Design and Evaluation of Coastal Web Atlases: Best Practices and Future Opportunities for Map Representation, Interaction, and Usability

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ABSTRACT

In this article, we examine best practices and future opportunities for the design of coastal web atlases (CWAs) supporting adaptive management. Coastal zones face significant challenges, and CWAs have emerged as a resource to organize maps and geospatial data in support of education, exploration, and decision-making about coastal issues. Our research is motivated by the Wisconsin Coastal Atlas (https://www.wicoastalatlas.net/)—one of several U.S. state-based CWAs that are members of the broader International Coastal Atlas Network (ICAN: https://ican.iode.org/). Specifically, we conducted a needs assessment that bridges adaptive coastal management user needs with three tenets of interactive cartographic design relevant to CWAs: map representation, interaction, and usability. The needs assessment included two stages: a competitive analysis of 10 state CWAs and a user survey with stakeholders from those states about their experiences with and opinions on CWA design. In addition to characterizing design patterns and values, the needs assessment identified important gaps informing future CWAs, such as: inclusion of a wider range of thematic maps; provision of hybrid basemaps providing context about the land and water sides of the coastline; implementation of spatial calculations and temporal sequencing for analysis and exploration; use of story maps to support CWA learnability; improved responsiveness between mobile and non-mobile devices; and customization of advanced analytical tools that support decision making about the most pressing issues facing our coasts. This research serves coastal managers, planners, researchers, educators, outreach specialists, and related stakeholders who benefit from findable, accessible, interoperable, and reusable (FAIR) data and effective decision tools to guide management of coastal resources.

KEYWORDS

adaptive management; cartography; coastal web atlases; interactive maps; usability
Introduction

In this article, we examine best practices and future opportunities for the design of coastal web atlases (CWAs) supporting adaptive management. Coastal zones at the land-water interface support many types of ecosystems and activities that hold a range of aesthetic, economic, and environmental value (Ramesh et al. 2015). Yet, coastal zones face significant challenges, including storm flooding, bluff erosion, habitat loss, and pollution, among many others (Beatley, Brower, and Schwab 2002). Increased population density (Crowell et al. 2007) and climate change (Gronewold and Rood 2019) further exacerbate these pressures on our coasts. Adaptive management of dynamic coastal resources involves applying a structured, iterative process of decision-making under high levels of uncertainty, and, at its best, enables stakeholders from multiple perspectives to integrate multiple forms of knowledge in order to build shared understandings and collaborative actions (McLain and Lee 1996; Hart and Hamilton 2012).

Coastal zone dynamics are inherently spatial and coastal web atlases (CWAs) have emerged as a resource to organize maps and geospatial data in support of education, exploration, and decision-making about coastal issues (O’Dea et al. 2007; Dwyer and Wright 2008; Wright et al. 2008; Wright et al. 2010; Wright, Dwyer, and Cummins 2011; Dwyer et al. 2012; Dwyer and Kopke 2014; Kopke and Dwyer 2016). Our research is motivated by the Wisconsin Coastal Atlas (https://www.wicoastalatlas.net/)—one of several U.S. state-based CWAs that are members of the broader International Coastal Atlas Network (ICAN: https://ican.iode.org/)—with the Wisconsin Coastal Atlas focused on the Wisconsin coastlines along Lakes Michigan and Superior that are part of the Laurentian Great Lakes. The target audience is purposefully broad, with intended use by coastal resource managers, planners, researchers, educators, and outreach specialists. The Wisconsin Coastal Atlas was developed incrementally since 2010 through collaboration of the University of Wisconsin Sea Grant Institute, the UW–Madison Land Information and Computer Graphics Facility, the University of Wisconsin Cartography Lab and other campus partners, with specific modules informed by municipal, state, regional and federal government partnerships (Hart 2011; Hart 2014).

The Wisconsin Coastal Atlas includes four types of modules (Figure 1):

- **Maps**: exploratory interactive maps with customized data and representation solutions related to specific coastal issues in Wisconsin;
- **Tools**: spatial decision support tools relevant to coastal management on the Great Lakes;
- **Catalog**: data portals to discover, synthesize, and download geospatial data for the Great Lakes coasts of Wisconsin;
- **Learn**: place-based learning materials to promote a stronger understanding of our coasts for K-12 (primary and secondary school) and higher education as well as public awareness and outreach.

Beyond a functional resource, the Wisconsin Coastal Atlas serves as a case study for understanding how maps and geospatial data—and the associated principles of interactive and web cartography informing these maps and geospatial data—can be employed more effectively to support adaptive coastal management. Cartography
describes the art, ethics, science, and technology of mapmaking and map use, with interactive and web cartography extending print cartography to include new design opportunities associated with online and mobile technologies (International Cartographic Association 2003).

Specifically, we ask three research questions to understand and improve the cartographic design of CWAs:

1. What are the current best practices and unmet needs for cartographic representation in CWAs? *Representation* describes the graphic encoding of data, geospatial or otherwise, using symbols (MacEachren 1995).
2. What are the current best practices and unmet needs for interactive functionality in CWAs? *Interaction* describes the ways users can manipulate the map display to support their objectives (Roth 2013a).
3. How do target users value the relative usability and utility in CWAs? *Usability* describes the ease-of-using an interactive map or other tool while *utility* describes its usefulness or functional scope (e.g., the representation and interaction features combined), with usability and utility often in tension during design (Ooms and Skarlatidou 2018).

We conducted a two-stage needs assessment study to address our research questions. First, we completed a competitive analysis of 10 state coastal web atlases, comparing their functionality by representation and interaction techniques and making qualitative evaluations of their relative usability and utility. Next, we surveyed stakeholders from those states about their experience and opinions regarding each module type within their state’s coastal web atlas, with survey questions organized by representation, interaction, and usability/utility.

This research serves coastal managers, planners, researchers, outreach specialists, educators, and related stakeholders who benefit from findable, accessible,
interoperable, and reusable (FAIR) data (Wilkinson et al. 2016) and effective decision tools to guide management of coastal resources (Collini et al. 2022; Lathrop et al. 2012). Our work addresses technical issues relating to the use and management of coastal resources and proposes ideas for delivering timely geospatial information to guide coastal management. The needs assessment study bridges adaptive coastal management needs and cartographic design tenets, with the findings suggesting future opportunities for CWAs.

**Background: Coastal cartography**

The role of interactive and web cartography for adaptive coastal management continues to grow. Much related research employs and adapts geographic information systems (GIS), spatial analysis, and remote sensing to monitor, model, and predict coastal systems dynamics (e.g., Reina-Rodríguez and Soriano 2008; Basile Giannini et al. 2011; Ballesteros et al. 2007). However, Bannon et al. (2010) note that maps themselves are the primary mode for analyzing the dynamics of coastal systems. Today, maps are more than one-off, static outputs from a GIS, but instead serve as intuitive interfaces to voluminous geospatial databases and sophisticated data analytics (Andrienko et al. 2007). Accordingly, interactive web maps are a user-friendly “front-end” to otherwise “black-box” geocomputational algorithms, services, and technology found in spatial decision support tools, effectively scaling-up human reasoning capacity for diverse audiences to make sense of complex, interconnected coastal system dynamics while providing a collaborative platform to establish common ground in support of adaptive coastal management (Roth and MacEachren 2016).

In past work, we evaluated the efficacy of interactive web maps for one pressing adaptive coastal management issue: sea-level rise resulting from climate change (see Roth, Quinn, et al. 2015, Roth et al. 2017). Such water level visualizations depict the exposure or inundation of land as a result of historic and current storm events or future climate change predictions (e.g., Monmonier 2008; Kostelnick, McDermott, and Rowley 2009; Retchless 2014; Neset et al. 2016). We structured our analysis of existing water level visualizations based on functional recommendations for CWAs from O’Dea et al. (2007) and tenets of interactive and web cartography, resulting in three design dimensions: representation, interaction, and usability versus utility (Table 1). We scale this analysis to all CWA contexts in this article.

**Cartographic representation**

Arguably, mapping coastal zones is more difficult than the land or water themselves due to its diversity of map features and substantial elongation to the mapped extent (Monmonier 2008). Thus, novel and hybrid *representation* solutions are needed to account for this unique coastal mapping context (Research Question 1).

Two broad classes of maps are distinguished by their representation purpose: reference versus thematic. *Reference* maps represent the locations of many geographic phenomena at specific places while *thematic* maps represent the attributes of just one
or several geographic phenomena across space (Tyner 2014; Golebiowska, Korycka-Skorupa, and Slomska-Przech 2021). While this dichotomy is potentially useful when planning map design, most interactive web maps include some combination of reference and thematic layers. Here, the reference map often is described as a basemap or underlay, with additional reference or thematic layers described as overlays atop

| Code | Definition |
|------|------------|
| 1    | Map        | Exploratory interactive maps with customized data and representation solutions |
| 2    | Tool       | Spatial decision support tools |
| 3    | Catalog    | Data portals to discover, synthesize, and download geospatial data |
| 4    | Learn      | Place-based learning materials |
| 5    | Choropleth | Thematic maps shading enumerated units according to aggregated attribute values |
| 6    | Proportional Symbol | Thematic maps scaling symbols in proportion to the attribute value of either individual or enumerated information |
| 7    | Isoline/Surface | Thematic maps interpolating attribute values to create areas of uniform values |
| 8    | Dot Density | Thematic maps scaling dots in proportion to the attribute value |
| 9    | Flow       | Thematic maps representing relationships between places using linear, often graduated symbols |
| 10   | Point/Icon | Thematic maps using shapes and/or icons to denote point features |
| 11   | Street     | Basemaps displaying transportation routes and water features |
| 12   | Satellite  | Basemaps displaying remote sensing imagery |
| 13   | Hybrid     | Basemaps displaying play satellite imagery with boundaries, roads, and labels |
| 14   | Topographic | Basemaps displaying terrain and elevation data |
| 15   | Palette    | Basemaps displaying artistic, generalized information |
| 16   | Reexpress  | A change to the map type used in the visualization |
| 17   | Sequence   | A progression through an ordered set of maps with different information |
| 18   | Arrange    | A reorganization to the layout of views |
| 19   | Resymbolize | A change to the symbolization of the map without changing the map type |
| 20   | Search     | A query for a specific map feature or location of interest |
| 21   | Filter     | A refinement to the map to only include features that meet a set of conditions |
| 22   | Overlay    | An addition, removal, or reordering of layers |
| 23   | Retrieve   | A request for details about a map feature or location of interest |
| 24   | Calculate  | A computation of new information about a map feature |
| 25   | Pan        | A change to the center position of the map |
| 26   | Zoom       | A change to the scale of the map |
| 27   | Reproject  | A change to the map projection, including rotation |
| 28   | Import     | A upload of data to the visualization |
| 29   | Export     | A download of data from the visualization |
| 30   | Annotate   | An annotation to the visualization with text and sketches |
| 31   | Edit       | A change to the data in the map |
| 32   | Save       | A save of the visualization in its current state for later use |
| 33   | Share      | A share of the map in its current state |
| 34   | Utility    | The usefulness of the interface for a user to accomplish a task |
| 35   | Learnability | The speed a user can learn an interface without prior use |
| 36   | Memorability | The speed a user can learn an interface after a break |
| 37   | Efficiency | The speed a user can utilize the interface once learned to complete their task |
| 38   | Error Frequency | The number and severity of mistakes made with an interface |
these basemaps (Roth 2013b). Basemaps therefore provide contextual information about the mapped phenomena (Fish and Calvert 2017) of coastal systems dynamics and associated coastal management decisions.

Thematic map layers sit on top of the basemap to convey qualitative or quantitative attributes about specific phenomena of interest. Thematic maps can be applied to point, line, and area dimensionalities, and can depict either individual-level information (e.g., a single feature or observation) or enumerated information (e.g., the number of features or observations along a section of the coast or within a regulatory coastal zone). Further, thematic maps vary by visual variable, or the graphic dimension used to represent information (Bertin 1967). Examples of different visual variables include size (total area) versus shape (outer form) or color hue (e.g., red, green, blue) versus color value (light versus dark).

Finally, thematic maps vary in the visual metaphor they evoke about how the mapped phenomenon exists in space (discrete versus continuous) and varies across space (abrupt versus smooth) (MacEachren and DiBiase 1991). For instance, a visual metaphor of continuous and smooth suggests environmental or geophysical processes of the “natural” landscape while continuous but abrupt suggests the regulatory boundaries and infrastructure of the “built” landscape. A discrete metaphor in contrast often suggests the individual (smooth) or collective (abrupt) bodies or activities of humans or other wildlife species.

We evaluated six common thematic map types: choropleth, proportional symbol, isoline/surface, dot density, flow, and icon (Figure 2a–f). We then evaluated five common basemaps used in CW As to understand what contextual information is most useful and for what purposes: street, satellite, hybrid, topographic, and palette (Figure 2g–k). Table 2 provides additional information on how these thematic map types relate to each other by dimensionality, information type, visual variable, and visual metaphor.

**Cartographic interaction**

Digital media and pervasive computing have transformed fundamentally how maps are produced and consumed (Gartner, Bennett, and Morita 2007). Among the most revolutionary possibilities for cartography is user interaction with the map to request new representations as the need arises (Schnürer, Sieber, and Çöltekin 2015; Research Question 2). Accordingly, O’Dea et al. (2007) identify the digital interfaces that support such interaction as an essential component of CWAs.

The recommended amount of interaction, however, varies by user and use case (see MacEachren 1994 drawing on DiBiase 1990). Specialist users need complex interfaces to explore data in space, time, and attributes (e.g., through Map modules), as it is unknown which of many possible interactively-generated maps and diagrams may lead to new insights. Specialists then analyze patterns, trends, and anomalies through interactive statistical and computational calculations in support of decision making (e.g., through Tool modules specific to different coastal issues). Specialists then synthesize findings to triangulate explanations, potentially distributing data products and decision outcomes for diverse uses (e.g., through Catalog modules). Finally, specialists present
specific visual explanations and stories to a wider audience—the primary purpose of print cartography—with constrained interaction enabling users to customize the map to their locations and interests (e.g., through Learn modules).
The amount of interactivity is characterized in part by the implemented interaction operators, or generic functions provided to users to manipulate the map (Roth 2013b). Such operators are the building blocks of user interface design in a similar way that the visual variables are the building blocks of representation design. Accordingly, fewer operators should be implemented as the purpose shifts from exploration to analysis and synthesis and finally to presentation.

As with representation, there are two broad classes of operators: work and enabling. Work operators directly accomplish the user’s goal (e.g., explore, analyze, synthesize, present). Enabling operators are additional actions needed to prepare for, or clean up after, work operators, and thus should be limited wherever possible for efficiency (Davies 1998). Work operators are further subdivided by those that change the representation (reexpress, sequence, resymbolize, arrange), the map content (search, filter, overlay, retrieve, calculate), or the user’s viewpoint of the mapped content (pan, zoom, reproject). Enabling operators supporting this work include import, export, annotate, edit, save, and share.
We evaluated these twelve work operators and six enabling operators (Figure 3). Table 1 provides specific definitions of each operator.

**Usability and utility**

While representation and interaction defines the design space for CWAs, it is not advisable to implement all possible options in a CWA module, even ones supporting exploration (Nyerges et al. 2011; Kopke and Dwyer 2016). The actual scope of a given module depends on its purpose and the associated needs of the target audience (Robinson et al. 2005). Accordingly, navigating CWA design requires careful balance of usability and utility (Research Question 3).

Usability and utility often are in tension during design and development, with a more usable module resulting in a less powerful resource for adaptive coastal management, but potentially having broader user appeal, and a more useful module being more powerful for complex decision making, but also less intuitive possibly limiting the potential audience (Grinstein et al. 2003). **Utility** describes the usefulness of a module, and while there are intangible dimensions influencing the total value of a tool, utility often is collapsed with the *functional scope* of a tool across representation and interaction (i.e., how many map representations and interactions are available; see Roth 2013a).

In contrast, **usability** describes the ease-of-using a tool, and captures a range of nonfunctional considerations for improving the user experience with the implemented functionality in a CWA. O’Dea et al. (2007 p. 33) state that “the design and usability of an atlas are keys to its success.” Usability includes a module’s immediate learnability, its memorability over multiple uses, its efficiency once learned, the error frequency

*Figure 3.* Common interaction operators in web cartography taken from the University of Wisconsin-Madison, Space Science and Engineering Center’s Real Earth™ Application (https://realearth.ssec.wisc.edu/).
and severity during use, and the overall subjective satisfaction during use (Nielsen 1994). These measures of usability have been adopted and formalized through the Usability.gov website guiding best practices for web design, and have gained increased traction for the design of web atlases specifically (see Pucher 2015).

We evaluated trends in and opinions on the relative tradeoff between utility and usability by type of CWA module. Notably, a modular approach allows different components of a CWA to have differential usability/utility tradeoffs based on purpose and user needs.

**Method description**

**Competitive analysis**

We first performed a competitive analysis on 10 US-based coastal web atlases by their representation, interaction, and usability/utility. A competitive analysis is a usability engineering method that critically compares a group of applications designed for a similar purpose, such as CWAs, by their constituent functionality and relative merits (Nielsen 1992). Accordingly, a competitive analysis establishes a benchmark for current design practices, identifying common solutions and functional gaps that suggest future opportunities (see Roth, Quinn, et al. 2015 for our competitive analysis of water level visualizations).

We narrowed our sample to 10 CWAs from a candidate population of 25 state CWAs using three criteria. First, the CWA needed to conform to the official ICAN definition of a CWA, with several branded state CWAs either relying primarily on static maps or containing no maps at all. Second, the CWAs needed to run on modern web browsers without additional software plugins so that we could review functionality to the fullest extent. Finally, the CWAs needed to focus on the ocean or Great Lakes coasts, where U.S. coastal management programs have jurisdiction.

We then assessed 127 modules from the 10 sampled CWAs. We defined a CWA module as any webpage linked or searchable from the CWA homepage that included at least one supporting interactive map. We included modules created by external organizations as long as the module was referenced within the CWA domain. We then organized the 127 modules by Map, Tool, Catalog, and Learn modules. Our final sample included 59 Map, 52 Tool, 2 Catalog, and 14 Learn modules (Figure 4).

We developed our initial coding scheme based on the CWA recommendations from O’Dea et al. (2007) and tenets of interactive and web cartography. We set functional codes (representation and interaction) as binary presence/absence, with a module receiving the code if the feature was implemented at least once. We used a five-point scale to assess utility and usability ordinally following formal definitions from Usability.gov and Pucher’s (2015) interpretation of these concepts for atlas design. We did not attempt to rate subject satisfaction (a measure of usability), or employ traditional task-based performance metrics on utility and usability (e.g., GOMS or Goals, Operators, Methods, Selection rules after Card, Moran, and Newell 1983, NASA TLX or Task Load Index after Hart and Staveland 1988), because we intentionally did not attempt to access actual CWA users during the competitive analysis, instead pairing user input through the subsequent user survey after completing the broad analysis
of existing CWAs. Notably, ordinal rating on a five-point scale does still include coder subjectivity, and therefore utility and usability scores are best interpreted as relative rankings.

One coder applied the initial coding scheme on 10% of the sample, with the three-person project team then reviewing this pilot coding to refine definitions and add additional codes. Our final coding scheme contained 39 codes (Table 1). The coder then evaluated the remainder of the sample June–July 2019, using biweekly project team meetings to review coding.

**User survey**

We then surveyed 77 target users and developers of CWAs to capture their experiences with and opinions on their state’s CWAs. While the competitive analysis serves as a benchmark for current practices, the survey provided additional insight into the processes, bottlenecks, and gaps in CWA design to identify unmet user needs (see Collini et al. 2022 for a similar approach mostly outside of cartography and geospatial information).

Our sample of 77 participants was drawn from a candidate population of 359 individuals, resulting in a 22.3% response rate. We received 125 total responses and excluded 48 that did not complete more than 80% of the survey.
Survey participants had on average 13 years of experience, with the median experience of 17 years. Most participants described themselves as people who use but not develop geospatial data and web maps for coastal planning (Figure 5). Only four participants indicated they have never used a CWA, with 72.7% using a CWA at least monthly.

We organized survey questions into five categories. A first set covered demographics and background experience with CWAs (summarized above). The second set captured use of data for different coastal issues, giving us important context about user needs we could not infer from the competitive analysis. The remaining sets of questions captured experience with and opinions on representation, interaction, and usability/utility, affording analysis of gaps and opportunities between current design practices and unmet user needs. We provided text definitions for representation, interaction, and usability/utility concepts that may not be familiar to participants, and provided static graphics for representation questions and animated gifs for interaction questions to provide a visual example (see Figure 6 for an example). The survey was administered online using Qualtrics and took approximately 25 minutes to complete. The complete survey is provided in the Supplemental Materials.

To capture relative experiences and opinions, we included two kinds of rating scales for the module-specific questions. We used a five-point rating scale for questions on experience (e.g., “How often do you work on...”): daily, weekly, monthly, rarely, never. We used a seven-point rating scale for questions on opinion (e.g., How important are...”): “1” not important, “4” neither important or unimportant, and “7” essential. We did not perform inferential statistics given the goal of characterizing broad needs rather than testing for controlled differences.

Results and discussion

Competitive analysis

Representation

Figure 7 presents results of the representation coding from the competitive analysis, delineated by thematic maps versus basemaps. Icon maps were the most common thematic map type in the sample, found in 87.4% of all modules. Icon maps encode qualitative information with detailed symbol shapes (i.e., icons) that closely resemble

Figure 5. Areas of expertise self-reported by the survey participants. Size and shading are used redundantly.
the feature or observation they represent (see Bell 2020 for an overview). Accordingly, icon maps are useful for general audiences given their relatively intuitive symbolization and more immediately learnability. Icon maps also are among the most straightforward thematic map to implement and share on the web, an important consideration for developing and maintaining CWAs.

However, a focus on icon maps in the sample over other thematic mapping techniques suggests several gaps and future opportunities for CWAs. First, all icons suffer from
variation in cross-cultural and cross-domain meanings (Kelly 2021), and thus easily lead to incorrect understandings. Second, the icon maps we surveyed primarily referenced the location of individual-level information, with relatively few thematic examples encoding higher-level categories or quantitative attributes through the symbol size, frame shape, or icon color (see Nelson et al. 1997). Nearly all icon maps in the sample using a simple geometric symbol (e.g., a circle or teardrop marker) can better support adaptive management if they employed an additional visual variable to encode an attribute or timestamp. Finally, icon maps suffer from visual clutter and symbol overlap as the number of icons grows, inhibiting interpretation and reasoning (Poorthuis 2018). Other thematic maps provide a visual overview of the dataset to inform interactive drill-down into specific features or observations (after Shneiderman 2003), and thus are recommended for scalability when icon maps contain large point datasets or default to regional scales.

Isoline/surface (58.3%) and choropleth maps (38.6%) were relatively common in the sample. Isoline (lines only) and surface (shaded areas between lines; sometimes called “heat maps”) are appropriate for smoothly changing environmental or geophysical phenomena, and were used to represent land elevation, water bathymetry, temperature, rainfall, and water quality. Isoline/surface maps were used more frequently in Tool modules (found in 73.1% of Tools) rather than Map modules (only 49.2%), perhaps because isoline/surface maps provide important coastal context for environmental decisions.

In contrast, choropleth maps are appropriate for abruptly changing regulatory boundaries and infrastructure, and were used to represent sociodemographic data, hazard

| Coastal Web Atlas               | Supported Representation by Map Type |
|--------------------------------|--------------------------------------|
| Indiana Lake Michigan           | 85.7% 42.9% 28.6% 0.0% 28.6% 28.6% 71.4% 71.4% 57.1% 57.1% 0.0% |
| Maryland Coastal Atlas          | 90.9% 72.7% 27.3% 9.1% 0.0% 18.2% 90.9% 54.5% 45.5% 54.5% 27.3% |
| New Jersey Coastal Atlas        | 75.0% 70.0% 50.0% 10.0% 5.0% 0.0% 90.0% 80.0% 75.0% 70.0% 10.0% |
| New York Geographic Atlas       | 100.0% 100.0% 80.0% 0.0% 0.0% 0.0% 80.0% 80.0% 80.0% 100.0% 70.0% |
| Ohio Coastal Atlas              | 94.4% 44.4% 22.2% 22.2% 5.6% 0.0% 77.8% 77.8% 61.1% 44.4% 0.0% |
| Oregon Coastal Atlas            | 87.5% 62.5% 37.5% 31.2% 0.0% 0.0% 81.2% 75.0% 43.8% 68.8% 12.5% |
| Texas Coastal Atlas             | 100.0% 83.3% 33.3% 33.3% 0.0% 16.7% 83.3% 66.7% 83.3% 66.7% 16.7% |
| Virginia Coastal GEMS           | 100.0% 100.0% 100.0% 0.0% 0.0% 0.0% 100.0% 100.0% 100.0% 100.0% 0.0% |
| Washington State Coa...          | 80.0% 40.0% 70.0% 10.0% 0.0% 0.0% 100.0% 50.0% 60.0% 30.0% 0.0% |
| Wisconsin Coastal Atlas         | 85.2% 37.0% 18.5% 7.4% 3.7% 0.0% 48.1% 85.2% 33.3% 37.0% 14.8% |
| Overall Across Atlases           | 87.4% 58.3% 38.6% 13.4% 3.9% 3.9% 77.2% 74.8% 56.7% 56.7% 15.0% |

Figure 7. The percent of state coastal atlases’ modules supporting map types.
vulnerability scores, housing density, site suitability scores, and land use/cover, among others. While sociodemographic data can be mapped with a discrete representation (e.g., a dot density map), the preference toward choropleth maps makes sense for adaptive coastal management given the implications of management and policy decisions are at governmental units (e.g., municipalities, protected areas) versus individual households. Accordingly, both isoline/surface and choropleth are appropriate enumerated overviews for overplotted icon maps, with isoline/surface used for aspects of the “natural” landscape and choropleth for the “built” landscape.

Notably, all surface and choropleth maps were implemented using the Web Mercator projection that distorts area and thus the relative amounts of color onscreen (Sack 2017), a common problem with conventional web mapping technology. Further, surface and choropleth maps rely on the visual variables associated with color, which requires greater symbol coordination with the selected basemap, especially when transparency is used to blend the thematic layers with the basemap.

Flow (13.4%), dot density (3.9%), and proportional symbol (3.9%; N/127) maps were rarely implemented. The infrequent use of flow maps, the primary thematic map using line symbols, is surprising given the coast often is conceptualized as a line. While focusing on the “coastal zone” means point and area features are more common in CWAs, flow maps can provide a useful overview when zoomed out to regional scales, using the size or color of the line to represent an attribute or timestamp of individual sections of the coast. Other potential uses of flow maps include symbolizing the magnitude of flow from onshore rivers during flooding and qualitatively visualizing the processes of wave action and bluff erosion for learning materials. However, these additional flow map solutions remain a technical challenge, a barrier to wider use (see Jenny et al. 2018).

Proportional symbol maps were limited in CWAs, but could be applied for representing specific monitoring stations and field observations instead of coastal dynamics (i.e., to think about the data source for unique anomalies and error checking instead of the processes measured by the data). Dot density maps were restricted to species distribution maps and demographic data. The relative use of isoline/surface and choropleth over dot density and proportional symbol maps suggests an emphasis of conceptually continuous versus discrete phenomena in adaptive coastal management (MacEachren and DiBiase 1991), a potentially important consideration for decision support given an analytical focus on geographic phenomena and processes versus the typically point-based samples acting as proxy for these phenomena and processes.

Underlying the thematic layers almost always were satellite (76%) or street (74%) basemaps. Satellite and street basemaps provide rich information of the land-side of the coast, but much less information about depth and features on the water-side. Less frequent topographic (56.7%) and especially hybrid (15.0%) basemaps supply richer context on both sides of the land-water coastline.

Interaction

Figure 8 presents results of the interaction coding, delineated by work versus enabling operators. The most common work operators were zoom (96.1%), pan (94.5%), retrieve (89.0%), and overlay (74.0%), the four operators most commonly associated with web cartography. Such pannable and zoomable web maps support the experience of a “map
of everywhere”, with the addition of retrievable vector overlays supplementing the experience of a “map of everything”. On one hand, the ubiquity of these operators may suggest that design is being driven by technological convention rather than user needs, as most web mapping libraries natively support zoom, pan, retrieve, and overlay. On the other hand, these operators, and in particular panning and zooming, are essential for navigating the thin, elongated mapping context of coastlines and therefore should be more common in CWAs than other web atlases.

Search (62.2%) and filter (52.8%) also were implemented in a majority of the evaluated modules. Search presents features known to be of interest, acting like a shortcut through the interface to find specific information. Filter is part of a broader exploratory process of first working from an overview of all information, then filtering and zooming to delimit the information under consideration, and finally retrieving of potentially unknown details to learn something new about the depicted geographic patterns and processes (Shneiderman 2003). Accordingly, search is recommended for general education and outreach and filter for specialist adaptive management and decision-making (MacEachren 1994), suggesting a need to tailor some operators to the purpose of the module. Filter was more common in the specialist-driven Tool modules (79.0%) compared to others (34.7%), but search was implemented more evenly across modules (71.2% for Tools versus 56.0% for others), with search availability driven by state-specific technology stacks.

The majority of resymbolize (37.8%) implementations were limited to adjusting the transparency of overlays, a default function in Esri-based web map products; additional changes to the color scheme, scaling ratio, and (especially) classification scheme could support more advanced exploration and analysis. Interestingly, calculate (30.7%) was implemented in more Map (37.3%) than Tool (32.7%) modules while sequence (29.9%)

| Coastal Web Atlas                  | Supported Interaction by Operator                                                                 |
|------------------------------------|--------------------------------------------------------------------------------------------------|
| Indiana Lake Michigan...           | ![Table](table.png)                                                                                |
| Maryland Coastal Atlas             | ![Table](table.png)                                                                                |
| New Jersey Coastal Atlas           | ![Table](table.png)                                                                                |
| New York Geographic...             | ![Table](table.png)                                                                                |
| Ohio Coastal Atlas                 | ![Table](table.png)                                                                                |
| Oregon Coastal Atlas               | ![Table](table.png)                                                                                |
| Texas Coastal Atlas                | ![Table](table.png)                                                                                |
| Virginia Coastal GEMS              | ![Table](table.png)                                                                                |
| Washington State Coa...            | ![Table](table.png)                                                                                |
| Wisconsin Coastal Atlas            | ![Table](table.png)                                                                                |
| Overall Across Atlases             | ![Table](table.png)                                                                                |

**Figure 8.** The percent of state coastal atlases’ modules supporting interaction operators.
in more Tool (46.2%) than Map (22.0%) modules. This is counterintuitive given the differential goals of the modules. In particular, there is an opportunity to separate calculate operators from the central Map modules into supporting Tool modules to avoid overly complex Map modules while still supporting specific coastal issues. Other work operators were implemented infrequently, with the lack of arrange (5.5%) and reexpress (0.8%) suggesting unrealized design opportunities for coordinated multiview visualization of maps and diagrams (Kastens et al. 2009) and the underutilization of reproject (5.5%) identifying a key design gap in CWAs for overcoming known limitations of the Web Mercator projection for thematic mapping.

The CWAs implemented fewer enabling than work operators following interaction design recommendations (Davies 1998). The most common enabling operators were share (56.7%) and export (44.9%), two operators that support multi-stakeholder collaboration and decision-making important to adaptive management. The less common annotate operator could further support collaboration, particularly for group decision making, but was implemented in only 23.6% of all modules and only 17.3% of Tool modules. Notably, the scarcity of the edit operator (3.1%) suggests that most CWAs have a “data silo” mentality emphasizing control over internally datasets. Incorporating citizen science and volunteered geographic information in CWAs could be the next step to facilitate greater community engagement (Cigliano and Ballard 2017; Kelly et al. 2020).

**Usability and utility**

Figure 9 presents the average utility and usability scores across all state CWA modules. The evaluated CWAs scored highest on efficiency (mean = 3.6; median = 4.0) and utility (mean = 3.3; median = 4.0), a combination suggesting emphasis on specialist over general users and work productivity on data-driven adaptive management tasks over broader education and outreach.

Memorability (mean = 2.9; median = 3.0), learnability (mean = 3.1; median = 3.0), and error rate/severity (mean = 3.1; median = 3) scored relatively lower than efficiency and utility, although remained near the neutral midpoint across CWAs. The majority of evaluated modules used proprietary web mapping technology (Figure 10). Esri-based modules (66.1%) tended to have slightly improved learnability (mean = 4.0; median = 3.6) and memorability (mean = 3.4; median = 3.0) given the pervasiveness across modules and consistent design and layout, an indication that technology stack and not user needs is driving some CWA design conventions. While open source technologies offer a customizable range of representation and interaction solutions, they should be coupled with supporting documentation to ensure they are learnable and memorable for different coastal issues. Error rate and severity primarily was tied to the age of the technology, with 30.7% of the modules unavailable or substantially compromised when viewed on mobile devices.

**User survey**

**Use and user context**

Participants reported working on a variety of coastal issues (Figure 11), with the majority of participants working on flooding (72.8%), climate change (61.9%), erosion (59.3%),
sea level rise (56.5%), habitat loss (55.2%), restoration (53.3%), and water quality (53.2%) at least monthly. The diversity in coastal issues again reinforces a modular design to CWAs, as a one-size-fits-all approach inevitably serves some user needs better than others. However, most participants worked on multiple issues simultaneously and thus benefit from consistency across modules and intuitive navigation among modules. The majority of participants rarely or never work on pollution (67.8%) and marine traffic (80.6%), suggesting commercial use cases were less common in our sample than regulation and planning, yet still require some intermittent CWA support. Additional coastal issues mentioned by a pair of participants in the free response included land use, public access, and tsunami hazards.

Figure 12 lists geospatial datasets that participants used to address coastal issues. The majority of participants used imagery (56.5%), built environment (55.3%), and boundary (52.6%) datasets at least weekly. These datasets typically are provided as “satellite” or “street” basemaps, justifying the common inclusion of these two basemap options and the overlay (or underlay) operator in the competitive analysis. The majority of participants used physical environment (75.0%), land use/land cover (72.4%), and hazards (67.1%) datasets at least monthly. As these data layers describe environmental or geophysical phenomena, they commonly are represented as isoline/surface maps, explaining the relatively high inclusion of isoline/surface maps in the competitive analysis. While these data layers may be loaded as vector overlays, they

Figure 9. The usability and utility of state coastal atlases’ modules.
also can be processed as a unique basemap tileset to improve loading and interaction, such as the topographic and hybrid alternatives suggested above.

The majority of participants used the other assessed datasets rarely or never. These remaining layers commonly are loaded as retrievable vector overlays, and thus may be relevant only to specific coastal issues and CWA modules. Low use of points of interest and observation stations belies the pervasiveness of icon maps found in the competitive analysis, and possibly indicates that many participants use icon maps for their basemap and not the icon overlays. Some hazards can be symbolized as point icons, one explanation for icon maps, although this was uncommon in our competitive analysis. Low use of society datasets (e.g., population demographics, economic vulnerability) also suggests why choropleth maps were less common than isoline/surface in the competitive analysis. No additional datasets were identified by two or more participants in the free response.

Figure 10. State coastal atlases' modules by type supporting technology stacks.

Figure 11. How often do you work on the following coastal issue(s)?
Figure 13 presents the frequency participants worked with different types of data, suggesting opportunities for coordinating maps with other types of visualizations. Almost half (50.0%) of participants worked daily with spatial data, stressing the importance of maps and geographic thinking to adaptive coastal management. The majority of participants worked with photos (85.1%), illustrations (63.5%), and text (63.2%) at least monthly, pointing to a possible need for more qualitative visualizations, especially in the Learn modules. While most participants worked with temporal data at least monthly (57.9%), this relatively low use was surprising given most coastal issues require long-term strategic planning. Including the sequence operator in more Map modules may be one way to harness spatiotemporal analysis for adaptive coastal management. Most participants rarely or never worked with more complex multivariate (63.2%) and...
3D (53.4%) data, perhaps because far fewer relevant and local-scale multivariate and 3D datasets exist.

Not all currently available CWA modules are used equally (Figure 14). Participants currently rely most on Map modules, with over half (54.6%) using a Map module at least weekly. Catalog and Learn modules appear to fill more niche use cases, but the majority of participants still used these modules at least monthly (59.7% and 63.2% respectively). Tool modules were least utilized, with most participants rarely or never using a Tool (54.6%). Tools typically support complex and domain-specific analyses, and thus any given tool may have a narrower audience compared to the other modules. However, general lack of uptake of any Tool module is concerning given the sample of expert coastal managers, and suggests that perhaps the right tools are not being provided by CWAs or these Tools are not discriminated enough in their utility from other modules, especially Maps.

**Figure 14.** How often do you use the following kinds of coastal web atlas modules?

| How often do you use: | Frequency |
|-----------------------|-----------|
| Maps                  |           |
| Catalogs              | 2.6%      |
| Learn                 | 7.8%      |
| Tools                 | 3.9%      |
| Daily                 | 26.0%     |
| Weekly                | 28.6%     |
| Monthly               | 28.6%     |
| Rarely                | 14.3%     |
| Never                 | 2.6%      |

**Representation**

Figure 15 presents participant values regarding thematic maps for adaptive coastal management. Participants rated icon maps as the most important (mean = 5.5; median = 6.0), perhaps due to their pervasiveness as reported in the competitive analysis. While potentially less useful compared to alternatives, icon maps are a common and preferred thematic map type and thus serve as a baseline entry point within which additional thematic layers and interactions are added.

Participants rated choropleth (mean = 5.3; median = 5.0), dot density (mean = 5.2; median = 5.0), isoline/surface (mean = 5.1; median = 5.0), and proportional symbol maps (mean = 5.0; median 5.0) near evenly in their importance, despite isoline/surface being more common in the competitive analysis (Figure 6) and participants working more frequently with environmental/geophysical than social/economic data layers (Figure 12). Flow maps were viewed as the least important (mean = 4.5; median = 5.0), matching infrequent use in the competitive analysis.

The disconnect between current CWA representation strategies and participant values highlights a potential design opportunity, as the right choropleth, dot density, or proportional symbol map can be as useful or more so than isoline/surface for supporting adaptive coastal management. However, the utility of a choropleth, dot density, or proportional symbol map appears tied to specific coastal issues compared to isoline/surface maps often used as basemap context. Thus, these alternative thematic maps may be best purposed for special-case Tool modules or (for choropleth and proportional symbol) as a visual overview in overplotting icon maps.
Further, choropleth maps may be more useful when the data are aggregated to the regulatory boundaries most relevant to the given coastal issue, given their continuous and abrupt metaphor. The reexpress operator, implemented infrequently in the competitive analysis, also could support flexible reaggregation for choropleth maps across a variety of regulatory boundaries as well switching among different thematic map types.

Figure 15 complements Figure 15 with participant values about basemap options. Overall, participants rated basemaps (mean = 5.3; median = 6.0) as more important than thematic maps (mean = 4.9; median = 5.0), an unexpected finding given the utility of thematic maps for exploratory and analytical use cases supporting adaptive coastal

**Figure 15.** How important are the following thematic maps to the success of interactive maps in coastal web atlases?
management. Notably, participants prioritized hybrid basemaps (mean = 6.2; median = 6.0) above satellite (mean = 6.0; median = 6.0), street (mean = 5.7; median = 6.0), and topographic (mean = 5.6; median = 6.0) basemaps, despite hybrid basemaps being available in only 15.0% of surveyed modules in the competitive analysis. While hybrid may be the preferred basemap default, participants reported value in underlay of a range of basemaps to flexibly move between the land and water sides of the coastline.

**Interaction**

Figure 17 presents participant values on work operators for adaptive coastal management. Zoom (mean = 6.6), pan (mean = 6.5), overlay (mean = 6.4), and retrieve (mean = 6.3) were rated as essential by participants (all receiving a median of 7.0), mirroring patterns in the competitive analysis. Together, the competitive analysis and user survey
indicate that users want and even expect a baseline set of interactions conventional to web cartography. Notably, these four operators were rated as more important than any thematic map or basemap—and were among the highest rated features across the user survey—confirming the importance of treating interaction as an equal complement to representation during CWA design.

Participants also rated both search (mean = 6.2; median = 6.0) and filter (mean = 5.8; median = 6.0) as important, although responses were more variable for filter across the seven point scale. Because 79.9% of existing filter controls are implemented in Tools modules (see above), this variability corroborates patterns in Figure 14 suggesting that there is a subset of participants who never use Tool modules and thus infrequently encounter useful filter controls. However the general positive rating for filter gives preliminary evidence that filter is perceived as valuable, and thus a design gap exists to include filter in more exploratory CWA modules (e.g., Map modules).

Interestingly, calculate (mean = 5.5) and sequence (mean = 5.4) were rated nearly as important as search and filter (all four operators receiving a median rating of 6.0), but were found less frequently in the competitive analysis (only 30.7% and 29.9% for

**Figure 17.** How important are the following interactive functions (work operators) to the success of interactive maps in coastal web atlases?
calculate and sequence versus 62.2% and 52.8% for search and filter). Accordingly, calculate and sequence are evident gaps between current tools and user needs, with targeted effort needed to expand these operators in Tool and Map modules, respectively.

All remaining work operators received a mean rating of 5.0, suggesting some perceived value albeit relatively less to other work operators. However, only resymbolize (37.8% of current CWAs) was implemented in more than 5.5% of surveyed CWAs (and resymbolize primarily was provided only as a transparency control), and therefore should be more commonly considered for their niche use cases.

Figure 18 complements Figure 17 with participant values about enabling operators. Overall, participants valued enabling operators (mean = 5.1; median = 5.0) less than work operators (mean = 5.5; median = 6.0), which again reflects interaction design recommendations (Davies 1998). Export (mean = 6.1; median = 6.0) and share (mean = 5.6; median = 6.0) were notable exceptions enabling collaboration, mirroring the competitive analysis (implemented in 44.9% and 56.7% of existing tools, respectively). The slight inversion in export and share between the competitive analysis and user survey, while subtle, suggests a current user preference for desktop versus online workflows, a preference that could shift as adaptive coastal management moves to the cloud.

Usability and utility

Figure 19 presents participants values about usability and utility. Participants prioritized utility (mean = 6.5; median = 7.0) over usability (mean = 5.9; median = 6.0 across metrics), reflecting a specialist user profile needing more complex CWAs to support their work. Thus, CWA modules—particularly those supporting exploratory and analytical use cases—generally should err on the side of more interaction operators to enhance utility.

Participants still rated usability highly (all metics having a median = 6.0). Learnability (mean = 6.2) was valued as the most valuable usability measure, notably given the marginal learnability and memorability of existing CWAs found in the competitive analysis (Figure 9). Thus, while the emphasis is on utility, greater effort is needed to create learning materials that demonstrate how users can integrate complex CWAs modules into their workflows. Comparatively, efficiency (mean = 6.1) was better supported in surveyed CWAs with error rate and severity (mean = 6.0) again tied to the age of technology.

Follow-up survey questions on each usability measure identified opportunities for improving learnability through design of learning materials (Figure 20). Participants preferred story maps (mean = 5.7; median = 6.0) and stories (mean = 5.3; median = 6.0) to alternative learning materials. Story maps present real-world case studies of adaptive coastal management in a relatable linear narrative (e.g., Silbernagel et al. 2015), and thus can support both outreach and education as well as problem-based learning about specific CWA datasets and functionality. Other follow-up questions about usability did not result in actionable feedback.

The user survey also allowed us to collect feedback on additional nonfunctional requirements beyond usability made possible by the dynamic web platform (Figure 21). Participants rated interactivity as the most important dynamic consideration (mean =
Participants also rated scalability (mean = 6.2; median = 6.0), multiscale (mean = 6.0; median = 6.0), responsive (mean = 5.9; median = 6.0) as important. Priorities for scalability and multiscale are reflected in the ubiquity of zoom, pan, retrieve, and overlay operators found in the competitive analysis. However, the high rating of responsive design between mobile and non-mobile devices is a notable gap for CWAs given that almost a third (30.7%) of surveyed modules were unavailable or substantially compromised when viewed on mobile devices. The relative rating between responsive
and mobile-first (mean = 5.2; median = 5.0) or location-aware (mean = 5.1; median = 5.0) design suggests that most work with CWAs is completed on non-mobile devices but the option to view on a mobile device in some contexts is preferable.

Figure 21 on CWAs largely is consistent with a previous research on nonfunctional requirements for web maps (see Roth et al. 2015)—with a few exceptions such as reduced rating of design aesthetics for CWAs and increased rating of adaptability—possibly suggesting coalescence around persistent nonfunctional design considerations across interactive web maps.

Finally, Figure 22 presents participant values across CWA modules. Participants rated Map modules as most important (mean = 6.1; median = 6.0), mirroring their reported use (Figure 14) and values on interactivity (Figure 21). Participants valued Catalog modules (mean = 5.7; median = 6.0) slightly more than Learn modules (mean = 5.3; median = 6.0), despite using Learn modules more frequently, again pointing to a need for improving learnability such as story maps.

Figure 19. How important are the following practical considerations to the success of coastal web atlases?
Tool modules again lagged behind in participant ratings. While on average participants viewed Tool modules as more valuable than not (mean = 5.0; median = 5.0), opinions ranged across the seven-point scale, again suggesting a subset of participants did not find utility in Tool modules.

There are a number of potential explanations for this variability, such as increased investment in learning more complex and analytical Tool modules, decreased guidance in how to include Tool modules into collaborative decision-making workflows, and relative advantages of desktop GIS software over CWAs for analysis. However, participant feedback suggested that the primary bottleneck is that available Tool modules simply do not support the most common coastal issues for adaptive coastal management. The gap in available Tool modules was particularly prominent for restoration, climate change, sea level rise, and flooding (Figure 23). Taken together, future research and design is needed to identify the right “Toolkit” to support the diverse range of adaptive coastal management problems and contexts. The design of all modules can benefit from greater clarity in their purpose.

Figure 20. How important are the following kinds of learning materials for users of coastal web atlases?
Figure 21. How important are the following dynamic capabilities to the success of coastal web atlases?

Figure 22. How important are the following modules to the success of a coastal web atlas?
Conclusion and outlook: Transferable design insights for CWAs

We conducted a two-stage needs assessment to understand best practices and future opportunities for the design of coastal web atlas (CWAs): a competitive analysis of 10 state CWAs and user survey with stakeholders from those states about their experiences with and opinions on CWA design. Notably, the two-stage study on CWAs bridged adaptive coastal management and cartographic design, and we summarize major findings by our three organizing research questions drawing from interactive and web cartography:

1. **What are the current best practices and unmet needs for cartographic representation in CWAs?**

Participants unexpectedly valued basemaps over thematic maps for adaptive coastal management. While surveyed CWAs primarily include satellite and street basemaps, participants preferred hybrid basemaps with context on both the land and water sides of the coast. While a gap exists in effective, default hybrid basemaps, a range of basemap types should be provided through overlay/underlay interaction.

Icon maps were the most common thematic map among the surveyed CWAs, perhaps because participants made more use out of their basemap context than the icons themselves. The utility of icon maps can be improved by encoding higher-level information using additional visual variables (e.g., color, frame shape, size) and by providing an overview thematic map (e.g., choropleth, proportional symbol) to improve scalability for large point datasets and regional scales.

A major gap for representation existed with additional thematic map types. While isoline/surface maps and, to a lesser extent, choropleth maps were available in some surveyed CWAs, participants also valued proportional symbol and dot density. Because each of these thematic maps evoke a different visual metaphor and have other relative advantages and disadvantages when implemented online, more customization is needed by CWA module to deliver an optimal thematic map for a given coastal issue. A range of thematic map

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| Issue                                | Daily | Weekly | Monthly | Rarely | Never |
|---------------------------------------|-------|--------|---------|--------|-------|
| Restoration                          | -21.0%| -15.6% | 4.6%    | 14.2%  | 18.0% |
| Climate Change                       | -17.2%| -8.0%  | -6.8%   | 11.4%  | 20.6% |
| Sea level rise                       | -16.9%| -15.6% | 2.6%    | 15.6%  | 14.3% |
| Flooding                             | -13.0%| -10.4% | -9.1%   | 9.1%   | 23.4% |
| Water quality                        | -14.5%| -19.8% | 12.8%   | 3.5%   | 18.0% |
| Erosion                              | -10.5%| -13.2% | -4.2%   | 2.2%   | 25.8% |
| Habitat loss                         | -6.6% | -14.6% | -9.4%   | 11.3%  | 19.3% |
| Pollution                            | -6.5% | -11.7% | -3.8%   | -6.0%  | 27.9% |
| Marine traffic                       | 0.0%  | -3.9%  | -7.8%   | -6.5%  | 18.2% |

**Figure 23.** How often do you work on the following coastal issues as compared to how often do you use a decision tool from a coastal web atlas to address the issues?
options should be provided for exploratory and analytical uses cases through reexpress interaction. Flow maps, however, remain both a conceptual and technical challenge for CWAs.

2. What are the current best practices and unmet needs for interactive functionality in CWAs?

Participants expectedly valued work operators over enabling operators. Surveyed CWAs commonly included operators associated with “hamburger” web cartography, including zoom, pan, retrieve, and overlay. The pervasiveness of these operators makes sense both due to technology conventions and the elongated mapping context of coastlines. Participants also valued these operators among the most essential of any CWA requirements, indicating that users want and even expect this baseline set of operators.

Gaps with interaction existed for the calculate and sequence operators. Participants valued calculate and sequence similarly to filter and search, yet calculate and sequence were found far less frequently in surveyed CWAs. Whereas zoom, pan, retrieve, overlay, and possibly search should be implemented across CW A modules, filter (Map), sequence (Map), and calculate (Tool) should be better targeted for specific modules.

There are niche reasons for implementing the remaining work operators resymbolize (e.g., improving the display when exploring), arrange (e.g., coordinating in exploratory tools between maps and diagrams), reexpress (e.g., changing the regulatory zones used in decision making), and reproject (e.g., overcoming regional scale use of Web Mercator). Enabling operators, when implemented, should focus on collaborative decision support, such as export and share.

3. How do target users value the relative usability and utility in CWAs?

Overall, CWAs should prioritize utility over usability, and overall the surveyed CWA modules did score higher on utility than most measures of usability. However, while participants valued utility over usability to support their work, usability remained important.

One gap in usability existed in the learnability of CWA modules. Both learnability and memorability were driven by the technology stack in surveyed CWAs, with proprietary Esri-based tools driving convention. However, participants noted opportunities to improve learnability through story maps and other narrative forms, which could be implemented as Learn modules presenting real-world and problem-based case studies about specific CWA datasets and functionality. Responsive design across mobile and non-mobile devices was an additional nonfunctional gap requiring greater consideration in CWAs.

Perhaps the largest gap in CWAs was in the perceived value and uptake of Tool modules. Tool modules support complex analysis and therefore data-driven decision-making. However, participant responses suggest that available Tool modules do not match with the primary coastal issues considered in adaptive coastal management. Future research is needed to identify the right “Toolkit” to support the diverse range of adaptive coastal management problems and contexts. Further, the design of all modules can benefit from greater clarity in their purpose, with the four surveyed modules perhaps drawing inspiration from wider use cases in interactive cartography: Map supporting exploration, Tool supporting analysis and decision making, Catalog supporting synthesis and sharing, and Learn supporting presentation and education.

Coastal web atlases (CWAs) hold great potential for supporting adaptive coastal management, yet many gaps in the design of CWAs remain. Our own Wisconsin
Coastal Atlas remains under development, and ongoing extensions and revisions derived from this needs assessment study can be tracked at: https://www.wicoastalatlas.net/.

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