A Competitive Analysis of Web-based Water Level Visualization Tools

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Abstract This paper reports on the competitive analysis of water level visualization tools that support adaptive management in response to global climate change. A competitive analysis study is a theory-based usability engineering method administered to critically compare a suite of related applications according to their relative merits, to the end of revealing best practices and unmet opportunities. The competitive analysis was conducted to inform design and development of the U.S. National Oceanic & Atmospheric Administration (NOAA) Lake Level Viewer, a map-based visualization tool supporting adaptive coastal management of hazards related to future water level change across the Great Lakes (USA). Twenty-five (n=25) water level visualization tools were compared across two broad themes in cartography: (1) representation, or the graphic encoding of information in the map display, and (2) interaction, or the means by which the user is able to manipulate the map display. The competitive analysis of water level visualization tools serves as a case study that can be extended to other mapping and visualization contexts.

Keywords usability engineering, competitive analysis method, interactive cartography, geovisualization, web mapping, water level visualization, flood maps

1 Introduction

A *competitive analysis study* is a usability engineering method administered to critically compare a suite of similar applications according to their relative merits (Nielsen, 1992). While most usability engineering methods solicit feedback directly from targeted end users, a competitive analysis study is a *theory-based* method in which the design/development team leverages established theoretical principles to evaluate the collected suite of applications (Roth, 2011). In other words, a competitive analysis study is a content analysis of secondary sources—common to archival research in social science—conducted for the purpose of usability engineering. While not a replacement for user-based evaluation, a competitive analysis study may be beneficial in a variety of mapping and visualization contexts, such as when the design/development team knows little about the application domain, when a user-based needs assessment study cannot be completed due to limited project resources or limited access to targeted end users, when there are a large number of existing applications that implement similar functionality, and when there is a previous version of the visualization tool already in use. Thus, a competitive analysis study primarily is appropriate during the early, formative stages of design and development (see Robinson et al., 2005, for a discussion of formative versus summative usability assessment).

In this paper, we demonstrate the potential of the competitive analysis method for cartography through the case study of *water level visualization*, or map-based visualization tools depicting the exposure or flooding of land as a result of historical/current storm events or future climate change predictions (Kostelnick et al., 2009). The competitive analysis was completed during the formative stages of design and development of the U.S. National Oceanic & Atmospheric Administration (NOAA) *Lake Level Viewer*, a map-based visualization tool supporting adaptive coastal management of hazards related to future water level change across the Great Lakes (USA). The purpose of the competitive analysis was threefold. First, the competitive analysis captured existing best practices in water level visualization, allowing for identification of common design and development solutions to the end of identifying key user needs that must be supported in the Lake Level Viewer. Second, the competitive analysis suggested possible opportunities for the Lake Level Viewer, pointing out currently unmet user needs that may be supported by the tool. Finally, because the tools are compared according to theoretical principles in cartography, the competitive analysis revealed important gaps between theory and practice, helping to problematize suboptimal solutions and to stimulate discussion about functional and technological innovation.

The paper is structured in four additional sections. In the following section, we provide background on the case study: adaptive coastal management on the Great Lakes in response to fluctuating future water levels. Our method design is described in the third section. A total of twenty-five (n=25) water level visualization tools were compared across two broad themes in cartography: representation and interaction. We provide the results of the competitive analysis in the fourth section, with discussion split between insights related to representation design versus interaction design. In the final section, we provide a summary of design recommendations derived from the competitive analysis and report on future work to bring the Lake Level Viewer online.

2 Case Study

The Lake Level Viewer concept aligns broadly with tenets of adaptive management. *Adaptive management* describes 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). Adaptive management techniques have been applied for the management of renewable resources, such as forestry, fishing, water, and wildlife, and recently have been extended for management of coastal hazards as way to promote resilient Great Lakes communities (Hart and Hamilton, 2012). Adaptive management is particularly applicable for mitigation of coastal hazards related to climate change, which include coastal bluff erosion, habitat destruction, storm flooding, and water quality degradation, among others (Moy et al., 2011).

A pressing issue along the Great Lakes related to climate change is the prediction of, and response to, future water levels. Modeling of climate-related changes to the oceans suggests a marked increase in global sea levels over the next century under a variety of emissions scenarios (IPCC, 2007). In contrast, recent modeling of climate-related changes to the Great Lakes water levels suggests a possible decrease in lake levels, but an increase in the annual variation of water levels (Angel and Kunkel, 2010, Hayhoe et al., 2010). Prevailing thought 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, 2007, Lofgren and Hunter, 2010, DiMarchi and Dai, 2011). The water levels across the Great Lakes already have set or approached record lows in 2012-2013. Such significant and unprecedented lake levels require careful consideration of an array of new coastal hazards with no historical analog. Further, the potential decreases in lake levels requires different adaptive coastal management solutions compared to those applied for increasing sea levels.

Effective adaptive management of Great Lakes coastal areas in response to climate change relies upon the availability and accessibility of historical, current, and future water level visualizations. Such visualizations directly serve municipalities and local communities, state and federal government agencies, and universities or other research institutions. Such visualizations also are invaluable to the industries upon which Great Lakes communities are reliant, as lake level changes may negatively impact agriculture, energy, manufacturing, shipping, and tourism (Bosello et al., 2007). However, water level visualizations derived from future climate models are not readily available to stakeholder groups in the Great Lakes (Greene and Hart, 2011) and the visualizations that are publicly available vary greatly across models and are wrought with uncertainties (Nicholls and Cazenave, 2010, Moy et al., 2011).

The Lake Level Viewer water level visualization tool was proposed to address these issues. The Lake Level Viewer is a sibling visualization tool to the existing NOAA Sea Level Rise and Coastal Flooding Impacts Viewer, which supports adaptive management of coastal hazards along the Atlantic, Pacific, and Gulf of Mexico shorelines in the U.S; a second version of the tool was deployed in September of 2013 (http://csc.noaa.gov/digitalcoast/tools/slrviewer). While some elements of the Sea Level Rise and Coastal Flooding Impacts Viewer may be directly borrowed for the Lake Level Viewer, others need complete rethinking given the possibility of a decreasing water level and the geographic context of the Great Lakes. We completed the competitive analysis to survey alternative water level visualization strategies that also may be appropriate for the Lake Level Viewer.

3 Method Description

The competitive analysis study was completed on a sample of twenty-five (n=25) water level visualizations tools available online, including both versions of the NOAA Sea Level Rise and Coastal Flooding Impacts Viewer. The sample of visualization tools was gathered through recommendations from the University of Wisconsin-Madison Sea Grant Institute and feedback from NOAA partners. The only requirement for inclusion in the sample was that the visualization must be map-based, with the water level represented cartographically. Six (n=6) tools were developed by U.S. federal agencies, three (n=3) by U.S. state agencies, four (n=4) by university research centers, six (n=6) by non-profit agencies, and three (n=3) by private industry or independent consultants; the remaining three (n=3) tools were developed through partnerships of federal, state, municipal, and/or university stakeholders. Two tools (n=2) have a geographic coverage of the entire globe, seven (n=7) by a single country (six within U.S., one within Australia), nine (n=9) by one or several states (within this category, four displayed states in the Atlantic Northeast, three in the Gulf of Mexico, and two along the Pacific coast), and six (n=6) by a single municipality (five within the U.S., one in Australia). Table 1 lists each of the evaluated applications.

Several patterns exist within the sample regarding the purpose of the visualization tool, or the user goal that the visualization tool was intended to support. Following the MacEachren (1994) Cartography[3] framework, thirteen (n=13) of the tools primarily support the goal of presentation, constraining the user interface to ensure that communication of the waterline or flood extent is clear. In contrast, the remaining ten tools (n=10) primarily support the goal of exploration, enabling the user to formulate ‘what if?’ questions by interactively building user-defined scenarios; four (n=4) of these ten tools also provide basic support for analysis, allowing for the computation of user-defined statistics. The vast majority of tools (n=24) emphasize prediction, depicting the future threat of flooding and/or storm surges. A small subset of tools (n=3) present historical information, allowing users to visualize the future waterline or flood extent in the context of past events. A majority of tools (n=13) depict the potential damage to physical and social infrastructure, indicating a need to support planning and preparedness for at-risk areas. A large minority of tools (n=11) explicitly support adaptive management in response to climate change, symbolizing areas that will be impacted by rising sea levels according to different climate change predictions.

The sample of visualization tools were compared across a fundamental distinction within cartography: (1) *representation*, or the graphic encoding of information in the map display, and (2) *interaction*, or the means by which the user is able to manipulate the map display (Roth, 2013b). Within the cartographic representation theme, coding emphasized three topics: (1a) variation in the way in which the waterline or flood extent is symbolized, (1b) inclusion of uncertainty information about the waterline/flood extent and variation in the way this uncertainty information is symbolized, and (1c) variation in the basemap or overlay context information provided to enrich the interpretation of the waterline or flood extent. Within the cartographic interaction theme, coding emphasized two topics: (2a) variation across supported interaction operators (i.e., the basic system functionality) and (2b) variation in the web mapping technology used to implement the visualization, and the opportunities and constraints therein. The analysis was completed in September and October of 2013.

Table 1. The twenty-five water level visualization tools included in the competitive analysis.

NAME	AGENCY
Sea Level Rise & Coastal Flooding Impacts Viewer (v1)	NOAA Coastal Services Center
Sea Level Rise & Coastal Flooding Impacts Viewer (v2)	NOAA Coastal Services Center
New Jersey Flood Mapper	JCNERR, CRSSA, NOAA CSC, Sustainable NJ, Rutgers University
Green Bay LakeViz	UW-Madison, Department of Geography
Lakes Entrance Visualization	Monash University
Explore SahulTime	Monash University
Coastal Resilience Future Scenarios Map, NY/CT (v1)	The Nature Conservancy; Coastal Resilience
Coastal Resilience Future Scenarios Map, NY/CT (v2)	The Nature Conservancy; Coastal Resilience
Coastal Resilience Future Scenarios Map, Gulf Coast (v1)	The Nature Conservancy; Coastal Resilience
Coastal Resilience Future Scenarios Map, Gulf Coast (v2)	The Nature Conservancy; Coastal Resilience
Interactive Sea Level Rise Web Map	SBEP & MOTE Marine Laboratory
Sea Level Rise Visualization for AL, MS, & FL	NOAA - MS-AL Sea Grant, USGS
Sea Level Rise Threatened Areas Map	Cal-Adapt
Surging Seas	Climate Central
Connecticut Coastal Hazards Viewer	Connecticut Department of Energy & Environmental Protection
What Could Disappear	NY Times
Sea Level Trends	NOAA Tides & Currents
Coastal Flooding & Sea Level Rise Impact Viewer	George Mason University
Sea Level Rise Inundation Maps	Delaware DNR
Flood Map Water Level Elevation Map	Sameer Burle
Flood Maps	firetree.net
SLR Impacts for Wilmington, Delaware	NOAA, USGS, Delaware DNR
Impacts of Sea Level Rise on the California Coast	Pacific Institute
USGS Flood Inundation Mapper	USGS, NWS, USACE, FEMA
SLAMM View	U.S. Fish and Wildlife Service

4 Results

4.1 Representation of the Waterline/Flood Extent

Given the emphasis of the competitive analysis on water level visualization tools, we first analyzed the way in which the waterline or flood extent is represented across the tools. Graphic representations signify information by leveraging one or several *visual variables*, or basic buildings blocks of the visual scene (Bertin, 1967|1983). Commonly employed visual variables for vector-based signification include: location, size, shape, orientation, grain, color hue, color value, color saturation, arrangement, crispness, resolution, and transparency. Figure 1 provides an overview of the waterline/flood extent representation by visual variable.

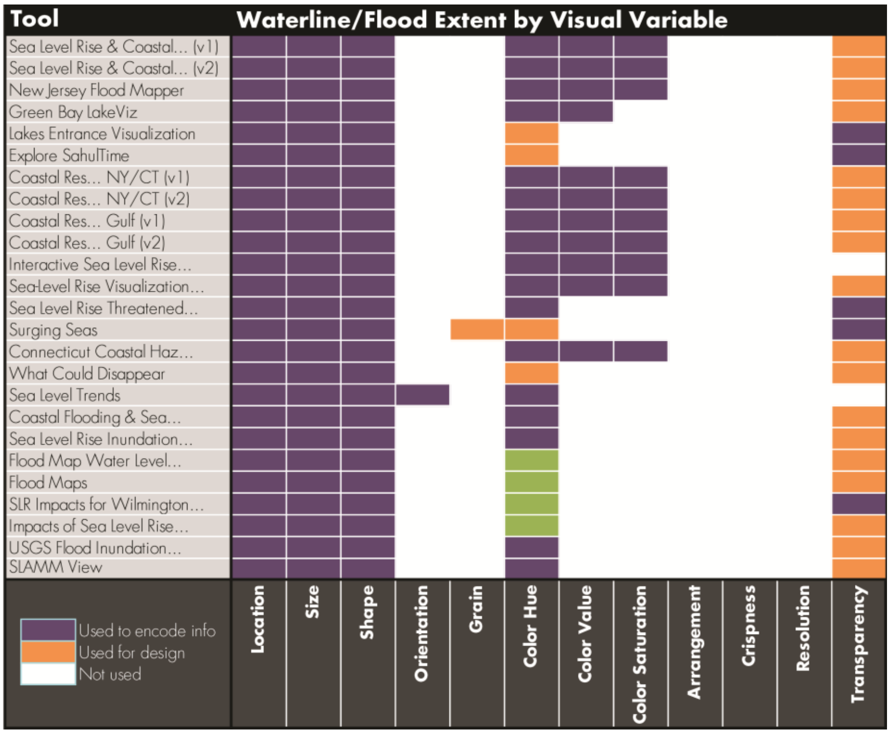

Figure 1. Waterline/Flood Extent by Visual Variable.

The competitive analysis revealed that the visual variable location (n=25) is used across all tools to represent the location of the waterline and the visual variables size (n=25) and shape (n=24) are used to represent the flood extent in all or most tools. The visual variable color hue is used in a large minority (n=8) of the tools as a design element for the flood extent (e.g., blue for flood), but not for communicating further information about the flood extent. The use of the visual variable location to represent geographic location is not surprising, given the case study on map-based visualizations and not other information graphics. However, the ubiquitous use of size and shape to represent the flood extent suggests that existing tools highlight not the position of the waterline as produced through a model or other mechanism, but the areas that will be inundated as a result of the shifting waterline. Thus, the sample of tools implicitly emphasizes adaptive management to future flooding hazards, rather than all hazards related to changing water levels. Because a decrease in future water levels for the Great Lakes is possible, the conceptualization of the Lake Level Viewer as a ‘flood’ visualization is inappropriate. Therefore, different symbolization may be needed for newly exposed land versus newly inundated land.

Many of the visualization tools encode the flood depth (a numerical variable) using an additional visual variable. Six (n=6) tools use color hue to represent water depth, two (n=2) use transparency, and one (n=1) tool uses a combination of color value and color saturation. Drawing from principles of semiotics, the use of color value + color saturation and transparency are predicted to be effective solutions for representing a numerical variable, while the use of color hue is not (MacEachren, 1995).

Finally, there are several unique representation solutions worth noting:

- The Connecticut Coastal Hazards Viewer and the Interactive Sea Level Rise Web Map make use of different color hues to represent flooding related to long term changes in the waterline and flooding related to localized storm surge changes, a distinction that is also important for adaptive coastal management on the Great Lakes.
- The Surging Seas visualization loads basemap layers of different detail for areas within the flood extent versus beyond the flood extent (Figure 2). This solution allows for impacted areas to be viewed in more detail without having a symbol overlapping that area, a limitation of most of the other tools; unfortunately, this solution may not be as useful for representing a declining water level, as imagery is not available for areas currently inundated. The Surging Seas visualization also makes use of the visual variable grain as a design element to show areas currently underwater; use of a texture or pattern may be a sufficient method for communicating the areas that are to become exposed in the Great Lakes.
- The Coastal Flooding and Sea Level Rise Impact Viewer uses hue to show building risk. This risk attribution effectively is an index combining waterline change scenarios from 2025 to 2100, with the building attributed with a higher risk if it becomes inundated within a shorter timeframe. Providing a benchmark index to interpret all future predictions may be a useful way to improve the interpretability of the waterline in the Lake Level Viewer.
- The Sea Level Trends tool makes use of the visual variable orientation to show the direction of historical change, with the amount of change represented redundantly using color hue and size (Figure 3). This is a particu-

larly effective approach when showing a large geographic extent, like the U.S. or multiple states, as the overall flooding extent is not visible when shown at a small cartographic scale. The Lake Level Viewer may benefit from this kind of representation as an informative 'overview', with the user then zooming and filtering to acquire details on demand (Shneiderman, 1996).

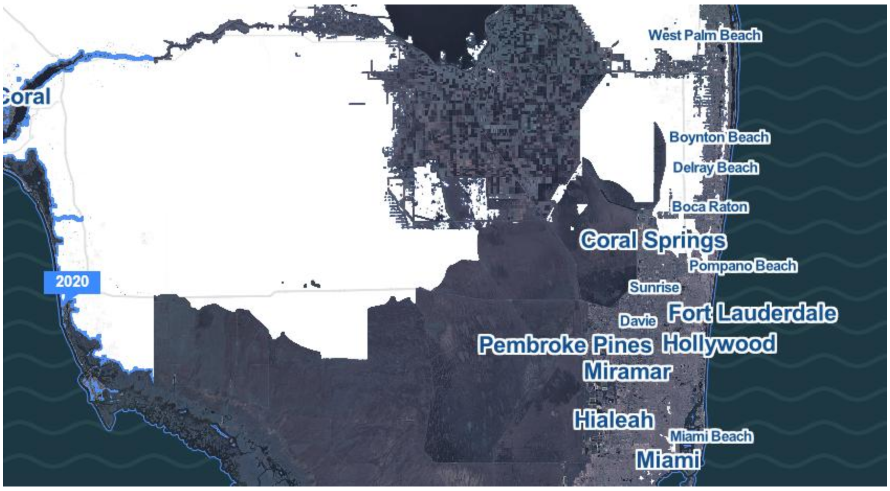

Figure 2. Representing Flood Extent Using Transparency. The Surging Seas visualization (http://sealevel.climatecentral.org/) presents a unique solution in which the flooded areas are show using a satellite image and the unaffected areas are shown using a generalized vector basemap.

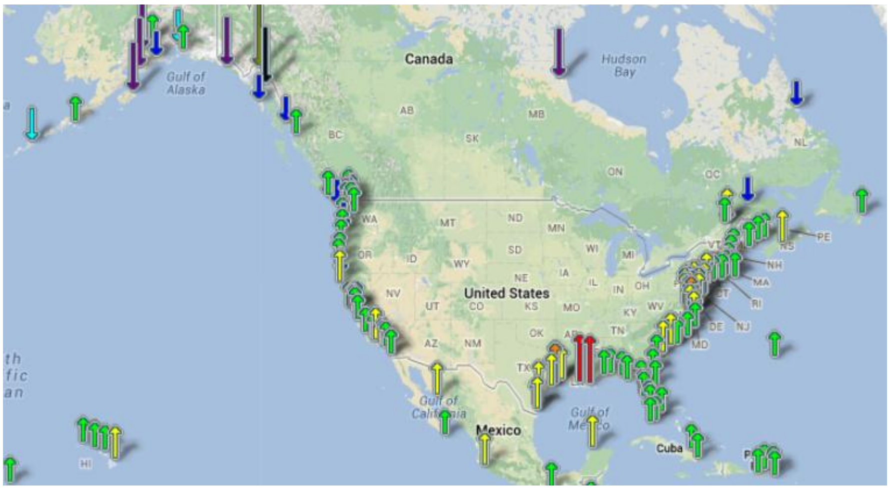

Figure 3. Representing Waterline Change Using Orientation. The Sea Level Trends visualization (http://tidesandcurrents.noaa.gov/sltrends/) symbolizes the direction of waterline change at a regular interval using orientation, an effective solution when showing a large geographic extent.

- The SLAMM View tool does not represent the waterline or flood extent, but instead only displays the land use type of areas that will become inundated; the visual variable color hue is used to discriminate among land use types. Thus, the SLAMM View tool provides additional detail in the impacted area, much like the Surging Seas tool, without obscuring the area with an additional symbol.

4.2 Representation of the Certainty of the Waterline/Flood Extent Prediction

The term *uncertainty* describes any cause for a mismatch between reality and the user's understanding of reality (Roth, 2009) and may be considered as a series of filters within the reality → variable-definition → data-collection → information-assembly → knowledge-construction pipeline (Longley et al., 2005). The proper collection and communication of information uncertainty has an important impact on both the assessment of current and future risks as well as the individual or collective decision making process about how best to respond to those risks (Agumya and Hunter, 2002). Thus, effective uncertainty representation is essential to the design of visualizations that support decision making, and adaptive management broadly. In GIScience, information uncertainty is considered multifaceted, exhibiting at least three components: (1) *accuracy/error*, or the correctness or freedom from a mistake of a measurement or estimate, (2) *precision/resolution*, or the exactness or degree of refinement of a measurement or estimate, and (3) *trustworthiness*, or the dependability or confidence that the user has in the information (MacEachren et al., 2012). Trustworthiness typically is conceptualized as a 'catch-all' category that includes aspects of the currency, completeness, internal consistency, credibility, subjectivity, interrelatedness, and lineage of the represented information (MacEachren et al., 2005). While these topics typically are considered as 'metadata', aspects of accuracy/error, precision/resolution, and trustworthiness can vary spatially and thus can be communicated visually using the visual variables introduced above. Figure 4 provides an overview of the uncertainty representation by visual variable.

Seven (n=7) of the twenty-five visualization tools represent some form of information uncertainty, with three (n=3) tools representing completeness, or the extent to which information is comprehensive for the area, and six (n=6) tools representing confidence, using the term in a way that is similar to trustworthiness. Completeness is represented using the visual variables grain (n=2) or color value (n=3), while confidence is represented using the visual variables color hue (n=6) or a combination of color value and color saturation (n=2).

The NOAA Sea Level Rise and Coastal Flooding Impacts Viewer is the only visualization tool in the sample to represent two kinds of information uncertainty. Completeness is represented using the visual variables grain ('Area Not Mapped') and color value (counties not touching the coast), while confidence is represented using the visual variable color hue (Figure 5). Representations of completeness and confidence are included in both versions of the Sea Level Rise and Coastal Flooding Impacts Viewer. The concept of confidence is defined in the Sea Level Rise and Coastal Flooding Impacts Viewer as the "Level of certainty that a mapped [sea level rise] scenario is correct, taking into account topographic and tidal surface errors". Description of the confidence metric and confidence threshold is provided in a linked methods document; repackaging this information in a more accessible format (e.g., an illustration, a slideshow, or a video) may improve the interpretability of the model-based confidence assessment, to the end of enabling better informed decisions.

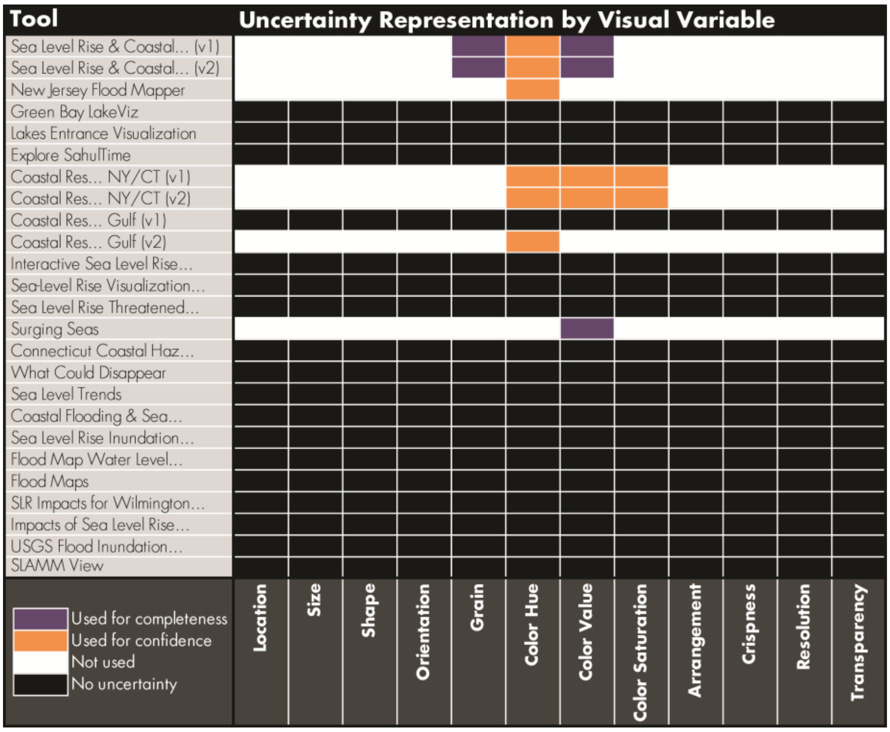

Figure 4. Uncertainty Representation by Visual Variable.

It is unclear how generation of this confidence metric will require revision for the Lake Level Viewer, as the current metric relies on a high resolution overland digital elevation model, the quality of which typically is not available for bathymetric information. Further, the confidence metric relies on a model of the contribution of tidal/wave action to flooding; this model may or may not require rethinking when applied to seasonal ice cover and snow melt, rather than extreme oceanic storm events. Minimally, use of a blue color hue to represent 'confidence' requires reconsideration in order to encode both exposed and inundated land.

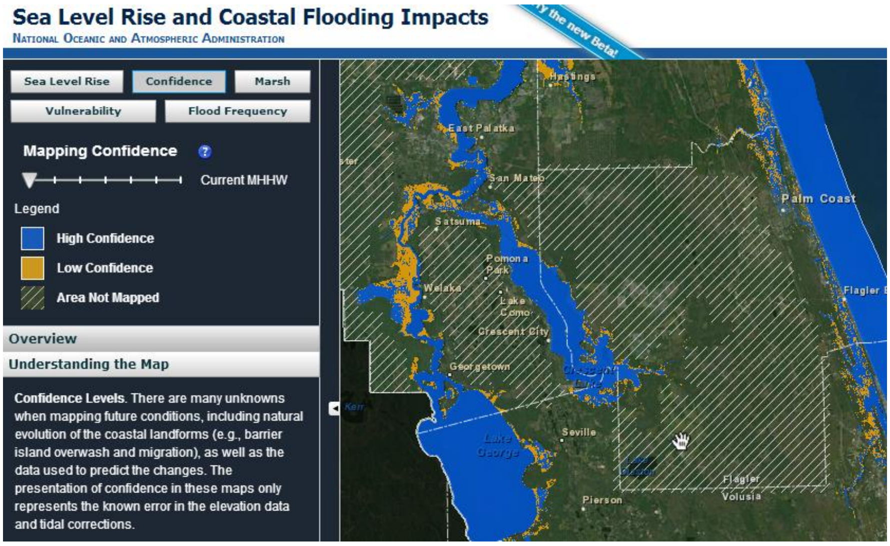

Figure 5. Representing Uncertainty with Grain, Color Value, and Color Hue. The NOAA Sea Level Rise and Coastal Flooding Impacts Viewer (http://www.csc.noaa.gov/slr/viewer/) represents completeness using grain ('Area Not Mapped') and color value (the counties not touching the coast) and represents confidence using color hue.

4.3 Basemap and Overlay Context Information

Provision of context information is essential for successful interpretation of the waterline or flood extent. Traditionally, the relative importance of different map features was communicated to the map user through a carefully designed *visual hierarchy* (Slocum et al., 2009); in the case of a water level visualization, the position of the waterline should rise to the forefront to ensure immediate visual inspection, with other context information receding into the background. The possibility of interactivity, along with historical constraints in web mapping technology, have transformed this traditional paradigm, with context information typically organized into *basemap* versus *overlay* layers for maps published online. Typically, the basemap layers are rasterized and served as a set of tiles to support instantaneous panning and zooming, while the overlays are drawn as vectors to enable retrieval of additional details about the features. The basemap tiles often add detail as the user zooms into the map, requiring a sophisticated *multiscale map design* from a highly generalized basemap to a highly detailed basemap (Brewer and Buttenfield, 2007); it is less common for overlays to increase in detail as the user zooms into map, although such behavior is appropriate cartographically.

Figure 6 provides an overview of commonly available basemap options. The competitive analysis identified four basemap layers commonly available in water level visualization tools: satellite or aerial images (n=24), street maps (n=19), a map-image hybrid that includes labels and some vector features (n=8), and a topographic map or other terrain representation (n=18). Twenty (n=20) of the tools provide more than one basemap option, while seven (n=7) of the tools provide all four basemap options. While provision of multiple different basemap options supports a wider array of map use tasks and allows users to set their preference, such provision also requires that the symbolization of the overlay features works across various basemaps. Twenty-one (n=21) of the tools include basemaps that are multiscale, providing additional detail as the user zooms. Finally, all of the included basemaps are much more detailed on the land side of the coastline compared to the water side, again a concern given the possibility of a declining water level in the Great Lakes. While Esri does provide a bathymetric tiling service, the current level of detail in the Great Lakes is not sufficient for most adaptive management use case scenarios. However, it is possible to serve custom tiles using open source rendering services like TileMill (https://www.mapbox.com/tilemill/), meaning that the basemap for the water side of the coast can be generated in-house and updated as better bathymetric information becomes available over time.

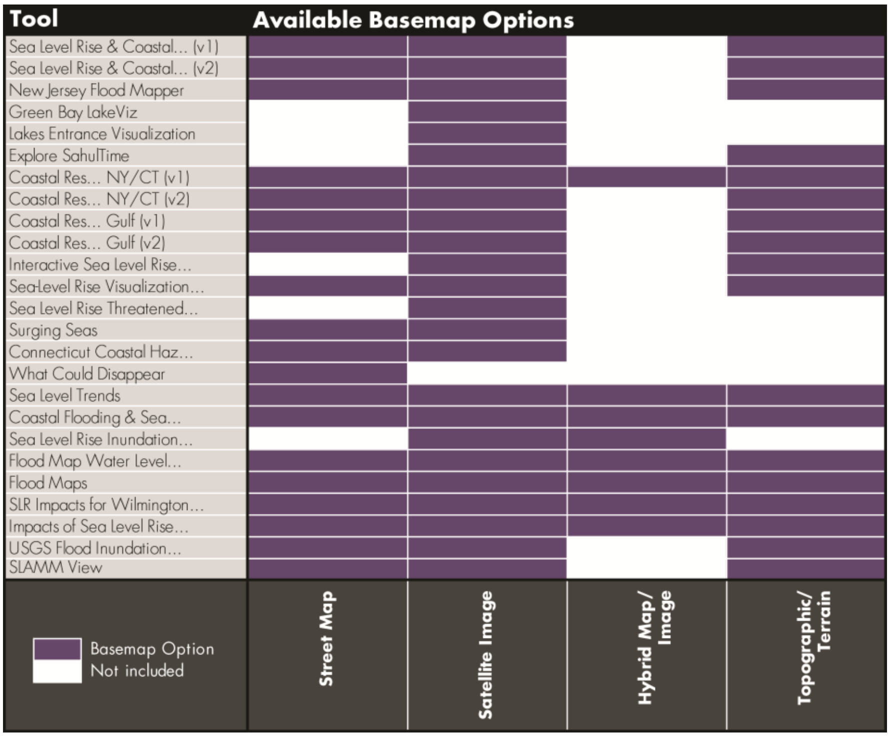

Figure 6. Available Basemap Options.

Most of the tools provide additional overlay context layers (n=18) beyond the waterline/flood extent or an indication of its uncertainty, as described above. The most frequent overlay layers provided are flood/surge benchmarks specific to a notable flood scenario or historical event (n=11). For instance, the Sea Level Rise Visualization for Alabama, Mississippi, and Florida provides a storm surge overlay for Hurricane Katrina and the Coastal Resilience Future Scenarios Map, New York & Connecticut (v2) provides several flood and storm surge benchmark overlays for Super Storm Sandy (Figure 7). Such benchmark overlays are useful because they provide a meaningful and memorable point of reference against which to compare future sea level rise scenarios (Harrower, 2002).

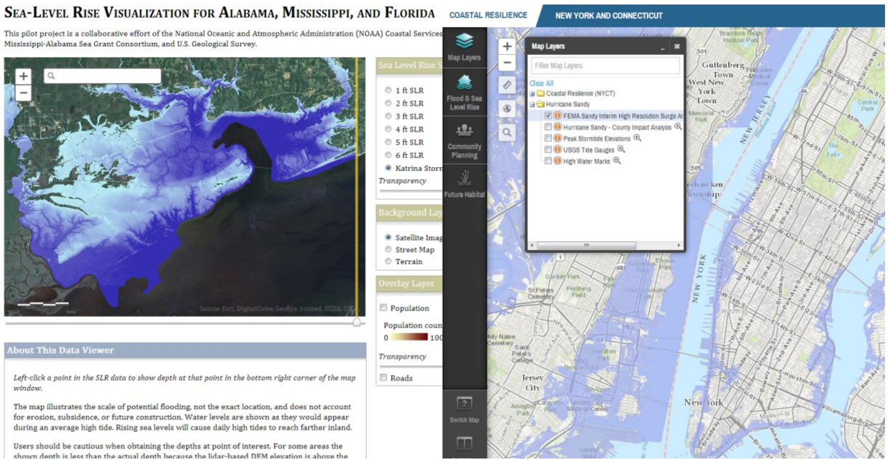

Figure 7. Meaningful Benchmark Overlays. **(left)** A storm surge overlay for Hurricane Katrina in the Sea Level Rise Visualization for Alabama, Mississippi, and Florida (http://gom.usgs.gov/slr/slr.aspx). **(right)** A series of flood and storm surge overlays for Super Storm Sandy in the Coastal Resilience Future Scenarios Map, New York & Connecticut (http://maps.coastalresilience.org/nyct/).

Additional overlay context layers provided by at least two separate visualization tools include: marsh/wetlands (n=9), critical facilities or infrastructure (n=8), socioeconomic vulnerability (n=7), land use or land management (n=4), populated areas (n=5), photos of historic or simulated flooding (n=4), parks or protected natural areas (n=3), and erosion susceptibility (n=2). The overlay options are perhaps the best way to infer the intended use case scenarios of the visualization tool using the competitive analysis method. There appears to be a split in emphasis between visualization tools supporting adaptive management of the human or built environment—with layers including critical facilities/infrastructure, socioeconomic vulnerability, and populated areas—and visualization tools supporting adaptive management of the physical or natural environment—with layers including marsh/wetlands, land use or land management, parks or protected areas, and erosion susceptibility. An integrated approach providing overlay layers about both the human and physical environment, and the interaction therein, supports a more robust geographic dialogue about the impact of changing water levels across the Great Lakes. It is recommended, however, to organize layers about the human versus physical environment into meaningful use case scenarios, with each scenario presented within the visualization tool as a recommended package of default overlay context layers, while maintaining the flexibility to add or remove overlay layers as the user sees fit.

4.4 Supported Interaction Operators

Interaction operators describe the generic kinds of interactive functionality implemented in the visualization (Roth, 2012, Roth, 2013a). Interaction operators can be delineated into *work operators*, or operators that are performed explicitly to accomplish the user's goal or objective, versus *enabling operators*, or operators that are performed to prepare for, or clean up from, a work session (Whitefield et al., 1993). Figure 8 provides an overview of the supported interaction operators (i.e., functionality) across the sample of visualization tools.

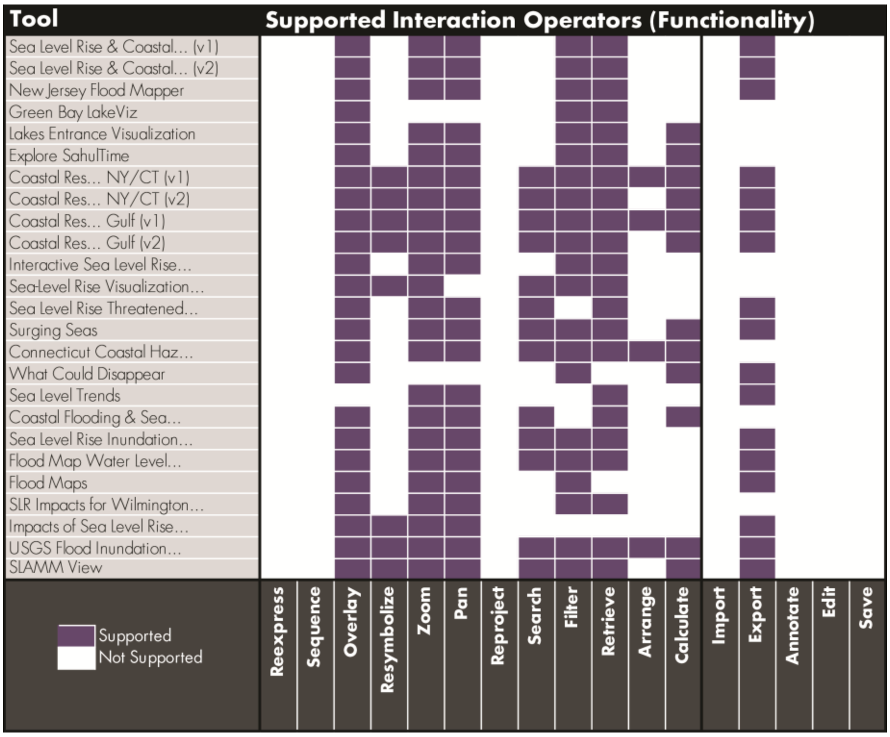

Figure 8. Supported Interaction Operators.

The most commonly implemented operator is *overlay* (n=24), which allows users to toggle the visibility of the overlay context layers shown in the display. While only nineteen (n=19) of the evaluated visualization tools include additional overlay context layers, the other five (n=5) tools implement overlay functionality for toggling of the waterline/flood extent itself. Such a use of overlay for the waterline/flood extent overcomes in part the aforementioned problem of obfuscating an area of interest with a polygonal symbol, albeit the basemap and flood extent still cannot be viewed in concert. Twenty-three (n=23) of the maps support *zoom*, or the ability to change the map scale, and twenty-two (n=22) of the maps support *pan*, or the ability to change the map centering, typically after zooming into the map. Also tied for the third most common operator is *retrieve* (n=21), or the ability to request specific details about a map feature in the visualization. The provision of overlay, pan, zoom, and retrieve to manipulate a multiscale basemap is increasingly common today due to the ease in implementing these features with contemporary web mapping technologies (Roth et al., 2013); a web map with this basic functionality often is described informally as a 'slippy' map. It therefore is not unexpected that the large majority of evaluated visualizations support these four operators.

Somewhat surprising is the frequency that the *filter* operator is implemented (n=21), or the ability to adjust the visualization to only show map features that match one or more user-defined conditions, as compared to *search* (n=13), or the ability to identify a single location or map feature of interest. The search operator is more common in general use applications for which users have a single, concrete task, and therefore need a single entry point (i.e., a 'search box') for locating the feature of interest; on the other hand, the filter operator is more common in expert use applications for which the users have abstract or undefined tasks and require iterative exploration through small changes to filtering parameters. Many of the visualization tools use the filter operator to adjust the water level. The one evaluated visualization tool specific to the Great Lakes, Green Bay LakeViz, supports filtering from -12ft to +9ft based on variation in flood gauge data from 1996-to-present (Figure 9). When search is implemented, it is provided to reposition the map to a particular location, not a particular map feature or water level.

A small majority or large minority of visualization tools implement the work operators *calculate* (n=12) and *resymbolize* (n=8). The calculate operator allows users to derive custom information about map features of interest. Implementations of the calculate operator include the dynamic calculation of total area impacted by a hypothetical flood (n=5), a spatial measurement tool (n=4), and the dynamic calculation of unique land use types impacted by a hypothetical flood (n=3). The resymbolize operator allows the user to set or change a design parameter of the map representation without changing the features displayed on the map (as with the filter operator). The resymbolize operator exclusively is provided to adjust the transparency of overlay context layers. Finally, the arrange operator is implemented four (n=4) of the visualization tools, allowing the user to adjust the position of map elements and interface functionality to avoid overlap with the map.

Importantly, the Figure 8 analysis reveals several opportunities for the Lake Level Viewer that could set it apart from other water level visualization tools.

First, none of the visualization tools implement the *reexpress* operator, which produces a new visualization of the same information, effectively 'showing it another way'. Viewing the inundated or exposed land from a profile view along a user-defined transect, for instance, is one way in which the visualization can be reexpressed to generate new insight. Second, only the SLAMM View tool implements the *sequence* operator, allowing for creation and comparison of side-by-side small multiples of different future scenarios (Tufte, 1983). However, no tool implements the sequence operator to control animations of the waterline or flood extent. Finally, while the *export* enabling operator is commonly supported (n=17) as a way to share the link of the current map view, the implementation of additional enabling operators may improve analytical work across use sessions. In particular, the *annotate* operator could support collaborative decision making, allowing users to externalize their thoughts into the map display for sharing with their project team.

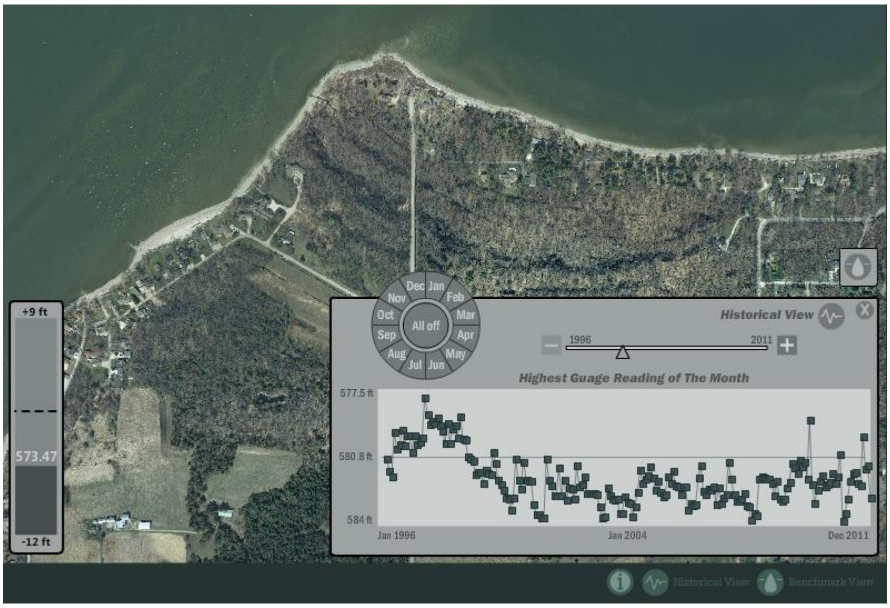

Figure 9: Filtering the Waterline. The Green Bay LakeViz tool (http://www.geography.wisc.edu/courses/geog575/s12/lakevis/floodvis_proof_of_concept.html) provides interactive filtering from -12ft to +9ft.

4.5 Web Mapping Technologies

Following analysis of the interaction operator functionality provided in the visualization tools, we then inspected the underlying technology used to implement this functionality. *Web mapping technology* describes the amalgam of frameworks, libraries, APIs, and web services that enable the creation and dissemination of web maps (Peterson, 2003). Our evaluation was limited primarily to the client-side or front-end implementation of the tool, given the focus on visualization and not processing. Figure 10 provides an overview of the client-side web mapping technologies leveraged by the visualization tools included in the sample.

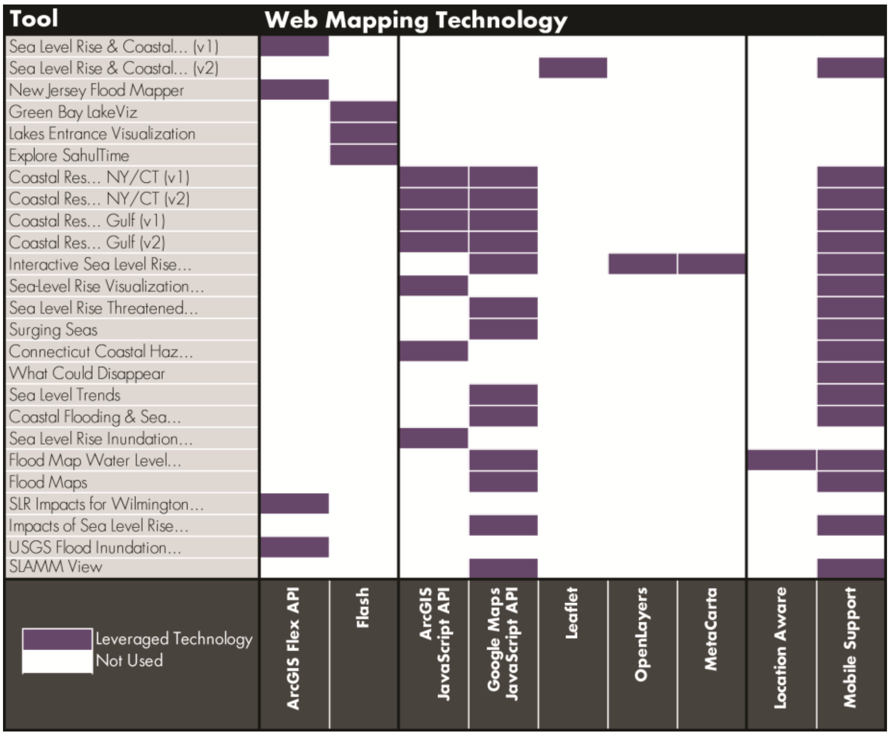

Figure 10. Leveraged Web Mapping Technologies.

Of the twenty-five visualization tools, eighteen (n=18) rely upon modern web standards (e.g., the browser-native definitions of HTML, CSS, and JS) while seven (n=7) rely upon a proprietary plugin to run a binary executable. For nearly a decade, a large number of web maps leveraged the FlashPlayer plugin by developing in the Adobe Flash or Flex authoring environments. Use of FlashPlayer resulted in a relatively small file size, a benefit for vector-based mapping, and improved cross-browser/cross-platform dependency. The use of FlashPlayer has waned in recent years, however, do the pervasiveness of AJAX, an application of JavaScript that enables on-demand loading of basemap tiles (among many other uses), and the increased emphasis on responsive design between desktop and mobile devices (Muehlenhaus, 2013). The FlashPlayer plugin is not supported by mobile devices, meaning the seven tools developed in Flash or Flex cannot be loaded on a smartphone or tablet (**Figure 10**, final column). Redevelopment of the second version of the Sea Level Rise and Coastal Flooding Impacts Viewer from the ArcGIS

Flex API to the Leaflet open source library is indicative of this broad transition in web mapping technologies from proprietary plugins to modern web standards.

Of the eighteen tools leveraging modern web standards, thirteen (n=13) use the Google Maps JavaScript API, seven (n=7) use the ArcGIS JavaScript API, two (n=3) use open source solutions (Leaflet, OpenLayers), and one (n=1) uses Meta-Carta. There is an emerging and active community of open source web map developers contributing their source code to the public commons for reuse; the aforementioned TileMill tool for rendering custom tiles is but one in a suite of resources available for web map developers. While open source solutions historically have suffered from poorer stability over time, they have the advantages of incorporating innovations more quickly into their code base and are free or near free to use. The choice of the open source library Leaflet for the second version of the Sea Level Rise and Coastal Flooding Impacts Viewer is particularly intriguing, and likely fruitful. A recent study by Roth et al. (2013) charting the parallel developments of the same web map in four distinct web mapping technologies (the Google Maps JavaScript API, D3, Leaflet, and OpenLayers) found that Leaflet was able to produce a web map of comparable functionality to the web map leveraging the Google Maps JavaScript API, but resulted in a much more satisfying development experience given the openness and extensibility of the code repository. The ArcGIS JavaScript API remains a viable option, particularly when the GIS functionality provided by the ArcGIS suite is needed.

Finally, only the Flood Map tool is explicitly *location-aware*, drawing on the user's IP location to recenter the map to his or her current position. Overall, this may be a missed opportunity, as users are increasingly encountering web maps that are updated to their specific use context (e.g., their geographic location, their past interactions, etc.). However, there may be privacy or accountability concerns explaining the lack of location-aware technologies in water level visualization.

5 Conclusion and Outlook

This paper provides a functional and technological comparison of map-based water level visualization tools to inform the design of the NOAA Lake Level Viewer. A competitive analysis of twenty-five (n-25) visualization tools was conducted according to criteria related to the representation or interaction design of the evaluated tools: (1a) variation in the waterline or flood extent symbolization, (1b) variation in included uncertainty information and uncertainty symbolization, (1c) variation in the provided basemaps and overlay layers, (2a) variation in the supported interaction operators, and (2b) variation in the underlying web mapping technology. The competitive analysis yielded the following recommendations:

- The waterline representation strategy requires rethinking for the Lake Level Viewer given the possibility that water levels will decrease across the Great Lakes. All current symbolization approaches connote 'flood' and thus are inappropriate of visualization of both increasing and decreasing water levels.

- There are two additional representation questions worth approaching with the Lake Level Viewer: (1) how can the map be designed so as to clarify, and not obfuscate, the exposed or inundated land, and (2) should an overview representation be provided when viewing the Great Lakes as a whole, and what should this look like?
- The use of blue for certain areas and orange for uncertain areas in the NOAA Sea Level Rise & Coastal Flooding Impacts Viewer requires revision, given the move away from a flood-centric visualization.
- All symbols need to 'hold up' against a variety of basemap tiles, given the increased expectation of multiple basemaps.
- Overlay context layers should be based on meaningful and memorable benchmarks, such as notable flood scenarios or historical events.
- As the number of unique overlay layers increases, they should be organized by use case scenario. These use case scenarios should span hazards regarding the human and physical landscape.
- A filtering range of at least +/- 12ft is recommended for the water level, given seasonal variation on the Great Lakes since 1996.
- The competitive analysis exposed several opportunities or gaps in the current functionality of water level visualization tools, including the implementation of the reexpress, sequence, and annotate operators as well as leveraging the user's location to configure the visualization.
- The move to Leaflet for the second version of the NOAA Sea Level Rise & Coastal Flooding Impacts Viewer was timely and appropriate, given the importance of supporting mobile and empirical evidence regarding the ease of implementing the Leaflet web mapping library.

The competitive analysis represents the first stage in a broader user-centered design and development process for the NOAA Lake Level Viewer. Insights generated through the competitive analysis currently are being combined with stakeholder feedback received through a set of needs assessment interviews to generate a first draft of a requirements document. Two additional stages of user feedback are planned in the future: a cognitive walkthrough study on wireframe designs of the Lake Level Viewer and an interaction study on an alpha version of the tool. The Lake Level Viewer is expected to be published online at the end of 2014.

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