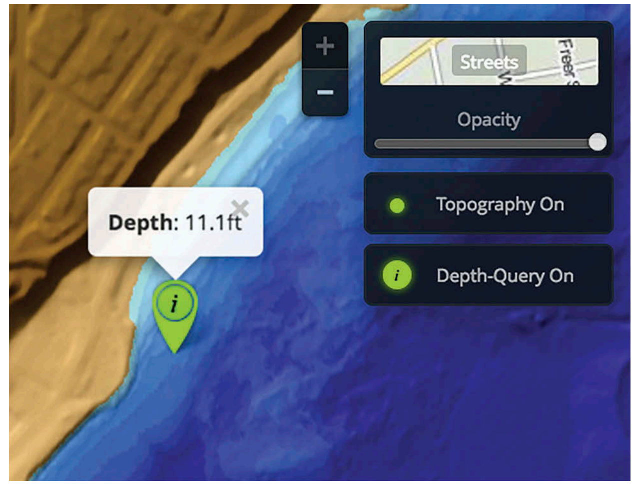

Figure 7. The map tools panel. Based on feedback from the cognitive walkthroughs, we grouped the map transparency and depth query tools into a map tools panel. This revision separates controls that configure the visualization (Figure 5) from those that provide additional context.

query and basemap toggle functionality, we revised the Lake Level Viewer concept to include a "map tools" panel to contain these tools, located in the top-right corner of the application in the position vacated by the lake selection inset map (Figure 7). The imagery and streets tilesets were provided as radio buttons that replace one other when selected, with the typography and depth query tools provided as checkboxes, both set to "off" by default.

4.5 Interface usability

The final category of codes identified overarching issues in interface design, signaling potential usability problems with the Lake Level Viewer. The interface design was the least discussed of the five categories (Table 3), with the depth of feedback constrained by the rough design of the low-fidelity interaction wireframes. Thus, we suspect that low-fidelity wireframes generally are better purposed for garnering input about the utility, rather than the usability of a proposed interactive and web-based mapping application. If understanding usability is the priority, high-fidelity wireframes and partially functional prototypes should be used instead. The most frequently applied code regarded statements about subjective satisfaction with the proposed Lake Level Viewer (U5), followed by the layout design (U1) and the minimized layout design (U2). Discussion regarding learnability (U4) and interface aesthetics (U3) was sparse.

The main suggestions for improving the layout design (U1) were mentioned above, including placing the lake level slider beneath the lake selection and overlay tools along the left side of the application as well as moving the map tools to the vacated position in the top-right of the application. In addition to the above discussion, participants justified such layout recommendations as a way of improving navigation, with users directed to start with the lake selection on the top-left, move down vertically to the overlay options, then adjust the water level in the lake level slider, and ultimately explore the map. All participants agreed that the minimized layout design would be a benefit for repeated use (U2).

Statements regarding subjective satisfaction helped us to understand two important use case scenarios for the Lake Level Viewer (U5). First, participants were eager to integrate the Lake Level Viewer into their outreach efforts, with one participant stating "we could include a lot of this information in some of those outreach events that we do, we could use the visualization aspect of this in our telling of the story of why the Great Lakes do what they do." Participants also were eager to use the tool to regularly download the updated LIDAR-based DEM for integration into their own analytical workflows, with one participant stating "the idea of being able to download is wonderful." Statements regarding subjective satisfaction also made it evident that wireframe evaluation helped to promote buy-in with participants and their respective agencies. One participant stated "I barely looked at it before, but now I think it's cool … I'm anxious for it to come out, actually [laughter] because I know it will be used for sure," while a second stated "I can tell you based on these [wireframes], I'm much more eager to see the digital product than I was going into [the evaluation]."

5. Summary and conclusion

The wireframe design and evaluation of the Lake Level Viewer proved valuable to both research and development. First, feedback elicited during the cognitive walkthroughs led to important changes to the Lake Level Viewer concept, including both its functional scope and visual design:

- We clarified the entry point to the Lake Level Viewer, adding a splash page that requires the user to select a specific lake before proceeding.
- We streamlined the interface layout, positioning tools used to *configure* the visualization (i.e. functionality used before exploring the map) in an accordion panel spanning the left side of the layout and tools providing additional map *context* (i.e. functionality used after interpreting the map) into a panel at the top-right.
- We redesigned the accordion panel and provided textual and visual explanations for each map overlay.
- We reimagined the lake level slider as a vessel to avoid user confusion with typical zooming controls and to evoke a visual metaphor of exposure and inundation;
- Finally, we enumerated a *wishlist* of advanced representation and interaction requirements that were outside of the initial project scope, but that should be considered in future releases of the Lake Level Viewer.

Second, the wireframe design and evaluation suggested several open design challenges for water level visualization tools supporting adaptive management of coastal hazards related to climate change. Each of these challenges requires future qualitative and quantitative research crosscutting the areas of adaptive management, climate change science, and geographic visualization:

- *Delineating the Shoreline*: Perhaps the most basic challenge to water level visualization is determining an appropriate shoreline datum for use as baseline. There is a tendency for users to interpret any baseline as the current water level, a shoreline that is impossible to delineate in real-time. The appropriate datum also is dependent upon the geographic context, with participants in the cognitive walkthroughs noting a large number of alternatives to IGLD. Flexible datum conversion may be the ideal solution in an interactive environment, but carries with it the technical challenge of preprocessing and serving multiple raster tilesets calibrated to each available datum.
- *Designing for Exposure and Inundation*: The Lake Level Viewer required representation of both exposed and inundated land. However, the possibility of both exposure and inundation is not unique to the Great Lakes, as changing climates will have substantial, geographically varying impacts on freshwater lakes, streams, and wetlands across the planet. Participants reacted positively to our diverging, blue-to-brown solution for representing relative levels of inundation and exposure, suggesting one potentially viable map design solution for follow-up performance testing.
- *Exploring by Scenario*: When well-designed, water level visualization tools act as "what-if" sandboxes, with the provided water level slider an important tool for explore potential future

scenarios. However, participants were split on the appropriate water level range for the Lake Level Viewer (i.e. the range of future scenarios for consideration), stating that each of the Great Lakes has its own natural range and geographic context. The ideal solution may be to base each lake level range on climate change models, explicitly constraining future scenarios with climate change science. Despite the potential value of scenario-based visualization, regional climate models remain underdeveloped in many locations susceptible to climate change, such as the Great Lakes, and interactive model steering using visualization remains an open research topic in Cartography and GIScience.

- *Supporting Non-Mapping Experts*: Effective use of a water level visualization tool requires a large number of competencies: local knowledge about the represented place, scientific knowledge of climate change and impacted physical and social dynamics, adaptive managerial knowledge about informed, geocollaborative decision making under conditions of uncertainty, and cartographic knowledge of map reading and interpretation, among others. Few users, however, will be expert across all of these competencies. Given a target user group with varying levels of expertise, a water level visualization tool should not be designed like a fully featured GIS, but rather a constrained interactive experience delivering only the necessary content for the supported adaptive management context.
- *Utilizing Uncertainty*: The majority of negative feedback on the high-fidelity representation wireframes was about the uncertainty design solution. It was clear from the cognitive walkthroughs that most participants were confused about the concept of confidence depicted in the wireframes and thus unlikely to utilize confidence information during their exploration of future scenarios. Our use of textual and visual explanations to improve the message about confidence was one solution to improve interpretation of uncertainty in the water level visualization. However, future research is needed to understand the myriad forms of uncertainties present in water level visualizations, best practices for representing these uncertainties in the map, and appropriate visual metaphors for interacting with and ultimately understanding these uncertainties.

Finally, the Lake Level Viewer case study allowed us to formalize recommendations for wireframing on large-scale mapping and GIS projects, further clarifying the role of wireframing as a prototyping step in a broader user-centered design process:

- First and foremost, wireframing early in the user-centered design process saved project time and resources. The Lake Level Viewer wireframe design and evaluation were completed before a single line of code was written. Ultimately, less than a month was required for development itself, demonstrating the coding efficiency gained from prototyping during user-centered design.
- The wireframing illustrated the value of teaming cartographers with developers, with cartographers taking on the larger role of UX designers and completing the interface designs and evaluations in addition to data processing and map design. All NOAA and UW project partners viewed this pairing of cartographers and developers as extremely fruitful.
- Feedback gathered through cognitive walkthroughs confirmed many of the advantages to wireframing discussed in the literature. Specifically, the cognitive walkthrough of the wireframes allowed us to relate functional requirements to user profiles and use case scenarios, explicitly linking cartographic considerations to the hazard/risk and user/task context.
- The high-fidelity wireframes used real data, enabling us to gather formative, mostly positive feedback on our proposed representation design and to garner important, critical feedback about our datum choice and water level range. Too often, the interface to a visualization tool is developed before knowing data formats or symbol styles, resulting in an inconsistent look and feel as well as usability issues from retrofitting an interface to a representation.
- We fully recommend designing a combination of high-fidelity representation and low-fidelity interaction wireframes for efficient use of project resources. However, our inclusion of low-fidelity interaction wireframes in the evaluation did have at least two notable limitations. First, we could not use the low-fidelity wireframes for benchmark tasks; although we found the modified, open-ended exploration insightful, we may have missed several issues with our interaction designs as a result. Second, we found that the low-fidelity interaction wireframes were considerably more helpful in garnering input about the utility of the proposed visualization tool compared to its usability. Finally, we do not recommend using

low-fidelity wireframes for representation requirements from our experience designing the Lake Level Viewer, given the value of assessing wireframes with real data.

- Finally, we found the wireframe evaluation influential in promoting buy-in within our target user group. Many participants clearly shared this excitement by the end of the cognitive walkthrough, verbalizing their eagerness to integrate the Lake Level Viewer into their analytical workflows and outreach activities.

The NOAA Lake Level Viewer was launched successfully in August of 2014 and is publicly available in support of adaptive management and decision making at http://coast.noaa.gov/llv/.

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