The Competitive Analysis Method for Evaluating 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 NOAA Lake Level Viewer is a sibling visualization tool to the NOAA *Sea Level Rise Viewer* (Figure 1a), which supports adaptive management of coastal hazards along the Atlantic, Pacific, and Gulf of Mexico shorelines in the U.S. While climate modeling suggests a likely increase in global sea levels over the next century (IPCC, 2007), regional climate modeling in the Great Lakes 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). The water levels across the Great Lakes already set or approached record lows in 2012-2013. Thus, a fundamental redesign of the Lake Level Viewer was necessary to support the very different adaptive management context in the Great Lakes.

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 determining 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 three additional sections. Our method design is described in the following 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 Method Description

The competitive analysis study was completed on a sample of twenty-five (n=25) water level visualizations tools available online, including two versions of the NOAA Sea Level Rise Viewer. The sample of visualization tools was gathered through recommendations from the University of Wisconsin 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

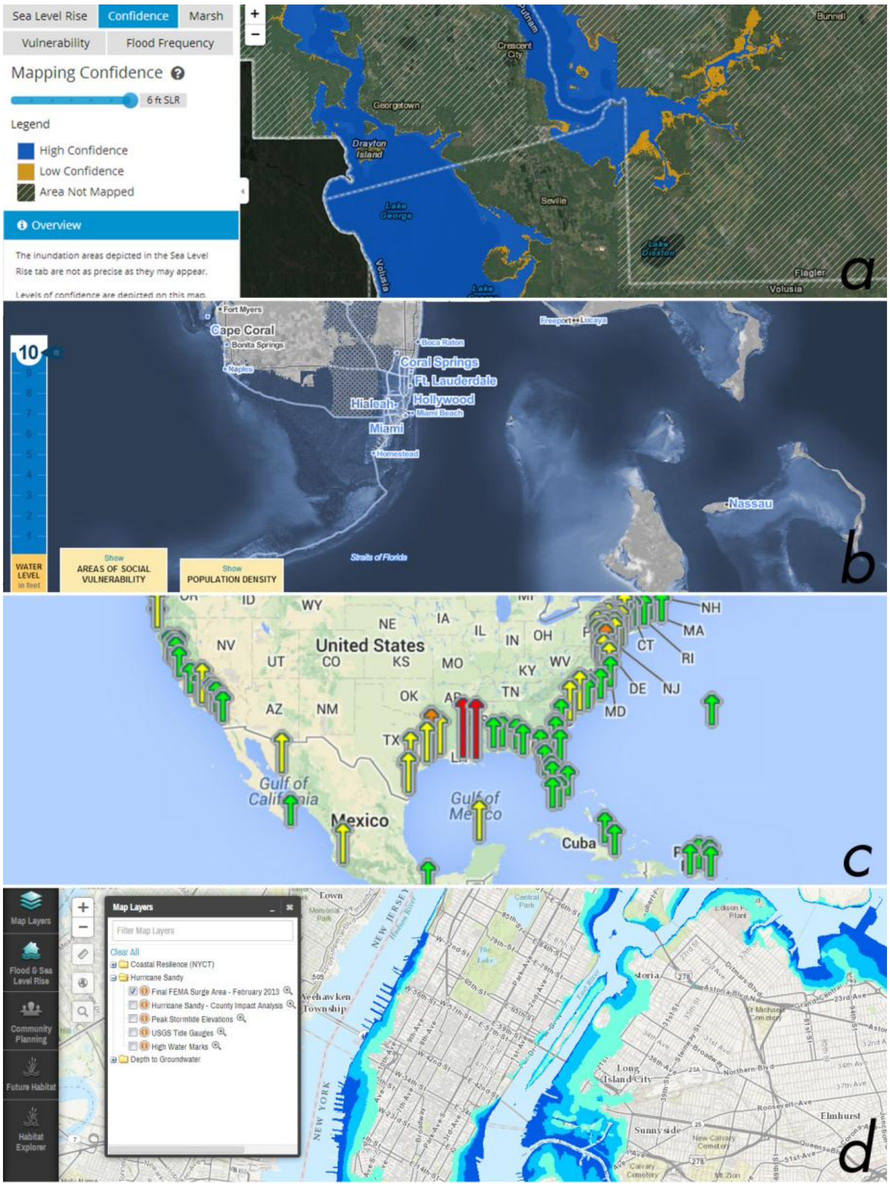

Figure 1. (a) The NOAA Sea Level Rise and Coastal Flooding Impacts Viewer (http://www.csc.noaa.gov/slr/viewer/); (b) Surging Seas (http://sealevel.climatecentral.org/); (c) Sea Level Trends (http://tidesandcurrents.noaa.gov/sltrends/); and (d) Coastal Resilience Future Scenarios Map, New York & Connecticut (http://maps.coastalresilience.org/nyct/).

3 Results

3.1 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. Table 2 provides an overview of the waterline/flood extent representation by visual variable.

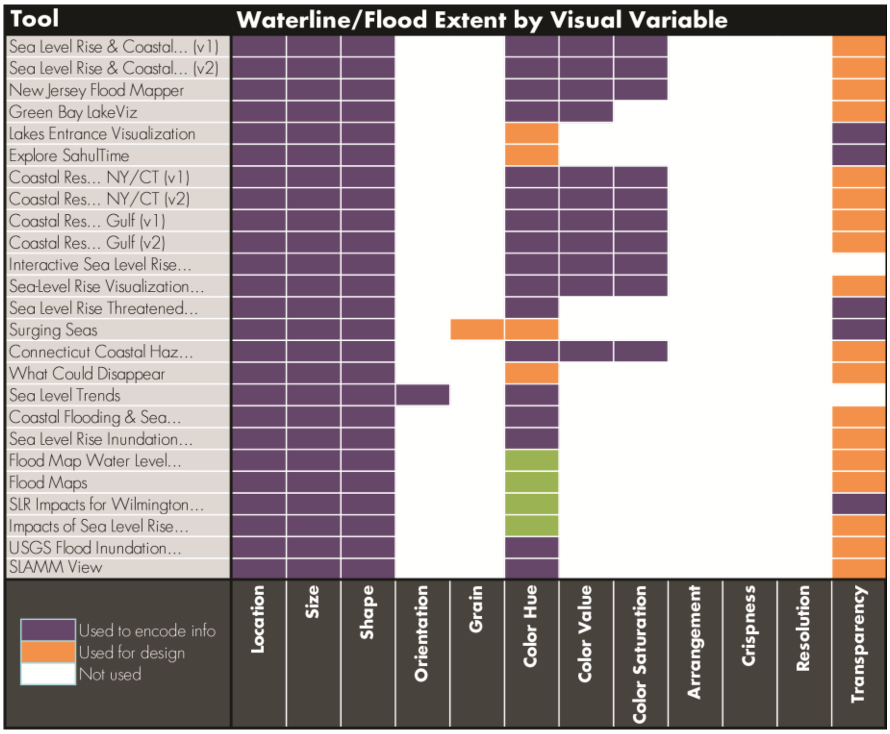

Table 2. Waterline/Flood Extent by Visual Variable.

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 ubiquitous use of size and shape to represent the flood extent suggests that existing tools highlight not the predicted position of the waterline, but the areas that will be flooded as a result of the shifting waterline. 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 is 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 semiotics, the use of value + 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, two unique representation solutions are worth noting. First, the Surging Seas visualization loads basemap layers of different detail for areas within the flood extent (satellite imagery) versus beyond the flood extent (a generalized vector map) (Figure 1b). This solution allows for impacted areas to be viewed in more detail without a flood symbol obfuscating the area of interest, a limitation of other tools. Unfortunately, this solution may not be as useful for representing a declining water level in the Great Lakes, as imagery is not available for areas currently inundated. Second, the Sea Level Trends tool makes use of the visual variable orientation to represent water level change at a small cartographic scale, with the amount of change represented redundantly using color hue and size (Figure 1c). The Lake Level Viewer may benefit from such an 'overview' (Shneiderman 1996), as land flooding or exposure on the Great Lakes is confined to a relatively small area along the coast that is viewable at large cartographic scales only.

3.2 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). Effective uncertainty representation is essential to the design of visualizations that support decision making (Agumya and Hunter 2002). In GIScience, information uncertainty is considered multifaceted, exhibiting at least three components: (1) *accuracy/error*, or the correctness of a measurement or estimate, (2) *precision/resolution*, or the exactness of a measurement or estimate, and (3) *trustworthiness*, or the 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).

Table 3 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).

Uncertainty Representation by Visual Variable

Tool	Location	Size	Shape	Orientation	Grain	Color Hue	Color Value	Color Saturation	Arrangement	Crispness	Resolution	Transparency
Sea Level Rise & Coastal… (v1)	Not used	Not used	Not used	Not used	Used for completeness	Used for confidence	Used for completeness	Not used	Not used	Not used	Not used	Not used
Sea Level Rise & Coastal… (v2)	Not used	Not used	Not used	Not used	Used for completeness	Used for confidence	Used for completeness	Not used	Not used	Not used	Not used	Not used
New Jersey Flood Mapper	Not used	Not used	Not used	Not used	Not used	Used for confidence	Not used	Not used	Not used	Not used	Not used	Not used
Green Bay LakeViz	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Lakes Entrance Visualization	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Explore SahulTime	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Coastal Res… NY/CT (v1)	Not used	Not used	Not used	Not used	Not used	Used for confidence	Used for confidence	Used for confidence	Not used	Not used	Not used	Not used
Coastal Res… NY/CT (v2)	Not used	Not used	Not used	Not used	Not used	Used for confidence	Used for confidence	Used for confidence	Not used	Not used	Not used	Not used
Coastal Res… Gulf (v1)	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Coastal Res… Gulf (v2)	Not used	Not used	Not used	Not used	Not used	Used for confidence	Not used	Not used	Not used	Not used	Not used	Not used
Interactive Sea Level Rise…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Sea-level Rise Visualization…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Sea Level Rise Threatened…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Surging Seas	Not used	Not used	Not used	Not used	Not used	Not used	Used for completeness	Not used	Not used	Not used	Not used	Not used
Connecticut Coastal Haz…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
What Could Disappear	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Sea Level Trends	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Coastal Flooding & Sea…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Sea Level Rise Inundation…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Flood Map Water Level…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Flood Maps	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
SLR Impacts for Wilmington…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
Impacts of Sea Level Rise…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
USGS Flood Inundation…	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty
SLAMM View	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty	No uncertainty

Used for completeness
Used for confidence
Not used
No uncertainty

Table 3. Uncertainty Representation by Visual Variable.

The NOAA Sea Level Viewer is the only visualization tool in the sample to represent two kinds of information uncertainty (Figure 1a). 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. The concept of confidence is defined in the Sea Level Rise Viewer as the "Level of certainty that a mapped [sea level rise] scenario is correct, taking into account topographic and tidal surface errors". This confidence metric will require revision for the Lake Level Viewer, as the seasonal processes of ice cover and snow melt on the Great Lakes influence water levels as much as tidal processes and storm events. Minimally, use of a blue color hue to represent 'confidence' requires reconsideration in order to encode uncertainty in both exposed and inundated land.

3.3 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.

Available Basemap Options

Tool	Street Map	Satellite Image	Hybrid Map/ Image	Topographic/ Terrain
Sea Level Rise & Coastal... (v1)	Basemap Option	Basemap Option	Not included	Basemap Option
Sea Level Rise & Coastal... (v2)	Basemap Option	Basemap Option	Not included	Basemap Option
New Jersey Flood Mapper	Basemap Option	Basemap Option	Not included	Basemap Option
Green Bay LakeViz	Not included	Basemap Option	Not included	Not included
Lakes Entrance Visualization	Not included	Basemap Option	Not included	Not included
Explore SahulTime	Not included	Basemap Option	Not included	Basemap Option
Coastal Res... NY/CT (v1)	Basemap Option	Basemap Option	Basemap Option	Basemap Option
Coastal Res... NY/CT (v2)	Basemap Option	Basemap Option	Not included	Basemap Option
Coastal Res... Gulf (v1)	Basemap Option	Basemap Option	Not included	Basemap Option
Coastal Res... Gulf (v2)	Basemap Option	Basemap Option	Not included	Basemap Option
Interactive Sea Level Rise...	Not included	Basemap Option	Not included	Basemap Option
Sea-Level Rise Visualization...	Basemap Option	Basemap Option	Not included	Basemap Option
Sea Level Rise Threatened...	Not included	Basemap Option	Not included	Not included
Surging Seas	Basemap Option	Basemap Option	Not included	Not included
Connecticut Coastal Haz...	Basemap Option	Basemap Option	Not included	Not included
What Could Disappear	Basemap Option	Not included	Not included	Not included
Sea Level Trends	Basemap Option	Basemap Option	Basemap Option	Basemap Option
Coastal Flooding & Sea...	Basemap Option	Basemap Option	Basemap Option	Basemap Option
Sea Level Rise Inundation...	Not included	Basemap Option	Basemap Option	Not included
Flood Map Water Level...	Basemap Option	Basemap Option	Basemap Option	Basemap Option
Flood Maps	Basemap Option	Basemap Option	Basemap Option	Basemap Option
SLR Impacts for Wilmington...	Basemap Option	Basemap Option	Basemap Option	Basemap Option
Impacts of Sea Level Rise...	Basemap Option	Basemap Option	Basemap Option	Basemap Option
USGS Flood Inundation...	Basemap Option	Basemap Option	Not included	Basemap Option
SLAMM View	Basemap Option	Basemap Option	Not included	Basemap Option

Basemap Option
Not included

Table 4. Available Basemap Options.

Table 4 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. 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.

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 1d). 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).

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.

3.4 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).

Table 5 provides an overview of the supported interaction operators (i.e., functionality) across the sample of visualization tools. 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 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.

Tool	Reexpress	Sequence	Overlay	Resymbolize	Zoom	Pan	Reproject	Search	Filter	Retrieve	Arrange	Calculate	Import	Export	Annotate	Edit	Save
Sea Level Rise & Coastal… (v1)			■		■	■			■	■				■			
Sea Level Rise & Coastal… (v2)			■		■	■			■	■				■			
New Jersey Flood Mapper			■		■	■			■	■				■			
Green Bay LakeViz			■						■	■							
Lakes Entrance Visualization			■		■	■			■	■		■					
Explore SahulTime			■		■	■			■	■		■					
Coastal Res… NY/CT (v1)			■	■	■	■		■	■	■	■	■		■			
Coastal Res… NY/CT (v2)			■	■	■	■		■	■	■		■		■			
Coastal Res… Gulf (v1)			■	■	■	■		■	■	■	■	■		■			
Coastal Res… Gulf (v2)			■	■	■	■		■	■	■		■		■			
Interactive Sea Level Rise…			■		■	■			■	■							
Sea-Level Rise Visualization…			■	■	■			■	■	■							
Sea Level Rise Threatened…			■		■	■		■		■				■			
Surging Seas			■		■	■		■	■	■		■		■			
Connecticut Coastal Haz…			■		■	■		■	■	■	■	■					
What Could Disappear			■						■			■		■			
Sea Level Trends					■	■				■				■			
Coastal Flooding & Sea…			■		■	■		■		■		■					
Sea Level Rise Inundation…			■		■	■		■	■	■				■			
Flood Map Water Level…			■		■	■		■	■	■				■			
Flood Maps			■		■	■			■					■			
SLR Impacts for Wilmington…			■		■	■			■	■							
Impacts of Sea Level Rise…			■	■	■	■								■			
USGS Flood Inundation…			■	■	■	■		■	■	■	■	■		■			
SLAMM View			■	■	■	■		■	■	■		■		■			

Supported
Not Supported

Table 5. Supported Interaction 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. 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 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 in 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 Table 5 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.

3.5 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.

Tool	ArcGIS Flex API	Flash	ArcGIS JavaScript API	Google Maps JavaScript API	Leaflet	OpenLayers	MetaCarta	Location Aware	Mobile Support
Sea Level Rise & Coastal... (v1)	■								
Sea Level Rise & Coastal... (v2)					■				■
New Jersey Flood Mapper	■								
Green Bay LakeViz		■							
Lakes Entrance Visualization		■							
Explore SahulTime		■							
Coastal Res... NY/CT (v1)			■	■					■
Coastal Res... NY/CT (v2)			■	■					■
Coastal Res... Gulf (v1)			■	■					■
Coastal Res... Gulf (v2)			■	■					■
Interactive Sea Level Rise...				■		■	■		■
Sea-Level Rise Visualization...			■						■
Sea Level Rise Threatened...				■					■
Surging Seas				■					■
Connecticut Coastal Haz...			■						■
What Could Disappear									■
Sea Level Trends				■					■
Coastal Flooding & Sea...				■					■
Sea Level Rise Inundation...			■						
Flood Map Water Level...				■				■	■
Flood Maps				■					■
SLR Impacts for Wilmington...	■								
Impacts of Sea Level Rise...				■					■
USGS Flood Inundation...	■								
SLAMM View				■					■

■ Leveraged Technology; (blank) Not Used

Table 6. Leveraged Web Mapping Technologies.

Table 6 provides an overview of the client-side web mapping technologies leveraged by the visualization tools included in the sample. 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, due to the pervasiveness of AJAX 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 (Table 6, final column). Redevelopment of the second version of the Sea Level Rise 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 MetaCarta. There is an emerging and active community of open source web map developers contributing their source code to the public commons for reuse. 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 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.

4 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.

Overall, we deem the competitive analysis as successful in meeting the project goals. First, we were able to identify and assess current practices in water level visualization, such as the use of a blue gradient in flood-centric representations, the inclusion of a common set of basemap and context options, the widespread support of the pan, zoom, overlay, retrieve, and filter interaction operators, and the general move away from web mapping technologies using proprietary plugins to those leveraging modern web standards. Second, we were able to identify unique solutions that potentially represent unmet user needs, including representation of exposed as well as flooded land, design of a flood representation that does not obfuscate the area of interest, provision of an informative overview at small cartographic scales, representation of multiple kinds of uncertainties, inclusion of meaningful and memorable benchmarks, and support of the reexpress, sequence, and annotate interaction operators. Finally, the competitive analysis helped to identify important gaps between theory and practice, namely the relative lack of uncertainty communication across the reviewed tools, the overall separation of tools designed to manage the build or human landscape from those designed to manage the natural or physical landscape, and the surprising implementation of filter rather than search for a public-facing visualization tool. Notably, the higher-level distinction between representation and interaction proved to be a useful way for coding the similarities and differences across the evaluated set of water level visualization tools; we anticipate that this distinction will be remain useful when completing a competitive analysis of visualization tools purposed for a different domain.

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.

Acknowledgments

The research was supported by the U.S. National Oceanic & Atmospheric Administration through Award #167152.

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