Title
Building Resilience to Coastal Hazards: An Analysis of Decision-Making and Environmental Justice on Changing Coasts

Author
Stoltz, Amanda Daria

Publication Date
2024

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

BUILDING RESILIENCE TO COASTAL HAZARDS: AN ANALYSIS OF DECISION-MAKING AND ENVIRONMENTAL JUSTICE ON CHANGING COASTS

A dissertation submitted in partial satisfaction
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ENVIRONMENTAL STUDIES

with an emphasis in COASTAL SCIENCE AND POLICY

by

Amanda D. Stoltz

September 2024

The Dissertation of Amanda D. Stoltz
is approved:

Professor Katherine L. Seto, Chair

Professor Anne R. Kapuscinski

Professor Gary B. Griggs

Professor Michael Orbach

Peter Biehl
Vice Provost and Dean of Graduate Studies

Table of Contents

List of Figures

Abstract

Building Resilience to Coastal Hazards: An Analysis of Decision-Making and Environmental Justice on Changing Coasts

Amanda D. Stoltz

As sea levels rise, shorelines change, and coastal hazards intensify, the need for sustainable and holistic coastal adaptation is paramount. However, successful implementation of strategies that avoid maladaptation and provide the most positive outcomes—ecologically, socially, and economically—is rare. In the US, coastal adaptation efforts are often short-term and piecemeal. Shoreline armoring, despite its negative ecological impacts, is still the most popular coastal adaptation strategy, and if shoreline armoring continues at its current rate, nearly one-third of the contiguous US coastline will be armored by 2100. Meanwhile, despite growing evidence for the effectiveness of nature-based solutions, uptake has remained surprisingly limited. Using the methodologies of systematic literature review, focus group, and interview, this dissertation investigates coastal hazards through an environmental justice lens, what coastal stakeholders need to make scientifically informed decisions, what science agencies need to provide effective decision support, and the barriers to coastal adaptation options that are long-term, large-scale, and nature-based. This research finds that the causes of maladaptation are often structural and go beyond the need for more accessible and actionable science. Maintaining the status quo, and continuing our current path, will lead to myriad negative consequences, some of which will be worse than the original problem. In each chapter, I recommend a version of the following reflection: As our coastal ecosystems undergo irreversible ecological transformation, so should our social systems.

Dedication

This dissertation is dedicated to Anja Sjostrom.

Acknowledgements

During the last five years, I have been supported by an amazing team of mentors, friends, and family, without whom this dissertation would not have been possible. I would first like to thank my parents for believing in me and encouraging me to wander a path they both found unfamiliar.

My Ph.D. cohort and I have been through the wringer, with wildfires, strikes, and a pandemic all happening within our first year of school. Despite this, we created a community founded on shared struggle rather than competition and supported each other. Brook Constantz, Indy Reid-Shaw, MJ Johnson, Suzanne Lipton, Astrid Hoefler, John Morgan, David Shaw, and Francis Joyce are my forever colleagues and friends. I could not have done this without you.

Audrey Morrow was my first friend in Santa Cruz. She was my lifeline and together we made the Ph.D. fun by always making time for bonfires and concerts. I'm very grateful that Audrey, Nathan, and Matt housed me when I was in town and made my move to San Francisco possible. I am lucky to have had an amazing community in Santa Cruz, including Jenny Thomas, a lifelong friend and confidant. To everyone who laughed with me, surfed with me, or danced with me over the last five years: you were a part of this accomplishment.

Under great uncertainty, I found mentorship and meaning through my work with USGS. Amanda Cravens, Erika Lentz, Emily Himmelstoss, and Nicole Herman-Mercer trusted me with work that was sensitive and impactful and showed me how to stay enthusiastic and optimistic in the face of bureaucracy. I'd also like to thank Sara McBride, for starting the "Social Writing while Social Distancing" Teams channel, where we supported each other's writing efforts and helped everyone feel a little less alone while we worked from home.

To my friends in the Seto Lab, I could not have wished for a better group of people to work with. Special thanks go to Olivia Won and Emma Gee, who coauthored my first chapter and were amazing collaborators. My advisor Katy, of whom Indy and I were her first students, has proven to be a wonderful picker of people and a clear light in times of confusion and chaos. No matter the situation, I always felt better after speaking with Katy. I hope my graduation is the beginning of a long legacy of Seto Lab graduates.

Thanks to my committee, Anne Kapuscinski, Mike Orbach, and Gary Griggs for their mentorship and guidance throughout my Ph.D. This was a dream committee for me, and having access to their expertise was an honor.

And finally, behind this hardworking scientist, there is a supportive partner. Matthew Rohr has been solid in his support for my education and career. Big thanks to him for keeping me sane, making me brisket, and taking me on the loveliest walks.

The text of this dissertation includes reprints of the following previously published material:

- Stoltz, A.D., Won, O.M., and Gee, E.K.C. 2024. Environmental Justice of Coastal Hazards: A Systematic Literature Review, Climatic Change, https://doi.org/10.21203/rs.3.rs-4331822/v

- Stoltz, A.D., Cravens, A.E., Lentz, E., and Himmelstoss, E., 2023, User engagement to improve coastal data access and delivery: U.S. Geological Survey Scientific Investigations Report 2023–5081, 29 p., https://doi.org/10.3133/sir20235081.

- Stoltz, A.D., Cravens, A.E., Herman-Mercer, N.M., and Hou, C.Y., 2023, So, you want to build a decision-support tool? Assessing successes, barriers, and lessons learned for tool design and development: U.S. Geological Survey Scientific Investigations Report 2023–5076, 32 p., https://doi.org/10.3133/sir20235076, produced by the U.S. Geological Survey

Introduction to the Dissertation

Climate change is one of the greatest challenges of the 21st century and refers to the long-term shifts in global temperatures and weather patterns contributed to significantly by human activities such as burning fossil fuels. When fossil fuels, such as coal, oil, and gas, are burned, they generate greenhouse gases that trap the sun's heat and raise temperatures. The consequences of climate change are myriad and ripple throughout every aspect of our society, including impacts on our water resources, food supply, health, environment, and infrastructure (Franchini & Mannucci 2015; Hansen & Cramer 2015; Mehran et al. 2017; Nasr et al. 2019; Ridha et al. 2022).

Human adaptation to climate change also presents a 'wicked problem', a multi-dimensional challenge that is difficult to resolve due to incomplete information, uncertainty, differing views on the nature of and solutions to the problem, and complex interactions with other issues (Davoudi et al. 2009; Jordan et al. 2010; Perry, 2015). Some of the most acute manifestations of this "wickedness" are found in ocean and coastal systems, where adaptation is complex, multifaceted, and controversial.

It is crucial to understand and anticipate the effects of climatic trends and events on coastal social-ecological systems so that our adaptation strategies are sustainable, long-term, and effective (Dudley et al. 2021). Coastal planners, developers, and managers face options for coastal planning that have various tradeoffs in different dimensions but on the US coast, climate adaptation is on a less-than-desirable pathway, mired by expensive, short-term, and small-scale solutions that do not match the scale of the problem and can leave behind environmental justice communities. My dissertation explores why this may be the case and provides recommendations for moving towards more sustainable and holistic adaptation futures.

The first chapter of my dissertation is a systematic review of scientific literature that focuses on environmental justice in coastal systems. The included papers tackle how marginalized populations experience coastal hazards and identify groups that may face disproportionate risk alongside heightened vulnerability.

My second chapter explores the needs and challenges faced by coastal decision-makers who are concerned about environmental justice and are working towards more resilient coastlines. This chapter will satisfy the requirements of my Designated Emphasis in Coastal Science and Policy and has been completed in partnership with the USGS Coastal Change Hazards team. I conducted listening sessions with coastal stakeholders to understand which coastal data needs are already met, which aren't, and how agencies like the USGS can provide more actionable and accessible science.

My third chapter looks at the challenge of supporting scientifically informed decision-making in the face of climate change from the opposite viewpoint and asks how USGS scientists understand their role in decision-support and how they work to create decision-support tools. This paper offers guidelines for decision-support tool creators that will benefit coastal stakeholders who struggle with challenges outlined in my second chapter.

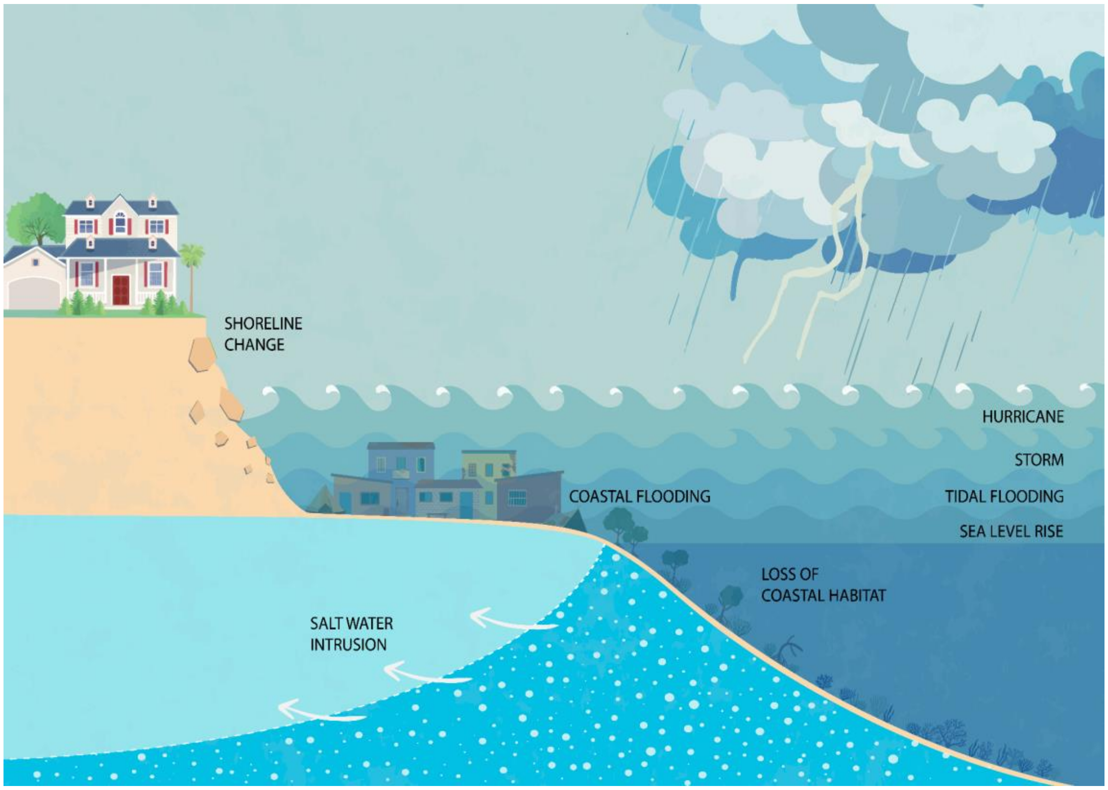
The rationale for my fourth chapter, is that if the scientific literature is clear about which coastal adaptation options are the most sustainable, both economically and environmentally, then what are the barriers that coastal decision-makers face in making scientifically informed and just decisions that go beyond data accessibility? Or, in other words, when is the science not enough? This chapter explores the non-information-based barriers that push decision-makers away from more sustainable options and towards maladaptation.

By examining efforts to build coastal resilience through the methods of systematic literature review, interview, and focus groups, this dissertation will provide a clear analysis of what the future of coastal adaptation in the US may look like under the current system, and a roadmap for US science organizations working to overcome barriers preventing coastal adaptation that is long-term, large-scale, and nature-based.

Chapter #1: Environmental Justice of Coastal Hazards: A Systematic Literature Review

Abstract:

As the ocean warms, sea levels rise, and coastlines change, there is a growing interest in environmental justice on the coast. Here we conduct a systematic literature review on environmental justice and coastal hazards around the world. Our analysis reveals a focus on both long-term phenomena such as sea-level rise and extreme acute events like storms or hurricanes. We found that environmental justice literature about coastal hazards has increased in recent years with most papers focused on U.S. coastal areas. A majority of the papers described low-income communities and economic vulnerabilities, however, the solutions presented in the papers primarily focus on increasing researcher awareness of environmental justice and promoting increased engagement with marginalized communities. Additionally, a majority of the papers rely on mapping census data for their analysis rather than more qualitative methods. Overall, 76 percent of the papers reviewed determined that the most vulnerable populations are also the most at risk to coastal hazards, but there was a dearth of information on the historical causes of this phenomenon. Only 37 percent of the papers mention systems of historical or systemic oppression, such as segregation or redlining, that have led to marginalized populations experiencing greater levels of exposure. Finally, we suggest policy implications for addressing environmental injustices and recommendations for climate change and coastal hazards researchers writing about environmental justice.



Graphical Abstract created by Vermouth Li

Introduction

As climate change begins to intensify environmental justice (EJ) concerns across the globe, this paper reviews the current state of scientific literature connecting EJ to coastal hazards such as inundation, shoreline change, and sea-level rise (SLR). EJ is defined by the EPA as the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies (US EPA 2024). This concept emerged in the U.S. in the 1960s in recognition of the inequitable allocation of environmental burdens placed on minority and low-income groups in the American South, including negative health impacts of pollution and waste dumping (Bullard 1993; Kuhl 2014; Flores 2021a). Research containing EJ concepts did not become widespread in the coastal hazards literature until the dramatic example of Hurricane Katrina and its impacts on Black and low-income Americans in Louisiana in 2005 (Chakraborty 2014). Hurricane Katrina inspired the rise of empirical research on the EJ implications of unequal exposure to flooding and other disasters caused by geophysical phenomena (Montgomery 2013; Dixon and Ramutsindela 2006; Ueland and Warf 2006; Colten 2007; Bullard and Wright 2009; Walker and Burningham 2011). From literature focused on Brazil (Pereira Santos et al. 2022) to Israel (Portman 2012) to Mauritius (Chacowry et al. 2018) to Hong Kong (Lo et al. 2019), Hurricane Katrina is used as an example of environmental injustice created or exacerbated by disaster. After Hurricane Katrina, scientific articles began to document not only cases where marginalized populations experience greater exposure to natural hazards but also how socially and economically vulnerable populations are expected to suffer more harm and have less capacity to adapt (Tedesco 2022). We expect this trend to continue as climate change intensifies EJ concerns on coastlines around the globe.

As the earth's climate changes, the ocean, which covers 71 percent of the earth's surface, absorbs a higher percentage of solar energy than the terrestrial environment. Some manifestations of climate change in our oceans include coral bleaching, intensifying storms, SLR, biodiversity loss, changes in marine species migration patterns, the increased frequency and intensity of harmful algal blooms, hurricanes, marine heatwaves, and many more. These changes will impact human communities that rely on our oceans for sustenance, tourism, recreation, and local economies. Furthermore, coastal communities are especially at risk as climate change rapidly alters the world's coastlines through both long-term directional trends like rising sea levels and increased frequency of extreme events like hurricanes.

SLR is predicted to displace a large proportion of the population over the next century via inundation and heightened SLR-related hazards (Black et al. 2011; Hauer et al.

2020). SLR-related hazards include coastal flooding, erosion, saltwater intrusion, and increased wave height during storm events (Nicholls and Tol 2006; Nicholls et al. 2007; Nicholls and Cazenave 2010). SLR is among the most costly and permanent future consequences of climate change (Hauer et al. 2020). The economic impacts are already occurring; data show that increased tidal flooding driven by SLR lowered US property values by USD 15.9 billion between 2005 and 2017 (Griggs and Reguero 2021). This trend will continue as sea levels rise, putting life, property, infrastructure, and coastal habitats across US coasts at risk (Griggs and Reguero 2021).

Scholars and practitioners have been working to research, describe, and document cases of environmental injustice on our coasts for decades, with a cohesive literature emerging in the early 2000s. Now, after over 20 years of publications, there is a critical mass of research on the topic that has yet to be synthesized comprehensively. A systematic literature review is needed to survey and understand the current research and literature on a topic (O'Donnell 2021).

Here, we review the scientific literature connecting concepts from EJ to coastal systems, specifically the impacts of coastal hazards on marginalized populations. This paper will note the challenges and opportunities identified in the literature, where gaps in the literature remain, and discuss the primary findings of the literature regarding coastal hazards and environmental justice concepts.

Methods

The purpose of this literature review is to understand the state of research connecting EJ to coastal hazards. To do this, we conducted a search of Web of Science, to include any one or more of the following EJ terms ("environmental justice", "low income", "minority", “people of color”, and “persons of color”) and any one or more of the following coastal hazard terms (“sea level rise”, “coast”, “coastal”, “flood”, “flooding”, “erosion”, “storm”, and “king tide”).

We compiled an initial list of papers (n=252) using the following search terminology: ("sea level rise" OR (coast* AND (flood* OR erosion OR storm)) OR "king tide") AND ("environmental justice" OR "low income" OR minority OR "people of color" OR "persons of color") on May 3rd, 2023. There were no bounds set on the year of publication or region of focus.

Exclusion criteria were defined to limit the selection and use of existing peer reviewed publications. Documents were excluded if they (1) did not include information on how marginalized populations are directly affected by coastal hazards, (2) were duplicate documents, (3) focused on inland areas or those adjacent to lakes or rivers, (4) described only pluvial flooding that was unrelated to a hurricane. This resulted in the 113 papers reviewed in this research.

We coded and analyzed the final list of included papers (n=113) using MAXQDA plus 2022 (Release 22.3.0). We coded the articles deductively and inductively, addressing different types of coastal hazards, fields of research, marginalized communities, and more (Supplementary Material: Codebook). The included 113 studies were published across 69 academic journals.

We determined the deductive coding framework on definitions of exposure, vulnerability, resilience, and adaptation provided by Berkes (2007) and Birkmann (2013). We used an inductive coding process to identify and describe themes present in the literature. This form of analysis was used to reveal data-driven themes, rather than attempting to determine themes prior to the analysis (Nowell et al. 2017).

To analyze geographic and temporal trends in the literature, we used the statistical computing software R (R Core Team 2021). To compare the number of studies by US state, we normalized using populations living in coastal counties according to the American Community Survey (NOAA Office of Coastal Management, n.d.). We performed a network analysis on citations between papers in the review using the network visualization software VOSviewer (https://www.vosviewer.com/).

Results

The literature we reviewed included research on 24 individual countries, as well as several articles that were regional or global in scale. The United States was by far the most studied country and just over half of the studies reviewed conducted research within the US (n=61; 54%). The next-most studied country was Nigeria, with 6 studies (Fig. 1A).

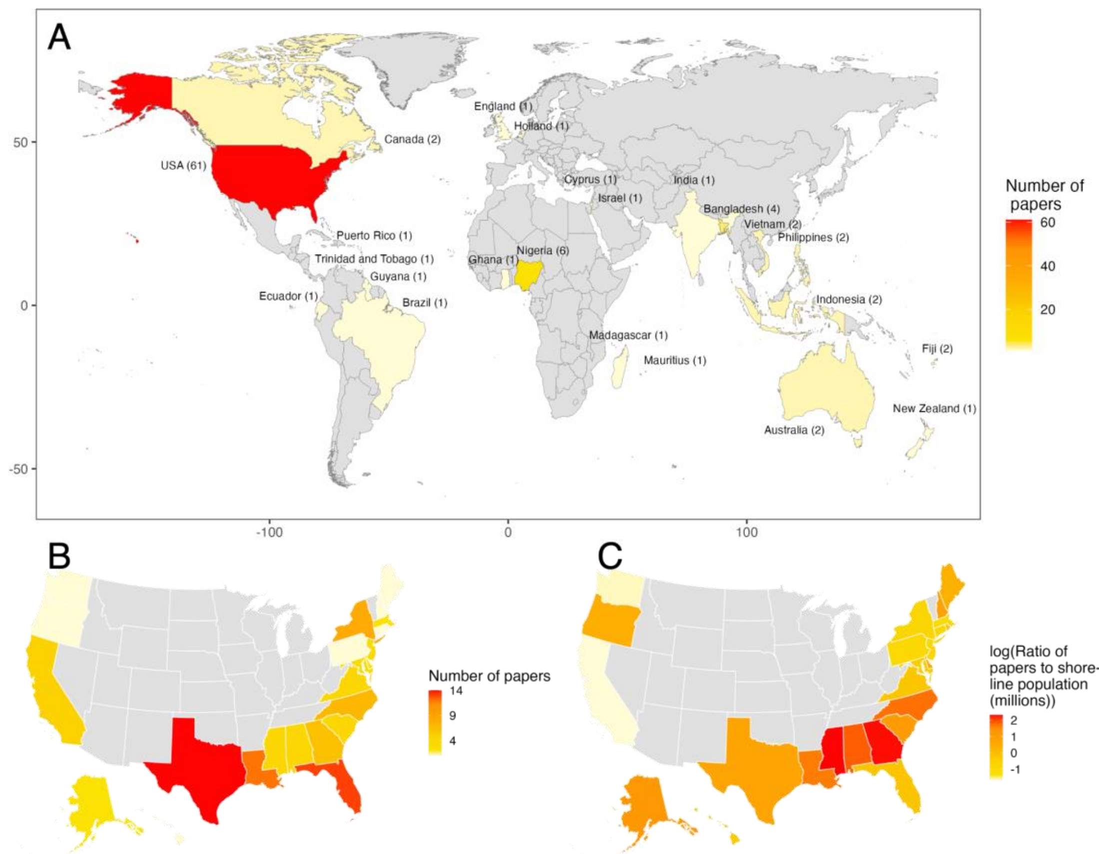


Figure 1. (A) Number of papers reviewed by country, (B) Number of papers reviewed by US state, and (C) Ratio of studies to shoreline population (NOAA OCM, n.d.) plotted on a log scale

Within the US, articles tended to focus on the Gulf Coast states of Texas, Louisiana, and Florida (Fig. 1B). Gulf Coast states were also the most studied relative to the number of people living in a shoreline county in the state. Mississippi and Alabama were part of larger-scale studies on Gulf and coastal states, but not the primary focus of any individual article. Within the most-studied US states, articles mostly focused on major urban centers, namely Houston, Miami, New Orleans, and New York City. Hawaii was only examined in a study of all US coastal states (Buchanan et al. 2020) and Alaska was only researched in two articles. Relative to the size of coastal populations, California and Washington were the most understudied US states (Figure 1C). The reviewed literature included only one study on a US territory, which focused on the impacts of Hurricane Maria on marginalized populations in Puerto Rico (Ferré et al. 2019).

The reviewed articles spanned years 2006 to 2023 and the number of papers published each year increased rapidly from 2009 to a peak in 2021, with a drop in 2020 (Fig. 2). The peak of publications in 2021 was likely due to researchers' limited ability to conduct new research during the COVID-19 lockdown and researchers' increased time to publish existing work or complete new research with already existing data. Papers that use the term "environmental justice" have similarly increased over time.

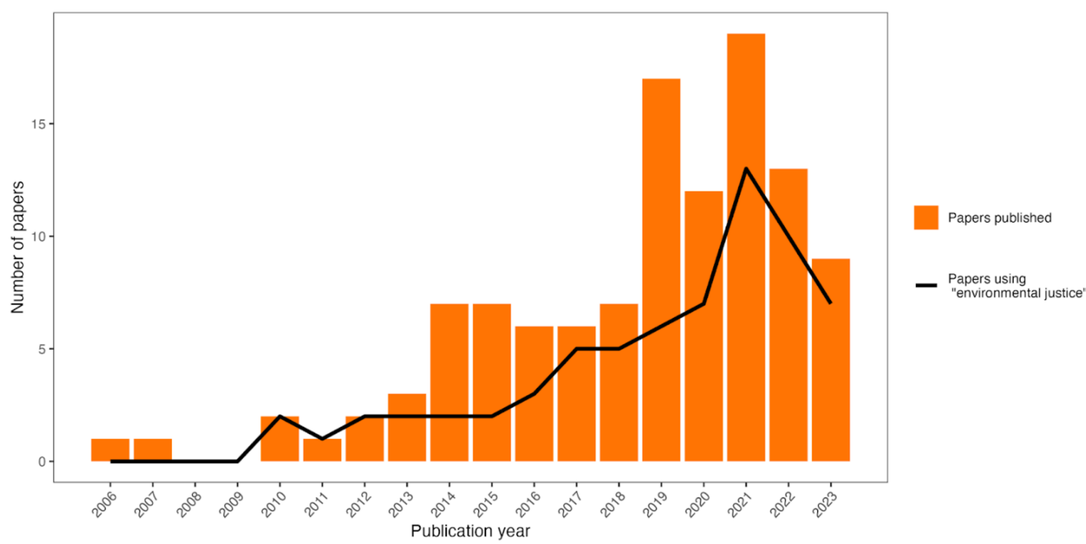


Figure 2. Publishing dates of reviewed articles (bars) and numbers of reviewed articles that use the term "environmental justice" (black line)

In examining the spread of journals where the literature in this review is published, we categorized each journal into thirteen types based on the title of the journal and the aims and scope described on the journal's website (Figure 3). While many journals label themselves as multidisciplinary, we only added journals to this category if they solicit papers on a range of topics that span both the physical and the social sciences. This was the largest category, followed by journals on environmental management and planning, which we categorized by whether the title of the journal was focused on planning or management or if it had an infrastructure focus (e.g., Australian Planner, International Journal of Disaster Resilience in the Built Environment, etc.). We categorized social science journals as those which only publish social science research and were topically broad (e.g. Population and the Environment), sustainability journals as those with "sustainability"or "sustainable" in the title, health journals if they had "health" in the title, multidisciplinary/climate change journals if they were climate change focused and solicited both physical and social science papers, policy journals if they had "policy" in the title, geography if they had "geography" or "geographers" in the title, justice journals if they had "justice" in the title, and transportation journals if they had "transportation" or "transport" in the title. There was one journal in the life sciences category (Philosophical Transactions of the Royal Society B - Biological Sciences), one in ecology (Urban Ecosystems), and one in "marine science and engineering" (Journal of Marine Science and Engineering).

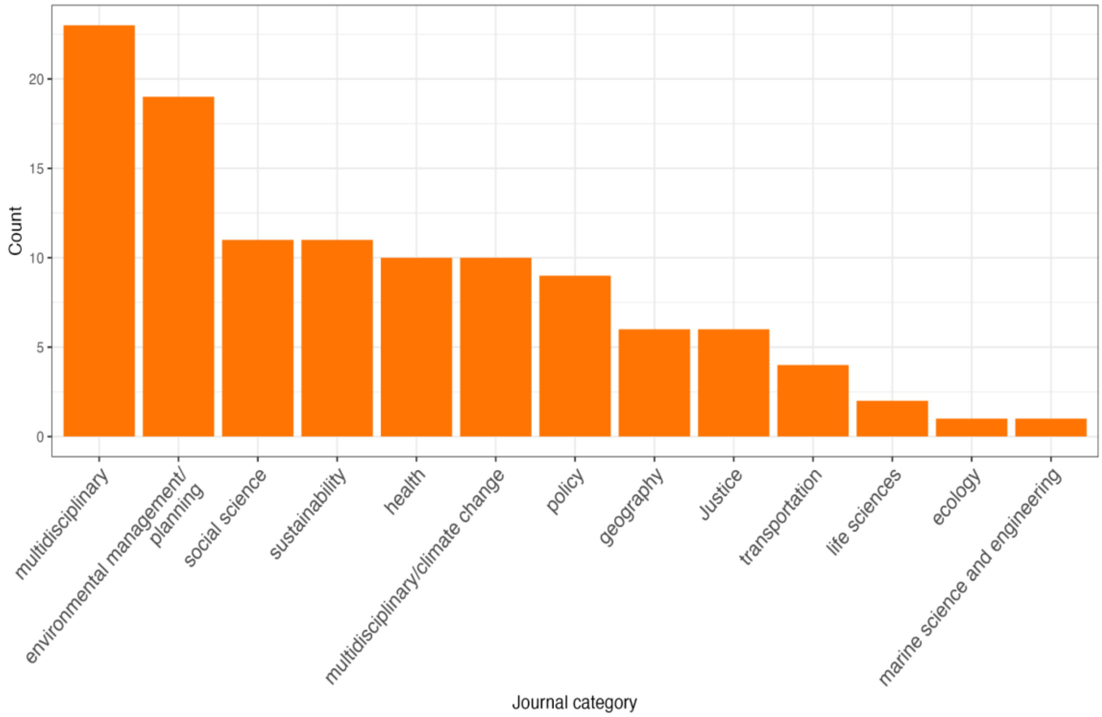


Figure 3. Types of academic journals represented in the review

We also coded the methods and data types used by the reviewed literature, most of which used multiple sources and approaches (Fig. 4). Census data, or other types of demographic indices data, were used in 34 of the articles. A common analysis employed by 25 papers was to understand how coastal hazard exposure overlaps with the locations of marginalized populations through spatial analysis and mapping. Qualitative data were also collected by the articles, which used methods such as interview (27 papers), surveys (18 papers), case studies (15 papers), focus group (9 papers), and ethnography (9 papers). Only 3 papers relied on historical data, usually in the form of archival maps or histories about the Black American experience in the South.

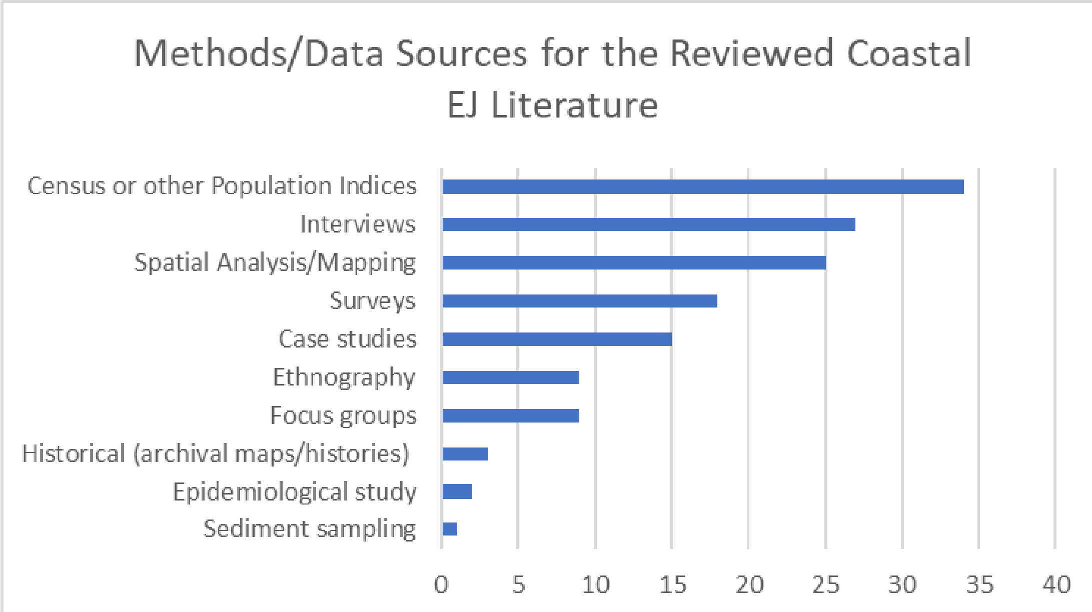


Figure 4. Methods and data used across reviewed literature. Reviewed literature was inclusively coded for specific methods and data sources employed. For articles with multiple methodological approaches, these were coded multiple times.

The articles in this review were largely disconnected from one another (Fig. 5). A group of forty-two papers were connected through citation, all from authors at American, British, or Canadian institutions researching primarily American communities. Outside of this main group, there were 8 smaller groups of pairs or triplets of papers in conversation, leaving 54 papers completely disconnected from the rest of the literature reviewed.

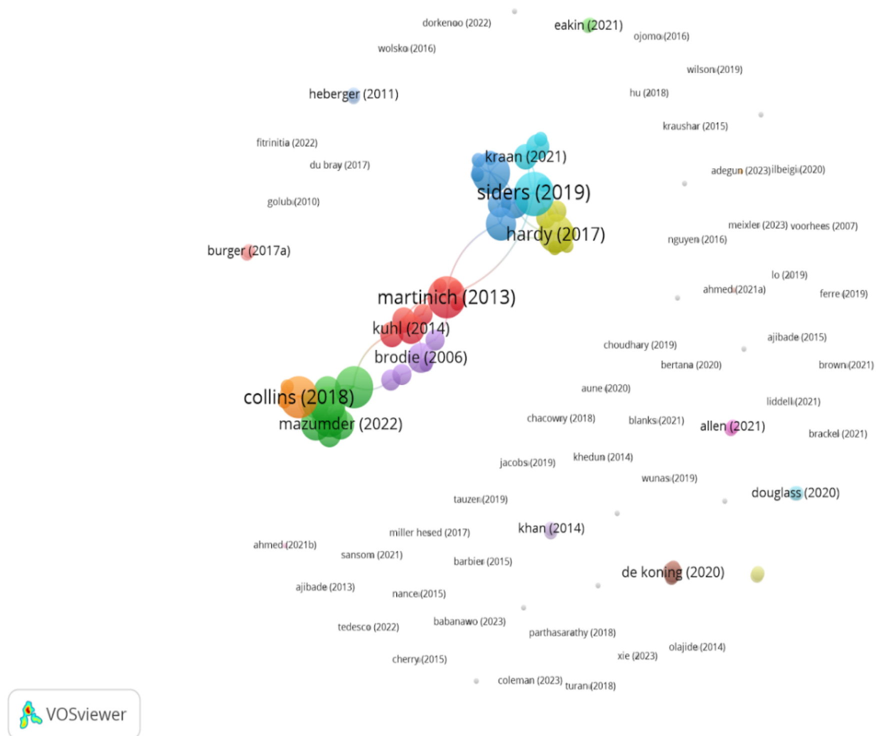


Figure 5. Citation analysis. Network map of citation relationships in the literature reviewed. Nodes are papers and their size is proportional to the number of times the paper was cited by others in the review. Links between nodes represent a citation.

Coastal Hazards

The coastal hazards mentioned in the reviewed literature included flooding, loss of coastal habitat, shoreline change, saltwater intrusion, storm and wave effects, hurricanes, and SLR (Table 1). Often, the articles mentioned multiple hazards in a list in their introduction before going on to describe coastal impacts on marginalized populations more generally.

The top coastal hazards mentioned by the articles were flooding (90%), SLR (74%), and storm and wave effects (73%). While flooding and storms have tangible, well documented impacts on coastal communities, SLR is a slower trend that in many cases has less identifiable or immediate impacts. The focus of the EJ literature on both extreme events and long-term directional trends demonstrates that the bulk of this work considers both present and future impacts to coastal communities.

When coding for flooding, the coding team used three distinct concepts: “coastal flooding” when papers used the term “coastal flooding” or described inundation in coastal areas; “tidal flooding” when papers used the term “tidal flooding” or described inundation due to tidal shifts; and “inundation” when papers mentioned flooding but did not specify the cause. While some papers also mentioned pluvial flooding, this was excluded as it is not directly tied to coastal hazards.

Approximately half of the papers in our review, 52 percent, mention hurricanes. These papers often studied the impacts of previous catastrophic hurricanes such as Hurricane Katrina in Louisiana (2005), Hurricane Sandy in New York (2012), and Hurricane Harvey in Texas (2017). Some studies are concerned about heightened hurricane intensity in the future, especially regarding low-lying areas and communities with older infrastructure more vulnerable to storm impacts (Burger 2017).

Table 1. Mentions of coastal hazards in the reviewed literature.

Coastal Hazard	**Frequency of Articles**	**Percentage of Articles**
Any Mention of Flooding	102	90%
Sea-level Rise	84	74%
Storm and Wave Effects	83	73%
Hurricane	59	52%
Coastal Flooding	53	47%
Shoreline Change	44	39%
Loss of Coastal Habitat	28	25%
Saltwater Intrusion	20	18%
Tidal Flooding	16	14%

The code “shoreline change” was used for any papers that mentioned erosion, subsidence, disappearing islands, or changing coastlines. This included 39 percent of the papers in this review and was often coupled with information about past, present, and future relocation efforts.

Only 25 percent of the articles directly mentioned the loss of coastal habitats such as mangroves, marshes, coastal wetlands, or dunes. This mention was most often in reference to the loss of natural shoreline mitigation elements that block wave pressures, tides, and gales. Papers that described habitat loss in more detail described the negative impacts of coastal habitat loss on livelihoods, especially for those involved in the fishing industry. One paper related the loss of mangrove forests as an important aspect of “marine justice”. In “What is Marine Justice”, Martin et al. (2019) write that the destruction of mangrove forests from both anthropogenic and natural causes “has ignited a global movement spanning from Latin America to Southeast Asia to Africa. In the words of one Ecuadorian activist, the effort to save these coastal forests is ‘la lucha justa’: the just fight (Warne 2011, 65).” Overall, the ecological and economic consequences of losing coastal habitats is clear in the coastal EJ literature, but not as commonly mentioned as the coastal hazards that have a more immediate impact on coastal communities such as flood risks.

The least mentioned coastal hazard was saltwater intrusion, which included any mention of saltwater intrusion into the groundwater (18%). Aside from papers that briefly mention saltwater intrusion as a result of SLR, papers described the potential health impacts of salinity in drinking water (Khan et al. 2014), detailed how aquifers, the primary source of water for coastal populations, are threatened by a combination of increased pumping and SLR (Khedun and Singh 2014), and commented on the broader threat to food and water security

(Rahman et al. 2019). Of all the papers in this review, 22 percent mention loss of freshwater resources due to coastal hazards.

Marginalized Communities

All the reviewed literature described the impacts of one or more coastal hazards on marginalized communities. While these results could indicate the relative importance of different populations in the EJ literature, they may also reflect where data is readily available for study. This may explain why the most studied populations reflect information collected in the census, which allows researchers easy access to demographic information on age, gender, employment status, and race, but does not provide the granularity needed for comprehensive analysis.

The majority of the literature reviewed (88%) mentioned impacts on low-income communities and used the term “low-income” to describe them. These articles labeled populations as low-income through readily available data on median income, housing values, and poverty status. This literature described how low-income communities can be more vulnerable to coastal hazards because they lack the financial resources to prepare or evacuate and may reside in homes with poor infrastructure. Low-income communities are also often located in less desirable areas that may experience greater exposure to hazards, such as floodplains. Another closely related factor mentioned in the literature was unemployment or people who live in areas where there is a dearth of job opportunities (27%). These factors, coupled with threats from coastal hazards, can lead to poverty traps, an outcome mentioned in nine of the articles reviewed.

Of the papers that mention race (70%), 41 percent mentioned Black people, 25 percent mentioned Hispanic or Latino people, 20 percent mentioned Indigenous people, and 4 percent mentioned Asian people. General terms that describe non-white racial groups were also used, such as “People of Color” (41%) and “Minority” (33%). Twenty papers mentioned immigrants, but only 15 papers spoke specifically about the difficulties faced by people who do not speak English as their first language (These composed 22% of papers focusing on a country where English is the most commonly spoken language).

Articles that mentioned elderly people or children comprised 44 percent of the papers reviewed. Elderly populations often lack transportation options and may have disabilities that lessen their ability to evacuate successfully. Several papers discussed coastal hazard impacts on nursing homes, and Wilson et al. found that vulnerability was higher for counties that house residents with limited mobility (2019). Some papers also detailed examples of how the elderly were forgotten during storm events. In some cases, there was no agency or organization to take responsibility for medically fragile or low-mobility individuals during evacuation efforts (Kraushar 2015). People with mental or physical disabilities, mentioned in 27 percent of the studies, were also often described in articles that advocate for more equitable evacuation strategies. Only one paper mentioned the heightened vulnerability of incarcerated people and described how they, like the elderly and people with disabilities, are particularly vulnerable to flooding (Minovi 2021).

While the broader coastal hazard literature commonly focuses on property owners, the EJ coastal hazard literature often concerns renters and people who live in slums or informal settlements (36%). Renters were described as vulnerable to coastal hazards because of their inability to acquire structural flood insurance or physically protect their rented home against coastal hazards (Montgomery & Chakraborty 2013). Similarly, 15 percent of papers described impacts to populations without or with limited access to insurance. While some papers (outside the US) detail the impacts of coastal hazards on slums or informal settlements, there were no papers that examined impacts to populations that were homeless prior to the coastal hazard event. Homelessness was only described as a result or downstream impact of a coastal hazard (22%).

Roughly a third of the articles (36%) included gender in their studies. Gender was often briefly included as one of the factors determining an individual's socioeconomic status, as men tend to have more economic opportunities and agency than women, especially when leading single-parent households (4%). Articles that went into detail about how women experience the effects of coastal hazards differently from men explained that in agrarian contexts, the impacts of climate events could lead to women either being subjected to forced migration, or having no other option but to stay in hazard-prone areas while their spouses leave in search of new work opportunities (Dorkenoo et al. 2022; Chandra et al. 2017). No articles mentioned sexual minorities.

While urban centers were the focus of most of the papers in our review, smaller, more rural communities were mentioned in 27 percent of the articles. Our review indicates that these areas receive less attention than urban centers but are subject to more isolation and less governmental support. Cost-benefit analysis often pushes smaller communities further away from the technocratic solutions provided to larger, more economically valuable communities. The negative impacts of cost-benefit analysis on small communities were mentioned in fifteen articles.

Vulnerabilities

Overall, 76 percent of the reviewed literature described a common theme: the most vulnerable populations are also the most at risk to coastal hazards. This finding reveals that the literature is primarily focused on the distributive justice dimension of EJ, which refers to the equitable allocation of, and access to, material costs and benefits for all social groups

(Ikeme 2003). It's important to note here that marginalized populations, whether elderly or unemployed, are not intrinsically vulnerable to coastal hazards. Their vulnerabilities, such as lower mobility or less financial resources, are the factors that determine their ability to cope with and recover from adverse events (Cutter et al. 2003).

In keeping with our finding that most of the literature describes the impact of coastal hazards on low-income communities, 71 percent of the papers explicitly described a lack of financial resources as the cause for increased vulnerability. Many of the other vulnerabilities mentioned in the articles are closely tied to economic status, such as residing in a home with poor infrastructure in an area with high exposure to coastal hazards (47%), lack of education (35%), less access to medical care (22%), or fewer transportation/shelter options (28%).

The second-most mentioned vulnerability was less representation in government or local institutions (50%). This finding is closely tied to the procedural dimension of EJ, which focuses on the fact that participation in decision-making is not always equal, and some groups and individuals can be excluded (Ikeme 2003). Racial and ethnic minorities and poor communities tend to lack adequate representation in environmental decision-making processes involving industry and government (Flores et al. 2021b). A lack of political influence and capital can stymie a community's efforts to obtain support for large-scale infrastructure improvements to reduce flood exposure (Tauzer et al. 2019), request a buy-out (Siders 2017), or meaningfully participate in planning and decision-making on siting of nature-based projects (Hobbie and Grimm 2020).

Another vulnerability described in the literature was when a population relies on their surroundings, making them unable or unwilling to relocate to an area less exposed to coastal hazards. As explained by a Tadgell et al. study on informal settlements in less developed nations, "feelings of belonging, lifestyle, family connections, and culture – can tether populations to their land" (2018). These place-based connections are strong, especially in the cases of people whose livelihoods are marine-based (Stoltz et al. 2021; Bragg et al. 2021).

When it comes to preparing for a storm event or recovering afterward, it's vital for communities to have access to information on potential assistance and aid. Unfortunately, 29 percent of the literature reviewed described situations where populations were unaware or unable to benefit from existing aid programs or other types of assistance. Oftentimes, aid is only available to privileged groups like homeowners, and people in the undocumented, immigrant, or renter populations are not provided with any resources to meet their recovery needs (Chrakaborty et al. 2014).

While any individual could experience one or more of the vulnerabilities described in this section, it is important to note that most EJ cases show environmental harms almost always result from the interaction of long-term structural and institutional causes (Supekar 2019; Apelberg et al. 2005; Flores et al. 2021a). The systemic causes for why some groups experience these vulnerabilities more than others is addressed in the section, "Systems of Historical Oppression".

Indirect Impacts

Coastal hazards impact people through both the hazard itself, like storm damage, and indirect or downstream effects, such as loss of electricity or freshwater. We defined these indirect or downstream impacts as long- and short-term negative effects caused by a coastal hazard.

The most frequently mentioned indirect effects of coastal hazards were health impacts, including disease, illness, and death resulting from hazard events and their aftermaths (47%). A quarter of papers (25%) identified exposure to contamination or hazardous materials resulting from hazards and 14 percent of papers noted that hazards disrupted access to healthcare, including access to medical facilities and medication.

Over a quarter of the papers (28%) reported specific mental health effects resulting from the aftermath of coastal hazards. Specific adverse psychological impacts included depression (du Bray et al. 2017), post-traumatic stress disorder (Cherry et al. 2014; Wolsko and Marino 2016), and anxiety (Khedun and Singh 2013; Ferré et al. 2019). In a study by Wilson et al. 2019 evaluating the vulnerability of nursing home residents in the Southeastern United States, they argued that stress during disasters can exacerbate or worsen cognitive health (Wilson et al. 2019). Several papers also identified mental health impacts from relocation and resettlement programs (Tubridy et al. 2022; Liebernect and Mueller 2023).

Reviewed papers noted the indirect effects of coastal hazards on basic needs including food insecurity (26%), loss of freshwater (22%), loss of livelihood (46%), and homelessness (22%). Additionally, studies noted both short- and long-term effects on access to electricity (14%), education (12%), and transportation (19%).

Reviewed studies noted that coastal hazards had deleterious effects on human relationships to coastal areas, including loss of attachment to place (26%), loss of social support systems (19%), and the loss of generational or cultural values that have been built over time in the coastal environments (17%). In cases of managed retreat and planned relocation, reviewed papers found poor quality of relocated sites (10%) and instances of retreat and return, when a relocated coastal community left the coastal area and then returned to the area (6%). A few studies (3%) noted that a specific indirect effect of coastal hazards for small island states could be statelessness, by which loss of territorial land mass would result in the loss of statehood (Dorkenoo et al. 2022; Sadai et al. 2022).

Systems of Historical Oppression

Thirty-seven percent of articles reviewed describe the historical systems of oppression that affect the relationship between coastal hazards and marginalized communities. These systems included systemic racism, segregation, sexism, classism, development inequity, colonialism, neoliberalism, slavery, and genocide. While these systems are overlapping and intersectional, they were only coded if the article directly referred to them by name.

The most mentioned system of oppression was segregation or discrimination (20%). In an article by Minovi on toxic floodwaters on the Gulf Coast, they explain that "due to a legacy of redlining, exclusionary zoning practices, and other systematic forms of housing segregation, the vast majority of people who live near chemical facilities are Black, Hispanic, and have low wealth" (2021), Maldonado et al. describe how in Austin, Texas, periodic flooding was a factor in the racial segregation of the city, where Hispanics and Blacks were marginalized to areas most prone to flooding (2016), and Golub and Kelly note that in many cases, the location of minority and low-income communities in areas of high exposure are determined by historical and current discrimination (2010).

Systemic racism was mentioned in 19 percent of the papers. Flores et al. for example, describe how racial marginalization and poverty are the factors that generate increased vulnerability to natural disasters (2021a). Some papers, including Malloy's work on adaptation planning (2023), describe how the racist ideology of United States policy has deepened these vulnerabilities through bias in flood relief payments against non-white populations.

Colonialism was mentioned in 10 percent of papers. In one article about small island states, Sadai et al. (2022) explained how colonization and globalization reduced the once high adaptive capacity for environmental change (Barnett 2001; Barnett and Campbell 2010; Bordner et al. 2020; Douglass and Cooper 2020; Nunn and Campbell 2020). Dorkenoo et al. (2022) write that the unequal processes in which adaptation leads to protections for some and damages for others are driven by relationships of power that are rooted in colonial practices of domination and dispossession.

Despite the long legacy of slavery in the US, only 7 percent of papers which focused on the US mentioned how slavery has shaped how and where people live on the coast. Hardy et al.'s article on the deep history of racial coastal formation argues that in Sapelo Island "the landscape, through the continued presence of its antebellum structures, slave-dug drainage ditches, as well as current labor, property, and governance relations, maintains an inscription of race and legacies of slavery that resonate in the everyday lives of local Geechee residents". Jurjonas et al. (2020) describe the impact of slavery on the coast more generally, and detail how African Americans moving off plantations in the reconstruction era sought to buy affordable, unoccupied land, which also tended to be in the lowest-lying areas (Morse 2008). Tracking mentions of historical systems of oppression across the literature provides a full picture of how scientists are, or are not, engaging with the history of the areas they study.

Solutions

The literature reviewed often provided solutions to environmental injustices on the coast, ranging from broad recommendations for improving practitioner and community knowledge, calling for more collaborative and participatory engagement in coastal hazards science, providing material changes to resource distribution, and even insisting that the only solution is broader societal transformation.

The most common solution identified by 58 percent of the reviewed articles was a need for scholars, managers, and practitioners to better understand the EJ implications of their work with coastal hazards. Generally, authors suggested that improving experts' or decision makers’ awareness and sensitivity to how different groups experience coastal hazards could improve planning and responses to coastal climate hazards. Many papers located the first step of this process as conducting local-scale or site-specific vulnerability analyses that pay finer attention to historically marginalized communities that may be impacted by coastal hazards. For example, a study by Minovi that evaluated coastal storm impacts on toxic chemical dispersal, argued that assessing facilities at higher flood risks in areas with historically marginalized communities can promote more targeted enforcement of pollution permitting and enforcement (2021). Other papers suggested leveraging this information to develop more specific hazard-related strategies tailored to these more vulnerable groups. For example, in Mazumder et al.’s study of flood risk vulnerability in Florida, they argue that the existing emergency notification system may be ineffective for younger and older individuals who are more dependent upon caretakers. Their evacuation success may be better supported by a targeted emergency notification system that accounts for their group-specific vulnerabilities (2022).

Over a quarter of papers (29%) identified a need to improve knowledge or education about coastal hazard risks within marginalized populations. Examples of these papers included improving community knowledge of flood risks, evacuation planning, and broader awareness of environmental issues. Some papers argued for disseminating new or improving existing knowledge of coastal hazards to engender public support for resilience strategies. For example, a 2017 study by Burger and Gochfield surveyed “uninsured, underinsured, and economically challenged people " in New Jersey to assess their understanding of severe storms and how ecological systems like marshes and dunes contribute to resilience. They argued that to build public will for investment in ecological protective barriers, “efforts by managers, public officials, and others to continue discussing (and including) marshes and dunes as part of a coastal resiliency strategy will increase the likelihood that funds and support will be available for beach and marsh restoration" (Burger and Gochfeld 2017). Other studies argued for improving community knowledge to promote self-determination and empowerment in responding to coastal hazards. For the example of the Lower Nyando Basin in Kenya, Triboan et al. argue that improving general knowledge about disaster-resilient infrastructure approaches can empower self-improvement of housing and roadways that promotes local job growth in addition to resilience to extreme weather events (2021).

A small number of papers identified changing scholars and practitioners' overall approaches to knowledge as a solution, specifically by pursuing interdisciplinary science (14%) and incorporating local knowledge (10%) into coastal hazard planning and management. For example, Orbach and Miller argue that given the complexities of coastal areas, "solutions will require more than the usual natural and social science, planning, and engineering expertise" and should incorporate human dimensions from humanities disciplines (2022). Beyond calls to move beyond "hard science" disciplines, some papers argue for going a step further by incorporating knowledge from historically marginalized groups, such as Indigenous communities. Indeed, Hardy et al. argue that including multiple knowledges is "fundamental to achieving equitable and just adaptation outcomes" because some communities have non-scientific forms of knowledge (such as historical and racialized experiences of flooding) that may otherwise be excluded (2017).

The second most common solution, presented by 49 percent of reviewed studies, was to increase the amount of collaborative, participatory, and adaptive engagement. Many studies suggested that addressing procedural inequities, or failures to include impacted groups in decision-making or planning processes adequately, would facilitate more just or equitable outcomes. Most argued that this entailed engaging stakeholders in meaningful and serious ways to ensure that decision-making groups are more representative of communities (Allen et al. 2021; Bautista et al. 2015). In addition to developing novel structures for participation like stakeholder advisory committees, several studies proposed amendments to make existing engagement protocols more inclusive, including multi-lingual outreach materials to reach non-English speaking communities and changes to flood-related, property buyout programs to support lower-income renters. The reviewed papers also identified scenarios where marginalized groups were left out of decision making spaces, leading to laws and policies that create more harm for these groups (31%).

Calls for engagement also focused on broader capacity building in socially vulnerable groups, including recommendations for creating plans or policies in under-planned communities (Allen et al. 2021), strengthening communication and information-sharing networks (Brodie et al. 2006), and recognizing the rights of marginalized groups to have a say in their futures (Wolsko and Marino 2016; Ajibade 2019).

In addition to general improvements in facilitating participation and capacity building, many studies called explicitly for equitable collaboration between groups to ensure that power was shared, and communities were not just disregarded or discarded (Adegun 2023a). The consequences of unequal collaboration are particularly apparent in managed retreat or resettlement projects (Bertana 2020; Tadgell et al. 2018). In a study evaluating a managed relocation of a Fijian village, Bertana found that though the project was billed as collaborative between the village of Vunidogoloa and the Fiji government, the government held a more powerful position and villagers were ultimately excluded from the planning of the new village's layout (2020).

Other identified solutions included the equitable distribution of economic resources and access to successful evacuation and recovery. This included specific calls for resources to strengthen the capacity of communities or local governance institutions and general calls to increase economic growth in vulnerable populations (16%). These calls are supported by arguments that capital can improve capacity to weather and respond to coastal hazards or disasters. In addition to generally increasing wealth or financial resources for vulnerable groups, five studies argued for diversifying livelihoods to move communities away from economic activities that are extractive, poverty-trapping, or particularly vulnerable to coastal hazards and climate change (4%).

Only one paper explicitly called for a redistribution of resources from high-income historically emitting countries to lower-income, developing countries. In a study evaluating autonomous household climate change adaptation and urban governance capacity building in Georgetown, Guyana, researchers argue that high emitters should commit more climate adaptation financing through international funds to address climate injustice (Mycoo 2014).

In addition to financial resources and successful evacuation and recovery from disasters, some authors argued for continued access to coastal resources, particularly those which are culturally important and significant to socially vulnerable groups (4%). In their study of EJ issues facing Native Americans, Liddell et al. argue that the loss of coastal habitat extent and requisite relocation will also include a loss of tribal identity, and any efforts to maintain coastal regions should include and involve Native American leaders (2021). Wolsko and Marino's work on Shishmaref, Alaska, argues that retreat and adaptation planning must include costs for infrastructure planning that will enable continued access to traditional lands to maintain socio-ecological relationships (2015).

Though less common than previously discussed solutions, four papers called for more transformative solutions that address broader changes to fundamental structures and systems. In response to the historical and ongoing marginalization of Native Americans, Liddell et al. and Liebernect and Mueller argued that achieving justice for these communities necessitates recognizing Indigenous sovereignty and self-determination (Liddell et al. 2021; Liebernect and Mueller 2023). Other recommended governance changes that afford more power to historically marginalized groups included converting coastal areas and their management to a common pool resource to de-privatize adaptation processes (Jurjonas 2020) and post-buyout land use plans that meet community-determined needs rather than developer's interests (Li & Spidalieri 2021; Liebernect and Mueller 2023).

Discussion

This paper provides a review of the literature that focuses on EJ and coastal hazards. Our results demonstrate that academic interest in the intersection of these fields has grown over the past decade, in line with a growing interest in EJ scholarship generally. Across the reviewed literature, the thematic consensus is that the populations who are the most vulnerable to the impacts of coastal hazards are also the most at risk of experiencing coastal hazards (76%).

Flooding was the most studied coastal hazard in the literature, which was expected as floods inflict massive losses on human life and property (Hirabyashi et al. 2013; Hu et al. 2018). The literature was also skewed towards a focus on low-income groups, emphasizing economic vulnerability over other dimensions of injustice or marginality. Most of the literature reviewed was published in multidisciplinary, environmental planning, and social science journals, rather than coastal hazards or physical science publications. This suggests that calls for coastal hazard researchers to understand the EJ aspects of their work may be dampened by the lack of EJ focused literature published in traditional coastal hazard journals and the lack of citations between authors in our review, indicating that much of this work is being done in a vacuum.

We identified major geographic and conceptual gaps in the literature on EJ and coastal hazards. Despite a heavy focus on the US, very few papers considered regions outside the continental 48 states. Hawaii was only examined in a study of all US coastal states (Buchanan et al. 2020), and Alaska was examined in one study. Of the US's five permanently inhabited overseas territories, only Puerto Rico was studied in one paper in our review. This paper focused on the impacts of Hurricane Maria, one of America's deadliest and costliest hurricanes to date (Ferré 2019). By contrast, the impacts of Hurricane Harvey, which occurred a month before Maria and had a lower death toll (Government Accountability Office 2019), were the central focus of three studies in the reviewed literature and mentioned in sixteen others. The US's other territories of Guam, American Sāmoa, the Northern Mariana Islands, and the US Virgin Islands are all island states facing threats of rising sea levels and intensifying storms. Yet/however, none of these were studied for the EJ dimensions of these hazards in the literature we reviewed. Island nations such as these face existential threats from SLR, with some predicted to be fully submerged by 2100, and there are distinct differences in the level of vulnerability faced by different populations within these states. Globally, our search found few papers focused on South and Southeast Asia, despite the countries in the region having three of the five most populous countries in the world and experiencing the highest rates of flooding and flood-induced mortality (Hu et al. 2018). We find that the literature has thus far largely failed to include the countries facing the greatest impacts from SLR and flooding.

While 22 percent of the papers reviewed described how homelessness is a potential downstream impact of coastal hazards, none of the literature reviewed examined impacts on populations that were homeless before the coastal hazard event. Similarly, only one paper mentioned incarcerated people. The lack of studies on these two populations is essential, as they are arguably the most vulnerable populations mentioned in the review. This research gap may be due to the barriers preventing researchers from studying these populations, such as: IRB restrictions, challenges (perceived and real) building rapport vulnerable communities, logistical challenges with accessing communities with no permanent addresses, and a lack of available data. The lack of data on these populations is pervasive, especially in the widely used policy tools like the Social Vulnerability Index (SOVI) or California Communities Environmental Health Screening Tool (CalEnviroScreen 4.0; https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40) that rely on census data. Though these tools aspire to help researchers identify populations that are most vulnerable to environmental hazards, they do not include information on homeless populations and other groups left out of indicator tools. The lack of homeless or incarcerated populations mentioned in the review reflects this social group's broader invisibility to policy and research agendas.

Since many papers focus on public health, it is interesting that saltwater intrusion was only mentioned in 18 percent of the studies. Saltwater intrusion can cause many negative health impacts, including hypertension, high blood pressure, and infant mortality (Shammi et al. 2019; Talukder et al. 2017). Increased salinity can also affect the corrosion rates of iron pipes in water distribution and wastewater collection systems, leading to indirect impacts on health (Tansel and Zhang 2022).

Most of the literature reviewed (63%) did not mention a historical cause for a marginalized population's increased vulnerability and exposure to coastal hazards. This could be due in part to coastal scientists' focus on coastal processes and impacts rather than viewing these issues through the lens of humanities and social science disciplines. Articles that did not name a historical form of oppression either ignored the sociopolitical history of their study site entirely or carefully avoided the topic, hinting at a reluctance to engage in a deeper discourse on justice. An example of this subtle phrasing is seen in this quotation from a paper that concerns coastal risk for African American communities in Virginia: “The origins of such differential risk exposure might stem from the historical movement of vulnerable populations to undesired neighborhoods” (Eghdami et al. 2023). This quotation uses the passive voice to avoid assigning blame for why “vulnerable populations” have moved to “undesired neighborhoods” rather than naming the actual cause: centuries of systemic racism and minority oppression on the Southeast coast by the US government (Spears 2021). EJ scholarship that does not address the reasons why injustice is present in the first place assumes that the negative impacts on marginalized populations are at best exogenous or at worst the fault of the marginalized populations themselves. This can serve to further victimize these populations and lead to mistrust between researchers and the communities who they study (Burghardt 2013; Hutcheon and Lashewicz 2014). Several of the papers reviewed described this research gap and explained why it is problematic. Jacobs writes, “Very little recent social vulnerability research, in planning and elsewhere, names racism, classism, sexism or other forms of oppression as the real issues in communities” (2019). They warn that labeling people at vulnerable “locates the fault within them rather than the way the world treats them, which leads to their needs, priorities, and disempowerments [being] overlooked and overridden.” Since 24 percent of the literature reviewed describes how coastal hazards can lead to a loss of agency for “vulnerable communities", we echo concerns that labeling a population as “vulnerable” without explaining why they became vulnerable could further erode their agency. Hardy describes the issue of adaptation planning that overlooks or dismisses racial inequality thus benefiting some populations while abandoning others as “colorblind adaptation planning” (2017). These and other papers that discussed this research gap argued that the future of this field must include better examinations of the complex intersections between race, ethnicity, and class (Apelberg et al. 2005; Flores et al. 2021).

Another theme that stood out to us in the literature reviewed was the issue of terminology. Two main terminology issues were brought to light by several papers in our review, including how researchers use the term “Hispanic” and the lack of differentiation between different types of flooding.

While the terms “Hispanic” “Latino”, “Latin American” and “Latinx" were mentioned in 25 percent of the papers, these terms were often treated as one homogenous group. Studies widely use census data because it is free and accessible, but some papers problematize how this coarse data obfuscates finer-scale details. A study by Montgomery and Chakraborty is one of the only papers that disaggregates the Hispanic category into relevant country-of-origin subgroups. This led them to the finding that neighborhoods in Miami with greater percentages of Colombians and Puerto Ricans are exposed to inland flood risks, while Mexican populations are inequitably exposed to coastal flood risks (2015). Maldonado et al. (2016) also explained why lumping all Hispanic people together in one category, as is common in most analyses, causes the loss of important characteristics not only in terms of immigration status but also linguistically and culturally. They write, “Disregarding those and other differences leaves a significant gap in hazards and EJ research… Due to this gap, hazard reduction efforts may fail to properly serve groups such as Hispanic immigrants.”

Since the literature reviewed was focused on the EJ aspects of coastal hazards and not the hazards themselves, the exact causes of flooding were often not described. It is unclear in most papers whether they are describing inland flooding, coastal flooding, tidal flooding, or pluvial flooding. Flood type is essential to understanding the impacts of flooding on communities and not distinguishing between inland flooding or coastal flooding can lead to conclusions unsupported by the broader EJ literature (Montgomery and Chakraborty 2015).

Conclusion

Scientific literature that examines coastal hazards with an EJ lens has grown over the years. The majority of the studies we reviewed focused on the US, coastal hazards that directly increase flood risk, low-income, elderly, or non-White populations, and negative impacts on physical and mental health.

When we examined solutions to EJ issues on the coast, there seemed to be a mismatch between the main cause of vulnerability mentioned — less access to financial resources — and the most commonly proposed solutions: increasing understanding of EJ issues among coastal practitioners and scholars and the need for more collaborative, adaptive, participatory engagement. These solutions will not alleviate the structural and economic reasons why some populations are presently more at risk to coastal hazards. Research has shown that there are ways of improving a community's access to financial resources, including giving money directly to socioeconomically disadvantaged households. Direct payments not only decreases poverty and improves psychological well-being, but can also lead to home improvements, increasing resilience to natural hazards (Haushofer and Shapiro 2016).

The studies that mention historical systems of oppression often called for more transformative solutions to environmental injustice on the coast, such as institutional change that considers coastal ecosystem integrity as a common pool resource (Jurjonas and Seecamp 2020). These transformative solutions were rare in the literature but in comparison make the other solutions, such as strengthening local governance and institutions, seem ineffective or incomplete. Such findings imply the need to dismantle racist, capitalist structures, and writing a paper on EJ without engaging in the discourse on justice cannot effect positive change.

Discussions about transformative adaptation systems change are slowly becoming more common. To quote the Fifth National Climate Assessment, “Adaptation planning can more effectively reduce climate risk when it identifies not only disparities in how people are affected by climate change but also the underlying causes of climate vulnerability. Transformative adaptation would involve consideration of both the physical and social drivers of vulnerability and how they interact to shape local experiences of vulnerability and disparities in risk” (May et al. 2023). It follows that as our coastal ecosystems undergo irreversible ecological transformations, so should our social systems.

In light of the literature review conducted here, which shows how coastal hazards can both uncover and exacerbate oppressive social structures, we suggest three recommendations for coastal hazard researchers and four policy recommendations. For coastal hazard researchers we recommend, that future EJ research on the coast more comprehensively engages with the oppressive social structures such as systemic racism that have led to the environmental injustices being described, that studies should acknowledge the limitations of using census data to describe communities in EJ research, and when possible, go beyond the use of previously-created indicators to pursue a deeper understanding of their study population, and proposed solutions to EJ issues on the coast should consider avenues for decreasing specific vulnerabilities to hazards as well as approaches to addressing the structural conditions that increase or maintain these vulnerabilities.

Our four policy recommendations for improving the state of coastal environmental justice are to,

1. take account of social groups that are likely to be excluded without intentional action when planning for coastal hazards,

2. improve the collection and accessibility of data and information related to underserved communities such as homeless and incarcerated populations so that they are not invisibilized in coastal hazard policy,

3. create spaces for marginalized social groups to participate in decision making procedures to ensure more representation of diverse perspectives and compensate them for their time,

4. address the systemic and structural drivers that render certain groups marginal and more vulnerable to coastal hazards.

Through sharing these findings, we hope to further the goal of the coastal EJ movement so that every coastal population enjoys the same degree of protection from environmental and health hazards, has equal access to the decision-making process, and has a healthy and safe environment in which to live, learn, and work.

Limitations

The significant bias towards papers in the US is likely partly because over 95 percent of papers indexed by Web of Science are written in English (Vera-Baceta et al. 2019). This likely also favored Western (European and primarily English-speaking, such as the US and Australia) institutions. Over three-quarters of the literature reviewed (78%) was authored solely by authors in Western institutions. American institutions were overrepresented in authorship – 83 of the 117 papers had an author affiliated with an American institution, compared to the 62 papers focused on the United States. Australia, Canada, and the UK were also overrepresented in authorship, being involved in 8, 5, and 11 papers, respectively.

Introduction to Chapter #2

As climate change intensifies environmental justice concerns on the coast, what tangible actions can be taken to support coastal stakeholders working on these issues? In my second chapter, I discuss how improving coastal data access and delivery can increase capacity and lead to better decision-making. This chapter was part of a US Geological Survey's Coastal and Marine Hazards and Resources Program (USGS CMHRP) project called, "State of Our Nation's Coasts".

The USGS CMHRP works to develop and apply hazard science to help promote the safety, security, and economic well-being of the Nation by delivering actionable assessments of natural hazards and risk. The "State of Our Nation's Coast" project was a transdisciplinary, cross-center project to improve the discovery and accessibility of products produced by the USGS CMHRP. This project was part of a continuing effort to better communicate the diverse portfolio of USGS coastal hazards science in an accessible way that could inform decisions by coastal actors.

Chapter two of this dissertation centers on the work that I have done to support the "State of Our Nation's Coast" project and the creation of the USGS Coastal Science Navigator[1], a platform and data portal that the USGS Coastal Change Hazards team has recently released. The findings of this work are broadly applicable and could support any organization hoping to better meet the needs of coastal stakeholders.

[1] https://www.usgs.gov/apps/coastalsciencenavigator/index.html

Chapter #2: User Engagement to Improve Coastal Data Access and Delivery

Executive Summary:

A priority of the U.S. Geological Survey (USGS) Coastal and Marine Hazards and Resources Program focus on coastal change hazards is to provide accessible and actionable science that meets user needs. To understand these needs, 10 virtual Coastal Data Delivery Listening Sessions were completed with 5 coastal data user types that coastal change hazards data are intended to serve: resource managers, consultants, local planners, State planners, and non-USGS researchers.

During these listening sessions, participants revealed challenges to coastal data use. Four key themes emerged:

1. Participants felt overwhelmed by the growing number of web tools that provide coastal data and explained difficulties differentiating and keeping track of similar tools from different agencies.

2. Local planners, State planners, and resource managers reported insufficient staffing and funding that hinder their ability to digest and discover relevant scientific information.

3. Participants noted difficulties searching for and finding the data they need.

4. Participants reported difficulties understanding and accurately applying coastal data to decision making.

The specific coastal data and information needs described by participants are highlighted with four main themes, including the following:

1. All participants reported data needs across every temporal scale, but user types differed in their spatial scale preferences.

2. Participants described persistent data gaps, including a lack of data in the surf zone and difficulties finding socioeconomic information on the coast.

3. All five user types used web tools in their workflows, but researchers and consultants often used web tools to validate results or download data, whereas local planners, State planners, and resource managers reported a need for more simplified web tools.

4. Participants reported that there is a need for increased public awareness, outreach, and education on coastal topics and climate change.

Many participants shared suggestions on how to make USGS coastal hazard science more accessible and actionable. They recommended leveraging data across study sites and regions to help improve capacity issues and called for more communication and collaboration among and within Federal agencies.

The synthesized information from the Coastal Data Delivery Listening Sessions provided in this report can help the USGS and those working on coastal challenges better understand barriers to coastal information use and the exact data requirements of different coastal data users.

1. Introduction

As part of the U.S. Geological Survey (USGS) Coastal and Marine Hazards and Resources Program (CMHRP), a priority of the programmatic focus on coastal change hazards (CCH) is to increase the visibility of USGS coastal hazards science and prioritize science that meets stakeholder needs, including actionable products and tools that support hazard mitigation and the protection of life and property. CCH products can fail to reach their intended user groups because they tend not to be codeveloped with potential users, and therefore, they may not be immediately applicable to specific coastal management issues or confuse users in the information space they occupy. Stakeholders have communicated to CCH scientists that they are already overwhelmed with too many tools, have a hard time keeping track of them all, and may not even be aware of which are most useful. As a result, the bar is high for stakeholders to adopt any new tool or information source.

As CMHRP staff work within CCH to provide meaningful and actionable information, a key consideration is how best to deliver science products such that the information they provide is easy to find, navigate, understand, and apply. Central to this problem is defining the intended audience. By considering who the intended users are for each type of information, USGS scientists can design and refine robust, relevant, and timely scientific products users can directly apply to meet their needs (Corburn, 2003). By placing users as central to work in CCH, user needs can effectively inform and guide scientific products to determine which needs are not yet met and how CCH scientists can provide more accessible and actionable data and information to meet them.

This study was part of a CMHRP effort guided by social science research to understand coastal stakeholder needs, particularly those of audiences the program intends to reach with its products but whose experiences and needs have not previously been investigated using empirical social science methods. To address this gap, this report summarizes the results from a series of listening sessions conducted in the spring of 2021 across five intended CCH user groups—resource managers, consultants, local planners, State planners, and researchers—to better understand how these different coastal data users integrate scientific information into decisions. Throughout this report, “stakeholder” refers to any group or individual who can affect or is affected by the achievement of an organization’s objectives (Freeman, 1984), and “users” refers to the subset of stakeholders who will use or operate the scientific product, data, tool, or platform being developed.

The next sections, “Background,” “Research Objectives,” and “Methods” describe the human-centered design (HCD) approach and how the focal user groups were determined. The remainder of the report shares participant suggestions to increase the accessibility and use of coastal science data products to support scientific agencies and organizations. These suggestions highlight data gaps and information needs and identify preferred data formats.

2. Background

This report is part of a larger effort since 2019 within the CMHRP CCH programmatic focus to improve applied scientific tools for end users by increasing the visibility of coastal hazards products and improving access to information for decision making and resource management use (CMHRP, 2020). This work includes the creation of robust products and tools that support hazard mitigation and coastal resilience, informed by stakeholder needs. To support this effort, USGS social scientists and physical scientists partnered in the application of an HCD approach to guide the iterative codesign of information products with stakeholders.

The HCD and related techniques (for example, user-centered design [Norman and Draper, 1986] and design thinking [Johansson-Sköldberg, Woodilla, Çetinkaya, 2013]) approach innovation as a repeatable and structured process. Further, the ability to innovate is considered a skill with which individuals and teams can develop greater competency through repeated practice (Ulibarri and others, 2019). For software development, one of the key theoretical and methodological insights of HCD is that user or stakeholder input can aid every phase of a tool design process (Seffah, Gulliksen, and Desmarais, 2011). The HCD process is used to humanize design and implies a highly empathetic approach that incorporates the emotional and psychological preferences of users and the tangible ways they interact with an information product (Norman, 2013). For example, the result of greater user input is often more successful web applications (Vredenburg and others, 2002).

Generally, HCD depicts the design process as a series of iterative stages by which a team develops an increasing understanding of users' needs and a finer match of a tool's capacities with those needs (fig. 6). By moving iteratively and consciously through the cycle of innovation—defining the audience of a tool and determining their needs in the "discovery" phase; brainstorming solutions, developing prototypes, and testing them with stakeholders in the "design" phase; and then scaling and evaluating in the "deliver" and "measure" phases—projects using the HCD approach can increase CMHRP capacity to effectively deliver actionable science. This research focused on the "discover" phase, particularly defining the audience and understanding their needs.

To be responsive in the "discover" phase, CCH scientists designed and conducted 10 Coastal Data Delivery Listening Sessions. Identifying which user types would be included in the Coastal Data Delivery Listening Sessions was part of CMHRP's effort to incorporate HCD methodologies and is described further in the subsection of this report, "Defining the Audience."

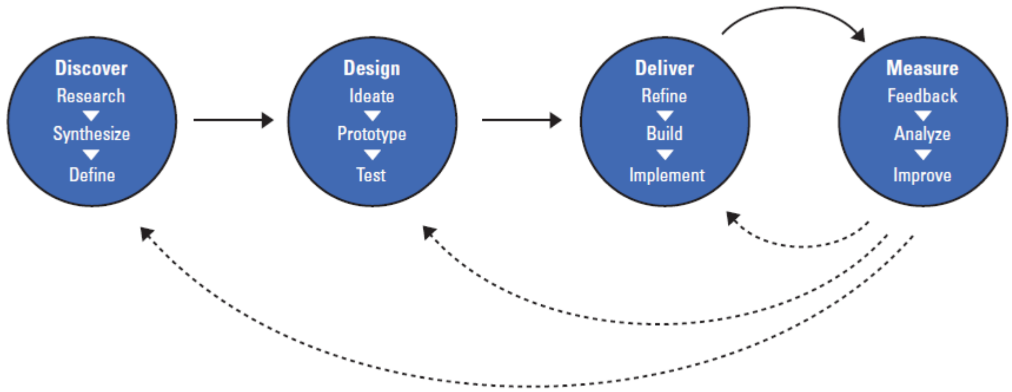


Figure 6. Depiction of the process of innovation using a human-centered design cycle. Human-centered design is a structured, cyclical process for designing information products or government services. Discover allows for deep and empathetic exploration of context and how intended users understand a problem space. Design ensures insights from stakeholder engagement are applied to develop and test one or more possible solutions. Deliver includes scaling and iteration. Measure gathers information to assess how well a product or solution performs and how it might be improved (from Office of Personnel Management, undated).

3. Research Objectives

A key objective of the CMHRP-CCH programmatic focus is to make science accessible and useful to coastal stakeholders. Meeting this goal requires identifying who uses CCH data, determining which needs are already met and which are not, and learning how CMHRP can improve accessibility and the relevance of the data it provides. The Coastal Data Delivery Listening Sessions were designed by USGS social scientists with input from CMHRP physical scientists to answer a central research question: Who needs what coastal data in what form to complete what tasks? This question provided the overall framing to understand how coastal decision makers—specifically resource managers, consultants, local planners, State planners, and non-USGS researchers—use data and information to make decisions. The structure of the listening sessions followed this main research question closely and included three intentionally discrete discussion topics: the tasks that users complete in their roles, the data or information they need to complete those tasks, and the required or preferred format of those data types.

To answer the main research question broadly, listening session participants were asked to speak about their experiences with coastal data and information in general, including USGS data and that provided by other sources. Understanding the full picture of how the five identified coastal data user types interact with data will allow USGS CMHRP coastal hazard scientists to understand (1) where there are information gaps that CMHRP science could fill, (2) where there are perceived gaps that, unknown to participants, the USGS may already be addressing, and (3) where there are already trusted sources of accurate information on a topic that CMHRP does not need to supply. Understanding the differences among user types will enable USGS CMHRP scientists, and other providers of coastal data and information, to provide more actionable science that is readily accessible to stakeholders in their preferred format.

4. Methods

This section includes information about the process of selecting the intended audiences on which to focus the project, the design of the listening sessions, and how data were analyzed.

4.1. Defining the Audience

Coastal stakeholders include a wide range of user types, from the public to resource managers to policymakers, with a correspondingly wide range of needs and preferences related to coastal data delivery. To learn more about these users' experiences and needs, CMHRP CCH scientists had to define exactly whom among these stakeholders they wanted to investigate further. This is sometimes referred to in the HCD literature as "defining the audience" (Loucks, 1995).

Recognizing that the listening sessions would only be able to investigate at most five user types in detail, a small group of CMHRP CCH scientists (15 participants) met over the course of several meetings to identify the specific types of coastal stakeholders who rely on USGS coastal data and information products to make decisions. The team was polled on which user types should be included in the listening sessions, and these results were ranked by the number of mentions across the group. This list served as the basis for the ensuing conversations about which user types most closely fit the following criteria: (1) if they were likely to use CCH information products, (2) if their needs had not already been specifically considered through existing CCH tools and products, (3) if they were assumed to have similar or compatible needs to the other user types selected for this research, and (4) if they had unique needs that needed to be addressed by separate, targeted research (for example, Tribal nations).

As a result of this team process, the five user types that were invited to the Coastal Data Delivery Listening Sessions included resource managers, consultants, local planners, State planners, and non-USGS researchers (table 2).

Although CMHRP CCH science supports users outside of these five user types, these types were agreed on as a starting point to streamline coastal information product development. User types that were identified as being important to the CCH mission but did not meet the initial selection criteria included investors, insurers, underserved groups such as the unhoused, national policymakers, congressional staffers, lawmakers, the public, boundary organizations, interagency groups, Tribal nations, and emergency responders. Additional research efforts could provide insight into the needs of these users.

4.2. Listening Session Rationale

Listening sessions were chosen as the method for this research because they allow for the collection of data about content (the "what" of things) and process (the "how" of things; Bernard, 2018). In listening sessions, the resulting data comes from participant interaction based on topics supplied by the facilitator who moderates the conversation (Morgan, 1997). This format allows researchers to capture interactions among people with similar qualities, which for the purpose of this research was user type. The listening session methodology ensures that when a participant explains an experience or a challenge, the other participants in the listening session can agree with their sentiment, build on it to refine or add nuance, or in some cases, provide an alternate experience or a possible solution to their problem. In one-on-one interviews, insights resulting from participant interaction are not possible. Another benefit of the listening session method was that it allowed researchers to gather information from more research participants in a shorter amount of time than could be accomplished with one-on-one interviews.

Table 2. Examples of tasks, goals, environments, and job titles of the five user types that were invited to the Coastal Data Delivery Listening Sessions, including resource managers, consultants, local planners, State planners, and non-U.S. Geological Survey researchers.

User type	Example task	Example goal	Example environment	Example job titles
Resource manager	Balance resource access and sustainability within parameters of laws and regulations	Save time and resources by finding interpretive information products that can be used to communicate to the public, politicians, and regulators	Resource limited, may not have certain software, works in an office setting	Coastal landscape adaptation coordinator, natural resources manager, regional coordinator
Consultant	Quantify benefits and tradeoffs of different adaptation methods	Get decision makers the right information, help clients figure out which scenarios to look at, determine which products help managers	Advanced computer user, high computing power, access to varied software	Principal engineer, sustainability and climate action manager, senior planner
Local planner	Sediment management, determine where and how to reuse sediment from shoreline replenishment, adaptation planning for sea-level rise	Find local human-based metrics to support decisions and defend those decisions to stakeholders	Overworked and resource constrained, attends internal and external (community) meetings, possibly tech savvy	Principal watershed planner, director of coastal resources, planning manager, climate resilience manager, city planner
State planner	Help communities access Federal funds, give grants to communities, get local government access to funding and consultants	Supply correct data on the correct spatial scales for users and consultants	Dependent on staff to conduct data collection and analysis, travels frequently to coordinate with State agencies	Senior coastal engineer, coastal resilience specialist, program manager
Non-U.S. Geological Survey researcher	Analyze the present risks of coastal hazards at different temporal scales	Find reliable information and data that they can plug into their research to serve as baseline data	Advanced computer user, high computing power, access to varied software	Professor, marine scientist

4.3. Sampling Method

The stakeholders who participated in the listening sessions were identified by USGS CMHRP physical scientists who work within CCH. These stakeholders, many of whom had existing relationships with USGS scientists and experience with USGS coastal data alongside other coastal data resources and tools, had local knowledge of how USGS science is or is not used in coastal decision making.

Prior to the listening sessions, CCH scientists were asked to provide a list of stakeholders with whom they interact who fit into the user types of resource manager, consultant, local planner, State planner, and non-USGS researcher. The resulting contacts (234 in total) were organized in a spreadsheet by user type, organization, and the region of the stakeholder. Invitations to participate in the listening sessions were sent by email to approximately 20 stakeholders of each user type, with care taken to invite stakeholders from all U.S. coastal regions included in the research: Southeast (including the Gulf and the

Caribbean), Northeast (including New England and the Mid-Atlantic), West Coast, Northwest-Pacific Islands, and National (stakeholders who work across multiple regions). Regions that were not included in this research were Alaska and the U.S. territories, which have unique needs. For every user type, 2 listening sessions were conducted, resulting in 10 listening sessions total. Additionally, 1 interview was conducted with a participant who was unable to attend the listening sessions but still wished to participate. Overall, 95 stakeholders were sent invitations to the Coastal Data Delivery Listening Sessions by email, and 48 participated in this research (table 3).

Table 3. Type and number of participants of the Coastal Data Delivery Listening Sessions.

Listening session	User type	Date (2021)	Number of participants
1	Local planners	23–Feb.	2
2	Local planners	24–Feb.	2
3	Researchers	4–Mar.	4
4	Researchers	5–Mar.	7
5	State planners	9–Mar.	[1]6
6	State planners	11–Mar.	9
7	Resource managers	24–Mar.	4
8	Resource managers	25–Mar.	4
9	Consultants	26–Mar.	6
10	Consultants	1–Apr.	4
Total	—	—	48

[1]This total includes one participant (State planner) who opted for a one-on-one interview on March 2, 2021.

4.4. Listening Session Structure and Protocol

Each Coastal Data Delivery Listening Session was designed to include people of the same user type from across regions, a design made easier by the virtual format of the listening sessions. For example, one of the listening sessions included consultants from Florida, Washington, California, and Massachusetts. This design allowed listening session participants of similar roles to compare notes and expedited data analysis after the listening sessions were complete. Furthermore, by including participants from different regions in each session, we decreased the chances that participants would know one another, as familiarity within groups tends to inhibit participant disclosure (Krueger, 1989).

The listening sessions were intended to include no more than six participants each to increase speaking time for each participant and participant interaction over the 2-hour period (Morgan, 1997). However, in two listening sessions, participants chose to bring additional members from their organization who were not originally on the invite list. These additional participants were included in the listening sessions as if they had been invited.

Two USGS CMHRP CCH researchers were present during the Coastal Data Delivery Listening Sessions at all times. One social scientist facilitated all 10 listening sessions while the CCH physical scientist role rotated, allowing 10 CCH physical scientists the opportunity to observe the listening session process and hear directly from coastal stakeholders. The CCH physical scientist was encouraged to turn off their camera and mute themselves after being introduced. They also helped handle technical questions and managed the chat box.

These listening sessions were based on a protocol for focus groups conducted by USGS scientists on water data delivery to support the Water Mission Area's development of a regional Integrated Water Availability Assessment (Restrepo-Osorio and others, 2022). For both projects, the protocol was guided by the key question following Cantor and others (2018): Who needs what data in what format to make what decisions? The focus groups concerning water data delivery were organized with a regional focus, and the user types were defined during data analysis. In contrast, the Coastal Data Delivery Listening Sessions identified user types before the research was conducted and based the sampling strategy on these user types. The listening sessions began with participant introductions that included asking participants to share the coastal issue that keeps them up at night. After introductions, the facilitator gave a short introductory presentation on the background of the USGS CMHRP

CCH programmatic focus, a brief overview of the CCH geonarritives (Lentz and others, 2020), and the impetus for the listening sessions: to answer the question, "Who needs what coastal data in what form to complete what tasks?" For the remainder of the listening sessions, the facilitator led the participants through a series of semi-structured, open-ended questions about participants' tasks, data, and data format needs (app. 1). Open-ended questions are those with answers not limited to a certain set of options that allow for a multitude of unique responses. The semi-structured nature of the listening sessions allowed for new questions to arise spontaneously in free-flowing conversation. This gave the facilitator the ability to keep the conversation active and ask follow-up questions of participants when more context was needed.

Participant responses were recorded by the facilitator on virtual sticky notes on a collaborative whiteboard visible to research participants. The whiteboard included four categories: tasks, data, format, and needs. Each listening session was 2 hours long, resulting in approximately 20 hours of data.

4.5. Data Analysis

Transcription of the listening session recordings was provided by a professional transcription service. The conversation transcripts were qualitatively analyzed using NVivo (release 1.3; Lumivero, Denver, Colo.) to provide more detailed information about how data needs differ by user groups and types of tasks. Qualitative analysis uses a rigorous, systematic process called coding that identifies concepts or themes and assigns labels and categories in sections of transcribed text (Saldaña, 2016). The analysis of the listening session transcripts used deductive coding, in which codes were developed before analysis takes place, and inductive coding, in which codes were developed iteratively throughout the coding process (Guest and others, 2012). For example, the code labeled "Data Needs" was created prior to the coding effort based upon the design of the listening session protocol, but its subcode categories (for example, “socioeconomic,” “real-time,” and “value”) were created iteratively as the coding took place. The full codebook can be found in appendix 2.

After the data were coded, the anonymized coded segments under “Data Needs” and “USGS Data Needs” were categorized and shared with several CMHRP CCH physical scientists to ensure that the data categories would suit their understanding of the data, making it more accessible to the primary intended audience of this information: CCH scientists and especially those working on coastal hazards and resilience. This cross-disciplinary collaboration among researchers ensures that the data collected (and presented in this report) is actionable.

5. Results of Listening Sessions

This section describes the results of the listening sessions, including the top reported concerns of participants, barriers that participants experienced using coastal data, needs that participants described, and participant suggestions for USGS.

5.1. Top Concerns of Listening Session Participants

Each listening session began by asking participants, “What coastal issues keep you up at night?” The analyzed responses shed some light on the coastal concerns of the listening session participants (fig. 7).

More than half of the participants (54 percent) responded with concerns related to climate change and sea-level rise (SLR). These included concerns about SLR, flooding, geologic hazards, climate change policy, and vulnerabilities faced by coastal communities.

Other top concerns were related to hurricanes and tsunamis (15 percent of participants) and data for decision making (also 15 percent of participants). Because the participants were volunteering to participate in a Coastal Data Delivery Listening Session, it is not surprising that data for decision making was top of mind. These participants were concerned about getting science directly integrated into decision making and making coastal data more applicable, accessible, and actionable. Participants concerned about storms and tsunamis were primarily from Florida and Hawaii. Their concerns centered on how to improve forecasting and emergency response efforts.

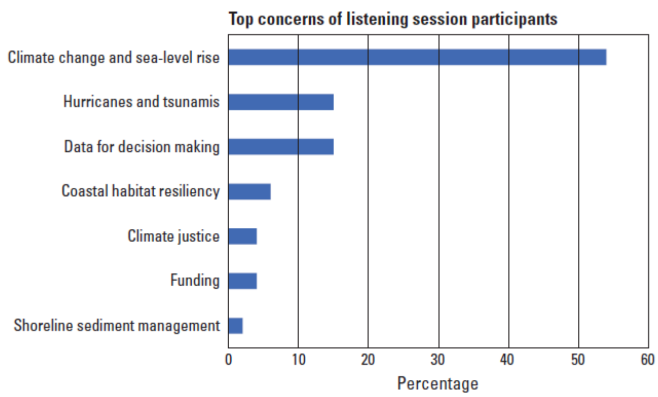


Figure 7. Top concerns of listening session participants by the percentages of participants.

The remainder of the responses focused on coastal habitat resiliency (6 percent of respondents), funding (4 percent), environmental justice (4 percent), and shoreline sediment management (2 percent). For those related to habitat resiliency, the focus was on habitat restoration; one respondent reported that they need to know what adaptation strategies "work with the ecology instead of against the ecology."

5.2. Participant Experience—Barriers and Challenges to Coastal Data Use

The listening session participants explained many different barriers and challenges that they face in their work, including the following:

1. Finding data and navigating among data sources;

2. Understanding how to apply data;

3. Being overwhelmed with too many web tools and applications;

4. Having insufficient time and personnel;

5. Needing data that does not exist, is not publicly available, or is in an inaccessible format;

6. Needing more education and outreach materials to describe coastal processes; and

7. Acquiring funding for projects.

The top two issues that were mentioned by all the participants in the listening sessions were locating relevant data and needing more guidance on how to apply coastal data and information. These top two barriers will be discussed in depth in the following sections: “Too Many Tools,” “Data Access and Navigation,” and “Understanding How to Apply Data.”

Another common challenge expressed by participants was a lack of capacity related to insufficient time and personnel. Participants called for more Federal interagency collaboration on coastal hazards as a method of relieving some capacity issues. In a listening session with resource managers, the group agreed that it is frustrating when they are trying to help their stakeholders find coastal information and must direct them to the Federal Emergency Management Agency (FEMA) site, then a National Oceanic and Atmospheric Administration (NOAA) site, then a USGS site, and then, after sifting through all three agency websites, explain all the different limitations associated with each data source. This desire for greater collaboration is described in more detail in the section “Participant Recommendations for USGS.”

Barriers participants spoke about that were less common included data formats that they were unable to access or use, needing data that may not exist, and needing more outreach and education on coastal hazards for the public from trusted sources like the USGS and other Federal science agencies. Listening session participants also spoke about difficulties acquiring funds for research efforts or funding that would allow coastal managers at the local and State levels to pursue scientifically supported coastal adaptation measures.

5.2.1.“Too Many Tools”

Advances in technology that facilitate near-real-time data collection and collaborative information sharing, coupled with computational advances such as machine learning and cloud computing services, have made it easier to develop sophisticated web tools (Shim and others, 2002). This also is the case in the coastal data and information space; however, a startling number of tools are never or hardly used at all (Adelman, 1992; Walling and Vaneeckhaute, 2020). One of the key results of the listening sessions was that participants felt overwhelmed by the number of web tools that serve coastal data and many said that there are “too many tools.” A resource manager explained how the number of web tools has increased through time,

> “10 years back * * * NOAA put together this whole guide to sea level rise tools. It was a book of about six or eight things. Now when you go to the [NOAA] Digital Coast and you look at the tools, it’s like a whole page that goes on and on and on. There are too many tools. You don’t know which is the right one to use for the right purpose * * * We don’t need another tool.” (user type: resource manager)

Given the high number of similar tools that answer similar questions, listening session participants explained how they account for this in their workflow either by picking one tool to be familiar with or, alternatively, by looking at everything available to corroborate their results. For example, one participant explained how they create a preponderance of evidence by incorporating multiple tools into their workflow,

> "Sometimes we're not sure exactly which tool is best for certain scenarios. Generally, what we do is look at everything that's out there * * * If a bunch of different mappers show an area subject to storm surge from a certain category of hurricane, then we can feel pretty comfortable saying, 'This area is still vulnerable'." (user type: resource manager)

Another solution that respondents reported was either prioritizing more localized tools or building their own localized tools. A resource manager on the Cape Cod Commission explained that their local SLR viewer (Cape Cod Commission, 2019) has become what most stakeholders in the region use to answer their SLR-related questions because of its accessibility, despite the Sea Level Affecting Marshes Model, or SLAMM model (Warren Pinnacle Consulting, Inc., 2017), potentially providing more specific information on salt marsh effect.

Although the large and increasing number of web tools that include coastal data and information represents a growing understanding of coastal processes and greater attention to making coastal information actionable, coastal stakeholders struggle with this surplus of tools and datasets, similar to stakeholders in other resource contexts (Cravens, 2018). Coastal data users reported that they often do not know which information product to use, especially regarding multiple models that all show SLR but differ in their estimations of projected sea-level increases. As a State planner described,

> "I'm just very concerned we're all looking for that one sea-level rise model that will give us that data and give us those answers and there's really no one model. That's our one issue as being the in-between between researchers and policy * * * that's my biggest fear." (user type: State planner)

The number of similar tools from different Federal agencies further complicates this landscape. Listening session participants described having too many tools to look at in too many places and needing to spend extra time sorting out the differences among tools from various agencies' websites. Calls for more interagency collaboration on coastal science, specifically among the USGS, NOAA, U.S. Army Corps of Engineers, and FEMA, were heard throughout the listening sessions and are described in detail in the section, "Participant Recommendations for USGS."

5.2.2. Lack of Capacity

The need for more time and additional staffing was expressed in the listening sessions held with local planners, State planners, and resource managers. Although there were specific comments about needing more personnel, especially those with expertise in geographic information systems (GIS) and engineering, many participants focused instead on needing more time. Many listening session participants seemed to believe that the number of staff in their organization was unlikely to change and often seemed to share pessimistic attitudes about not being able to do "enough." As a local planner said, "You're looking at the staff of one here. We're just a small municipality". These coastal data users are overburdened and never feel like their work is complete. Another explained this problem in depth,

"We're playing the Dutch boy with a finger in the dike, just trying to hold on as the things are changing. It's never enough * * * it's almost impossible to keep up with. I'm sure there are many issues that we'd like to deal with, but they just get pushed off to the back burner. We just deal with the crisis of the day, which is [a] typical governmental approach. It's just the nature of the beast." (user type: local planner)

Local planners and State planners with lean staff and insufficient time to digest and discover scientific information suggested that they would benefit from science organizations working together to support new ways of communicating and collaborating across coastal data users and producers. Coastal managers working to protect their communities from coastal hazards are often isolated from coastal managers in other locations who face similar challenges. This separation can lead to greater uncertainty and more effort than may be needed compared to when people working on similar issues are connected and able to share information with each other. As one explained,

> "We're at what I call the bleeding edge. We're doing stuff that others haven't done. You're kind of lonely out there and I think that makes it more of a challenge." (user type: local planner)

This local planner went on to explain that they work to solve this issue by finding people that are "kind of doing the same thing" but that it still feels like "the blind leading the blind." This led to a conversation with participants in the listening session about a need for better knowledge on who is doing what in the coastal decision-making space, especially in locations with similar coastal features and problems, and having access to those contacts.

In the same listening session, another participant explained that many coastal planning decisions are made by local boards consisting of citizens "wearing multiple hats" who lack either the access or time necessary to get the coastal information they need. They elaborated on this by sharing their own experience on a local coastal planning board,

> "I'm on one of these local boards and I thought so many times of, 'Wow, we really don't have this information * * * and my staff member doesn't have the capacity to tell me either.' The fact is all of that information is out there, but it's not getting down to the people sitting on the boards." (user type: resource manager)

Coastal stakeholders may know what types of information they need to plan but often either do not know where to find the information or lack the capacity to find it.

5.2.3. Data Access and Navigation

When asked about the barriers and challenges listening session participants faced while using coastal data and information, participants noted difficulty searching for, and finding, the data they need. Methods and places for finding coastal data reported by participants fell into three main categories: relationships, search engines or data portals, and web pages or web tools (fig. 8). Some interviewees also reported that they create their own data in house.

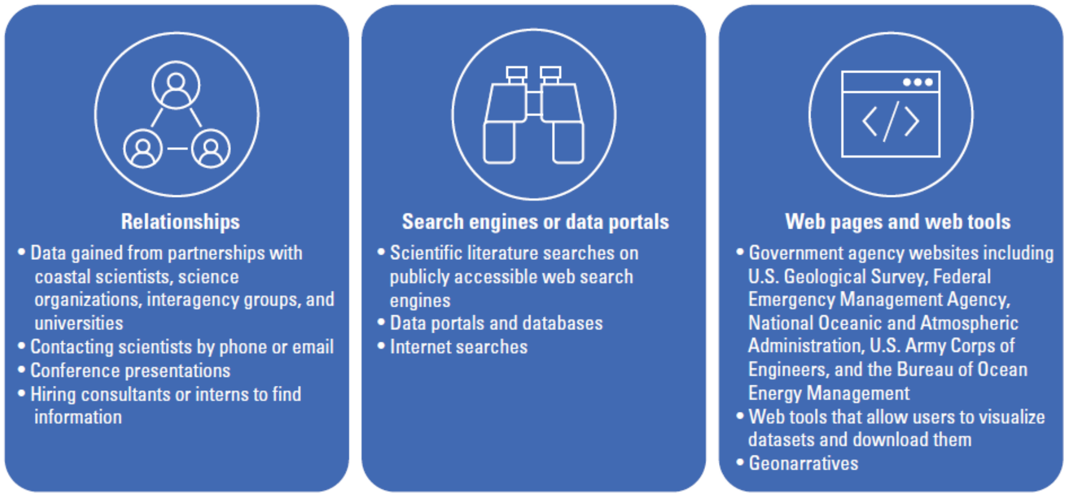


Figure 8. The three ways research participants locate and discover coastal data and information.

Although these methods of finding coastal data work well in many cases, listening session participants still reported trouble finding the data they need. For example, participants use internet searches to find coastal information and data suggests that they lack access to better pathways or specialized databases that are more reliable and trustworthy. A participant explained why they use internet searches to find coastal data,

"Well, I hate to admit it, but I go to Google just because when you enter a particular agency's site, they're all different. You don't know how to navigate. You don't know if you've even got the right agency. [Google] can be helpful, but also, it's detrimental in that it brings up a lot of garbage that isn't useful to you. Actually, what I'd love to do is be able to pick up a phone and talk to somebody and say, where would you get this? Do you know anybody?" (user type: local planner)

This quotation shows how the presence of multiple locations and websites for similar data can confuse coastal data users and make searching for relevant data more difficult. This is closely tied to the sentiment that there are too many web tools, resulting in difficulties for users who cannot figure out which tool is optimal for their needs. Although difficulties finding data were expressed by all user types, the challenge of accessing underlying data was more often described by the participants who fit into the non-USGS researcher or consultant user types because they are more likely to use underlying data for their own analyses than the other three groups. Local planners, State planners, and resource managers were more likely to rely on others, usually researchers and consultants, to collect and analyze data for them. Because all listening session participants had existing relationships with USGS CMHRP CCH scientists due to the sampling strategy, many participants explained that they will often contact USGS scientists for coastal information, especially to clarify the differences among different datasets, models, or tools. As one participant explained,

"There's so much. I find something that's useful and I use it, but I'm like, 'I don't know if this is the most up-to-date thing. I don't know if this is the best thing. I don't know if there's something else that somebody's working on that uses this to do something better." (user type: resource manager)

A possible solution to the issue suggested by this resource manager was to build more partnerships with data producers. However, participants reported that they often do not know whom they should contact about specific types of data or that sometimes the person they contact never responds. This shows how coastal stakeholders need more support in accessing coastal information than has historically been provided. It also suggests that there are likely other stakeholders without relationships with USGS scientists for whom this issue is even more acute or prevalent. Another method of data access included using geonarratives to learn about available coastal data,

"For me, the most helpful things are those StoryMaps that explain what the data is and walk you through a story in a really easy way to understand. Then I'm like, 'Oh. I know the people who would use this, and it would really help them in what they're doing.' That's, for me, the most useful kind of data delivery method in my day-to-day." (user type: resource manager)

To solve these data access and navigation issues, participants across all listening sessions explained that they would prefer to have a data navigation platform or one central database for trustworthy coastal data. A resource manager described how a data navigator could suit their needs,

"Sometimes I think it would be helpful if there were a data navigator. If you could go to USGS and there was a website where you could put in your data need and somebody could get back to you about, does that data exist? Point you to it. Advise you on what the best data source would be. Maybe there's three or four different datasets, and if there was an expert in those that could help you pick." (user type: resource manager)

This description of a data navigator shows how some coastal data users were looking for hands-on guidance about which datasets to use and how to use them. Without this hands-on assistance, much of the data needed for scientifically informed decision making does not easily or reliably get into the hands of the decision makers who want to find it.

5.2.4. Understanding How to Apply Data

Alongside challenges in finding the information they need, participants reported difficulties understanding and accurately applying coastal data to management decisions. Participants in the local planner, State planner, and resource manager categories reported needing more support making sense of data that spans multiple disciplines, figuring out which data most appropriately applies to their management issue, and understanding and communicating uncertainty of the data and how that uncertainty factors into their management decisions.

Reconciling discrepancies among different datasets, models, or tools was described as difficult for stakeholders, especially as they attempt to make decisions on complex issues like SLR, which integrates information from multiple systems (coastal, groundwater, and riverine) and therefore different scientific disciplines. Listening session participants use a wide range of strategies to locate relevant and up-to-date data and information. However, data coming from multiple sources often differ in format, how they are collected, and how they are presented. A resource manager described challenges synthesizing disparate data sources,

“Oftentimes, you’re dealing with piecemeal data. It may be good data, but it’s collected by different organizations. Pulling them together can be really difficult.” (user type: resource manager)

Difficulties associated with combining data from multiple sources were commonly mentioned in the listening sessions. A local planner explained how trying to use data from multiple sources can lead to greater uncertainty,

“Some of the data we're comparing apples to oranges, but it's what was out there. We used it the best that we could with a lot of caveats.” (user type: local planner)

Adding additional caveats to coastal information, especially in relation to projected data, means adding uncertainty on top of uncertainty. This issue was exacerbated when participants spoke about difficulties deciphering the risks posed by multiple hazards and their efforts to understand the interplay among different systems (such as creeks, rivers, groundwater, and the ocean).

Many reported issues surrounding the use of coastal data are linked to the inherent uncertainty of many data types, specifically those that project future outcomes under climate change. Coastal decision makers described working in a state of permanent change and struggled to understand which projections to use in their planning efforts. Local and State planners explained that they need to appropriately incorporate data uncertainty into their risk thresholds to make concrete, time-sensitive decisions, such as if to expand their water treatment plant close to the coast. Overall, listening session participants wanted better ways of communicating uncertainty, suggesting that coastal data providers should ensure that decision makers can understand the uncertainties present in their data and how to properly incorporate them in their decision making.

Consultants and non-USGS researchers who use data for additional modeling stated they sometimes struggle to understand the limitations of the data they input for analysis. In one of the listening sessions with non-USGS researchers, a participant explained their experience dealing with uncertainty in models,

"From the scientific perspective, when I'm trying to use datasets, sometimes I have to dig really deep in order to figure out what the uncertainties are or how they were modeled. From the decision-makers' perspective, I guess I just have heard a lot of people say, 'Well, what value should we be using?' They want one single value that they can use to design or to make decisions, so I think it might not be something that could be addressed through the data itself, but maybe just broader education on how to use these datasets in ways that are appropriate for planning." (user type: non-USGS researcher)

This quotation shows that even researchers can struggle to find details on the uncertainties associated with data that go into a model or assessment and why accessible metadata are valuable. As this non-USGS researcher suggests, other coastal data users may need more than access to metadata to understand uncertainty and how to apply it to their decision-making process. Such efforts to provide more guidance to coastal data users in using models represent a crucial part of the coastal data delivery process.

6. Participant Needs

Throughout the listening sessions, participants explained how in some cases they cannot find or do not have access to the data they need. Three categories of data needs and gaps are explained in more detail in the subsections: "Participants explained their spatial and temporal data preferences as detailed in the section, "Spatial and Temporal Data Needs."

Three categories of data needs and gaps are explained in more detail in the subsections: "Data Gaps," "Tool Simplicity," and "Outreach and Education."

6.1. Spatial and Temporal Data Needs

Coastal Data Delivery Listening session participants were asked to share their needs and preferences related to the temporal and spatial scales of the coastal data they use.

6.1.1. Temporal Scales

Listening session participants reported that they use data on a range of temporal scales including historical, projected, short- and seasonal-term forecasts, and real-time data. All these temporal scales are relevant to coastal data users, who need to understand episodic and gradual changes to the coast.

6.1.2. Historical Information

Historical information was used by listening session participants to understand how the coast and coastal habitats have changed through time and what the coastline looked like in past years. Types of historical information mentioned by participants included historical transformed wave characteristics, historical flooding, and past human activity effects to marshes and other habitats. Although listening session participants in the non-USGS researcher category often use historical information to calibrate models, other user groups explained needing historical information to communicate the history of ocean acidification, SLR, barrier islands evolution, and more. No information was too old to be of interest to the listening session participants; for instance, one non-USGS researcher explained their excitement about recent efforts by scientists to establish the long-term water-level change using handwritten archival tide charts from the 1800s. Another participant (State planner) mentioned using the Coastal Records Project (Adelman and Adelman, 2002), a California database that includes photographs of the coastline from as far back as the 1970s and allows users to compare photographs from different years.

Participants reported that historical datasets can be hard to find, however, and are often incomplete for an area of interest, which makes it difficult to make long-term comparisons. Of the data types, historical photos—particularly aerial photos—were useful to all coastal data user groups, but participants reported that this information was difficult to access, and several participants described a lengthy process of going to local historical societies to view old paper maps that had not been digitized or georeferenced. Participants also reported struggling to find historic storm surge levels.

6.1.3. Real-Time Data

Real-time data were used by all types of listening session participants; this information was used to determine sea surface temperature, tides, currents, precipitation, other hydrological data, and the location of harmful algal blooms. Real-time data were considered especially important for predicting storm effects. One non-USGS researcher explained why they need real-time data in their efforts to model tides,

"We're trying to get better at modeling tides in real time so we can take those out of the time series and make better tsunami measurements to better warn for landslide tsunamis right now. That involves being able to see a signal on a coastal gage and tell right away that it's a tsunami versus a storm." (user type: non-USGS researcher)

Participants also spoke about needing more tide gages. Another explained the following:

"We have a lot of interest in more tide gages because of the shapes of the Cape, there are some weird tidal differences. We have to interpolate between gages, and sometimes that doesn't result in super accurate information. Having that raw data would be great." (user type: resource manager)

6.1.4. Time-Series Data

All user types in the listening sessions reported using time-series data to understand trends and demonstrate changes through time. As a local planner explained, time-series data are crucial to their work,

"Almost any time-series data is good to have, just to show trends and to demonstrate what's going on. That's really powerful." (user type: local planner)

Whereas local planners may use time-series data to tell a story or communicate how changes have occurred locally, a non-USGS researcher explained in detail how they use time-series data to predict coastal hazards,

"We're looking at modeling waves and hydro in the Gulf of Mexico. We are using the NGOM2 (Topobathymetric Model of the Northern Gulf of Mexico, 1885 to 2021), the USGS merged bathy[metry], topo[graphy], elevation data for the grid, and then we are using historic, available online from the USGS time series Stellwagen database, grabbing bits of wave, current, and ADCP (acoustic Doppler current profiler) that were deployed and using that for model calibration running a historic time period." (user type: non-USGS researcher)

This quotation represents a much more technical use of time-series data than that of the local planner quoted in the beginning of this section. Although time-series data are a useful data type for all users, one participant explained some caveats for using this data format,

"We have our inventory and monitoring program, and so we have 32 different inventory monitoring networks across the country. They collect a variety of data and unfortunately for us, not all the parameters are collected in every network and even parameters that are collected, like water quality; the actual measurements aren't the same from network to network." (user type: resource manager).

These quotations show that time-series data are used differently by different user types and that there is a need for more time-series data standardization nationally.

6.1.5. Seasonal Forecasts

Seasonal forecasts were used by the listening session participants, particularly those in areas threatened by hurricanes. One resource manager explained the importance of seasonal forecasts for their region,

"Installations on the coast need to understand what's coming in a hurricane season if they can. That's gonna be seasonal as far as preparing for flooding or storms, or how many there are gonna be in a year. That information that we can't necessarily predict, but we can at least have some idea of, they are going to get worse; they're going to get more wet; they are going to be more. That's probably the biggest seasonal thing that coastal installations are thinking about because some of them have been flattened by some hurricanes in the last three years in our region." (user type: resource manager)

Similarly, non-USGS researchers in the listening sessions explained that they need to know if a hurricane is coming so that they can make their flood mapping available to hazard managers in a reasonable timeframe,

"We are interested in climate-change projections. We're interested in short-term forecasts and seasonal forecasts. For all these temporal scales, we use this combination of statistical models and hybrid models in order to create coastal-flooding maps." (user type: non-USGS researcher)

Non-USGS researchers also explained that understanding what will happen during the next 6 months (for example, if there will be an El Niño and other more temporary weather or atmospheric conditions that may affect ocean response) is critical to their research.

6.1.6. Long-Term Projections

Listening session participants of all user types reported using projected data for management decisions regarding infrastructure development, coastal habitat change, and shoreline change through time including, for example, data on where inlets and barrier islands will move. More specifically, data projected on a decadal scale was needed by all listening session participants. When asked specifically if they use data projected on a decadal scale, one resource manager commented,

> "Yeah. I guess the thing I'm wrestling [with] right now [is] which decade should we be looking at? * * * That's more of a policy issue, not a data issue." (user type: resource manager)

This quotation illustrates how the use of projected data is closely tied to issues related to the inherent uncertainty of this type of information. Although uncertainty issues are explained in depth in the "Participant Experience: Barriers and Challenges to Coastal Data Use" section, how coastal data users accounted for uncertainty in projected SLR data is crucial. In one listening session, a consultant explained how the State of California Sea-Level Rise Guidance highlights different future scenarios ranging from low risk to high risk and includes suggestions for when to use which category (for example, coastal pedestrian trails would use a lower risk scenario than critical infrastructure because the cost of damage would be considerably less; California Coastal Management Program, 2018). The consultant reported that this guidance made it easier to use the projected information for planning purposes.

While coastal communities need specific information on fixed time scales to make shoreline permitting decisions, a consultant explained that they use data projected on decadal time scales for some projects with mandated planning thresholds but not others,

> "In California, the Ocean Protection Council moved from a fixed date analysis to a more probabilistic assessment of changes in sea level. I think that was good—it introduces a great level of complexity. I think it's a better approach, even though it's a more complex explanation." (user type: consultant)

They went on to explain that coastal communities can understand that effects will occur when the sea level rises and that those effects will not occur at a predetermined date. This framing allows consultants to better defend probabilistic analysis of SLR than previous methods of providing a timeframe for coastal change that may or may not come to fruition by a certain date in the future.

6.1.7. Spatial Scales

The spatial scale preferences of the listening session participants differed across user types (table 4). Overall, there was a call for more fine-scale data, especially by local planners who tend to rely on data that are locally sourced. However, the tension among a need for regional or national datasets and the need for localized data was discussed in multiple listening sessions.

Table 4. Spatial scale and time scale preferences mentioned by the five user types that were invited to the Coastal Data Delivery Listening Sessions, including resource managers, consultants, local planners, State planners, and non-U.S. Geological Survey researchers

Coastal data user type	Spatial scale preferences	Time scale preferences
Resource manager	Parcel-scale and fine-scale data, regional data, data at the scale of the natural landscape, neighborhood-scale data, county-scale data	All time scales
Consultant	Needs parcel information at a county scale (needs to compare with property values and property uses), need regional-scale data, uses GIS but needs visual tools for sharing spatial information with partners	All time scales
Local planner	Meters, parcels, fine-scale data; data aggregated at a higher level	All time scales
State planner	Coarser data on a statewide scale, fine-scale meter data, not all State planners have geographic information system capabilities—they need simple web maps and spatial data for use in their own mappers	All time scales
Non-U.S. Geological Survey researcher	Meters and kilometers, needs more data at a fine scale and a neighborhood scale, uses shapefiles and webmaps	All time scales

It was clear that participants required large-scale and small-scale data. As a consultant described,

"You really need both because you need the site-specific information, but * * * people that are developing beach nourishment projects also need to be thinking about the regional scale implications of what they're doing at the site scale. I feel like people need both types of information, and integrating those things is really challenging." (user type: consultant)

Combining data collected or presented at different scales was a key challenge that listening session participants had when working with disparate data sources. For data users who are less hands on with data, there were some interesting drawbacks to data that were not fine scale. Listening session participants explained how data that are perceived as "low-resolution" can decrease a user's confidence in an information product,

"Some of the mappers and things don't let you zoom in quite far enough. I think that's probably due to the limitations of the data. If we could get more granular and specific with some of these datasets, that might help." (user type: resource manager)

This resource manager explained that when they use mapping tools, they need fine-scale data at the census block level (statistical areas bounded by visible features such as streets and nonvisible boundaries such as property lines and county limits) or ideally the parcel scale (data including vast amounts of detailed property information about individual parcels of land, primarily to support real property tax and land development). The spatial data scale used by listening session participants differed and is described in table 4.

6.2. Data Gaps

Listening session participants identified multiple data gaps, particularly in their efforts to acquire data about multihazards, the multiple processes influencing hazards at a single location, and the surf zone. Other topics that participants mentioned needing data on included the following: sediment management; historical data; riverine, estuarine, and other coastal environment information; monitoring data; socioeconomic data; real-time data; and ecosystem services and natural capital.

The lack of nearshore and surf-zone data is a persistent data gap due to difficulties in data collection. However, participants asserted that tide-controlled imagery and lidar of the shoreline are important for coastal planning and research. As a consultant reported, "Related to monitoring and other tasks, I recently had to estimate the existing bed profile through the surf zone because there's just no information there. It's really important if you're trying to do wave runup or some sort of beach project. You look at the available data; you have information offshore, and you have information onshore, but nothing in between where the surf zone is. That's going to really affect all of the modeling or calculations." (user type: consultant)

Participants also wanted better ways of combining information at the ocean and land interface in reference to multihazards. In one of the listening sessions, a State planner explained that their biggest issue is understanding the interplay among their bay and a local creek in relation to site-based adaptation solutions. Listening session participants also wanted more information on coincident flooding and how storms affect large and small bodies of water present in coastal areas. This complexity was explained by a State planner,

"When communities ask us, 'Well, it's nice to know about sea-level rise, but what about our hazard from riverine flow?' and the nearest river gage is 100 miles upstream or 75 miles upstream and there's 2 dams in between * * * We can't really answer their question." (user type: State planner)

Answering these complex questions proves to be a challenge that filling some of these data gaps may lessen.

6.3. Tool Simplicity

Listening session participants across user types reported using a variety of web tools provided by local, State, and Federal sources. However, the way users engaged with web tools differed based on user type. A common thread mentioned throughout the listening sessions was a need in coastal decision-making spaces for more simplified and synthesized information. This was particularly true for web tools, where participants who described themselves as not being data savvy (usually in the resource manager, State planner, and local planner user types) reported using web tools to answer questions and communicate with their stakeholders. Products that provided a dichotomous key approach to decision making where, for example, possible options for coastal adaptation are categorized as good, okay, or bad, were considered particularly useful by these participants. Often, participants used the term "model" to describe examples of these interactive information products. One participant described how they get requests from coastal managers for these more simplistic and synthesized information products, which they referred to as "stoplight models,"

"A lot of the managers like [stoplight] models because that's the depth of knowledge they need. Is this a good idea? Is this a bad idea? Or is this something not ready for prime time yet?" (user type: non-USGS researcher)

In contrast, non-USGS researchers and consultants were more likely to either dig into a tool to acquire the data for their own analysis or use the tool for outreach with their clients or partners, rather than looking for simplified or synthesized information. For example, although one non-USGS researcher explained they use the Environmental Protection Agency Environmental Justice Indicator tool (U.S. Environmental Protection Agency, 2023), when they were asked how they use it, they added that they cross-validate the results of the tool with data they are gathering from other local sources. Participants who were in the consultant and non-USGS researcher sessions reported they sometimes use web tools to visualize datasets before they download them because many datasets are much larger than the scope of their research questions. These users wanted tools that were easy to "pick apart" and offered clear ways of downloading the available data into useful formats.

Across all five user groups, participants reported using web tools in their work on coastal issues. When asked what makes a web tool successful, the features participants spoke about included intuitive user interfaces, usability, trustworthiness, and access to underlying data (fig. 9).

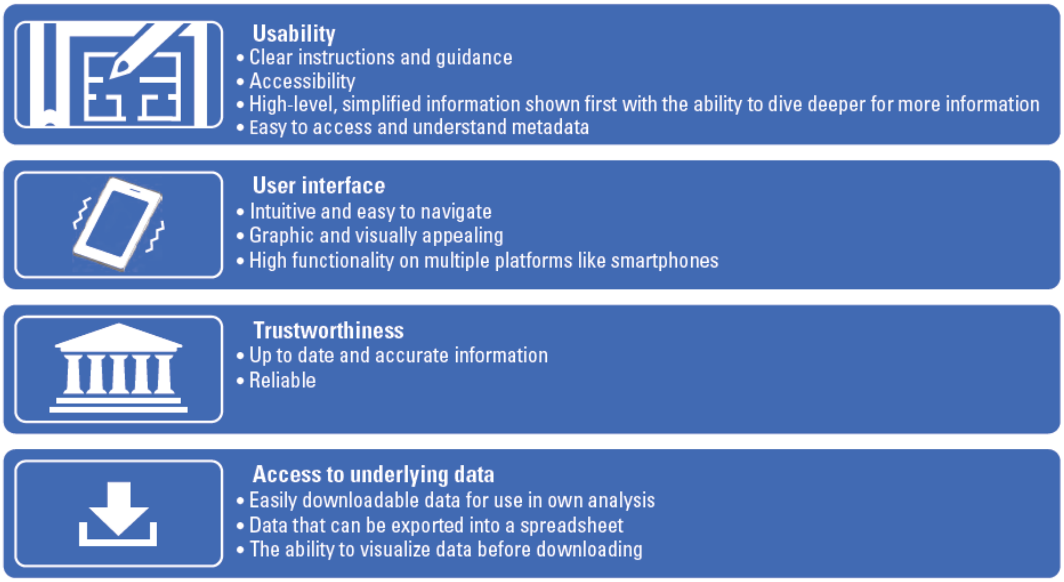


Figure 9. Desired web tool features by category as reported by listening session participants.

These desired web tool characteristics emphasize that producing a successful web tool goes further than simply enabling access to scientific information. When discussing web tools, listening session participants expressed preferences for tools that are visually appealing and easy to use. A State planner who uses many different tools in their work explained how some web tools are not user friendly to certain user types,

"Local officials need [accessible web tools], too. They don't find some of these viewers very user-friendly, so when I work with them and try to suggest resources for them, they're like, 'Well, I couldn't really figure that site out,' so they just skipped it and I hate to see them miss out on good resources." (user type: State planner)

This quotation exemplifies how web tools that present science needed for coastal decision making can be overlooked by users because of usability issues. This is especially the case when users are limited in the amount of time they can put into exploring a tool.

6.4. Outreach and Education

Listening session participants spoke about the need to increase public awareness, outreach, and education, especially in regions that do not share a consensus on climate change. Participants suggested that these educational materials should be provided by trusted, Federal science organizations. The USGS CMHRP CCH team has begun working to provide this kind of information in the form of geonarratives, which many of the listening session participants were familiar with. The participants reported that the USGS geonarratives (https://wim.usgs.gov/ geonarrative/ cch- ourcoasts/), which explain coastal processes and describe how to use different types of coastal data, have been useful in filling this gap. A local planner explained that,

"The [CCH geonarratives] are a great start and really start to get at the basic background and science. I think we need all the help we can get." (user type: local planner).

Three specific examples of coastal topics that listening session participants wished for trustworthy educational material on included (1) an explanation on how a bank erodes, (2) a description of the sloshing of the Pacific and how that accelerates SLR, and (3) a web tool that shows all the people across different Federal agencies who are researching the same topic.

7. Participant Recommendations for USGS

Overall, the listening session participants reported having a favorable experience with USGS CMHRP CCH data and personnel, which was not surprising given their existing relationships with USGS scientists, their agreement to participate in the Coastal Data Delivery Listening Sessions, and for some, their participation in previous CCH workshops. However, even among this sample, two local planners and one State planner noted that they do not use USGS coastal data, and some participants reported that they did not know what data the USGS provides beyond the geonarratives and CoSMoS (Coastal Storm Modeling System;). A local planner explained, "I went to a listening session, I guess it was probably two years ago, on the StoryMaps. I've taken a look at those, but otherwise, have never had a need to go back to USGS for any particular dataset beyond the CoSMoS model." (user type: local planner)

This result, that a local planner who has participated in two USGS listening sessions focused on coastal data delivery during multiple years still does not perceive the need to look to USGS coastal data to improve their workflow, suggests that there is substantial opportunity for the USGS CMHRP CCH to increase the effectiveness of its stakeholder outreach.

Beyond improving outreach, listening session participants suggested several ways that the USGS could improve in its delivery of coastal data and information. These suggestions were categorized into three subsections: "User Interface," "User Experience," and "Communication and Collaboration Opportunities."

7.1. Presentation

Participants shared their opinions about what makes websites and tools successful and suggested ways for USGS to achieve that success. This section has been split into two subsections, one on user interface and another on user experience.

7.1.1. User Interface

When asked how the USGS could improve, listening session participants commented on the visual appearance of USGS websites. Participants reported that USGS websites seemed "stuck in the past" and that USGS maps were "old looking" and included old GIS symbols. Although these observations may seem cosmetic, they sometimes led listening session participants to seek out other websites and data sources that were more visually appealing or modern and consequently perceived as being more credible. Cash and Belloy (2020) explain how scientific knowledge is more likely to be used in decision making if it is perceived as salient, credible, and legitimate, and the way information is presented visually is a quintessential part of this perception.

In the listening sessions, a State planner explained how presentation can be a barrier to usage and why they prefer the more user-friendly user interfaces of NOAA websites even when searching for the same data,

"I know a lot of the data that USGS has is available through NOAA and vice versa and a lot of the times, I find myself going to the NOAA site stash to get that data just because I'm used to their interfaces and they're a little bit easier to use. When I compare a lidar data download, for instance, I'll typically go to NOAA's data viewer to get that data 'cause it's easier to find and consistently download data using some of their tools, as opposed to some of USGS tools." (user type: State planner)

Participants reported that the more visually appealing a website was, the easier it was to interact with it. A particular example of this issue was provided by a local planner,

"We've used the USGS modeling data for our sea level rise vulnerability assessments. I think just even a slightly better public interface would help make that tool a better public tool. It's very technical." (user type: local planner)

Comments about the importance of better user interfaces for USGS products were common in the listening sessions, where participants expressed they wanted user interfaces to be more user friendly. Another comment related to user interface was provided by a scientist in the non-USGS researcher listening session:

"The USGS gage website drives me nuts. I think it's still in the '90s with its web interface. If I have an opportunity just to say, maybe it can be updated and be a little bit easier to navigate." (user type: non-USGS researcher)

When this comment was made, the group of non-USGS researchers in the listening session all agreed with this sentiment.

7.1.2. User Experience

Issues that coastal data users experienced with USGS websites went beyond visual presentation. Not only do USGS websites look dated to coastal data users, but the way they functioned was also perceived to be out of date. This result is consistent with research suggesting that coastal data users' expectations for how government websites function have evolved as technology has become more sophisticated (Cravens, 2016). The concurrent shift in expectations is clear in a State planner's description of their preferences for how to interact with coastal data:

"I think we're all getting used to this visual environment where we can just pull up a viewer—especially for those of us that don't use GIS all the time—and be able to interact with the data." (user type: State planner)

Smooth, easy, and visual ways of interacting with coastal data online have become the norm (Shim and others, 2002). As coastal data users become accustomed to new ways of interacting with data, dated systems and formats fall short of user expectations and, according to participants, result in loss of data users. Listening session participants often made comparisons among USGS information products and newer NOAA products. This is clear in this resource manager's explanation of the differences among a USGS tool and a NOAA tool,

"We use both the Coastal Change Hazards Portal and then NOAA's Coastal Flood Exposure Mapper. The thing I like about the NOAA version is that it—it's like an index, and it allows you to look at the different inputs. * * * You can actually identify the different parts that go into the index. Whereas in the Coastal Change Hazards Portal, looking at the Coastal Vulnerability Index, I don't see the same ability to pick apart the different parts of it." (user type: resource manager)

In the previous section on barriers and challenges, it was documented how coastal data users have trouble finding the data they need in general. However, listening session participants also spoke about difficulties searching for USGS data specifically and using USGS online search capabilities. A local planner commented on this issue and presented a possible solution, "The current system for searching [for USGS] data is confusing and makes it difficult to locate site-specific data. Either a guidance video or a document would be helpful or a map where the user can define an area and their relevant site-specific reports or data would come up." (user type: local planner)

This comment echoes the general need for more support locating coastal data, as described in the previous section "Data Access and Navigation." The participant's idea that there should be a video or document that explains how to search for data on USGS websites indicates that the current search function, as existed in 2021 at the time of the listening sessions, was not intuitive. Overall, listening session participants wanted to see USGS data more centralized and easier to navigate. In a listening session with non-USGS researchers, the participants agreed that USGS data are "some of the best data available" but that it is often difficult to find.

Listening session participants also explained that often USGS data are difficult to download due to the size and format. A consultant described why local planners struggle to access USGS data,

"We in the [State Geographic Information Office] hear a lot of complaints from local county staff and municipality staff having a really hard time bringing down some of the lidar-derived products just because of throughput and size. USGS for us provides three or four different download methods, but sometimes none of them work for the locals, so they'll come to us looking for the data." (user type: consultant)

This quotation shows a technical barrier when downloading certain types of information from USGS websites, indicating that it is not necessarily accessible to all coastal data users.

7.2. Communication and Collaboration Opportunities

Participants explained how leveraging data across study sites and regions could help improve the capacity issues faced by coastal decision makers. Listening session participants perceived that this goal could be achieved by Federal agencies working together and possibly assisting with the standardization of data collection methods across regions, though some methods of data standardization were seen as time intensive. Listening session conversations about increasing coordination to meet the challenges facing the Nation's coasts took several forms.

Listening session participants, particularly those in the State planner and local planner categories, expressed a desire to understand how other coastal communities in the United States are responding to similar coastal hazards and were at a loss for how to find this information. This need for collaboration and communication was explained by a State planner,

"How do you take advantage of what other communities have done well * * * so that communities [have a] better understanding of how they share common concerns [and] how they can share common ideas towards solutions." (user type: State planner)

Participants suggested that as a Federal agency, the USGS could potentially assist with facilitating communication among coastal decision makers and standardization of coastal data collection at a national level.

The listening session participants also expressed a desire for better communication and collaboration among and within Federal agencies. For example, many listening session participants did not understand what or how different Federal agencies (especially the USGS and NOAA) contribute to guidance on SLR. This overlap among agencies often confuses users searching for data that best suits their needs (Howe, 2011). Participants were also confused by the internal structures of Federal agencies, as explained by a resource manager,

"What I struggle with, with USGS and all the Federal agencies is, I can't keep track of all the different divisions. When I'm talking to someone from NOAA, someone tells me they're in oceans and coastal management, and I'm like, 'Okay,' but I don't really know what that means. You know? I know the [climate] adaptation science centers are one part of USGS, but that is a huge agency. That's a struggle I have." (user type: resource manager)

This resource manager went on to explain that they work with people on the same topic within the same agency and have no idea if those two people are in communication with each other. In two of the listening sessions, listening session participants suggested that a solution to this confusion could be to have a database, or some kind of web tool, that lists the key people at various agencies who work on specific coastal issues and how they are connected. This solution, they argued, would not only help coastal decision makers understand the Federal landscape on coastal hazard data and information but would also assist with strengthening the linkages horizontally and vertically across government.

Interagency collaboration was desired by the listening session participants, and any evidence of agencies working together was celebrated. A consultant explained why these collaborations are so important,

"I really like the Total Water Level Viewer collaboration with NOAA. It's refreshing to see the agencies recognizing where they excel and then working together to make a better product rather than trying to do it in-house. That interagency collaboration toward an improved tool is excellent." (user type: consultant)

Beyond collaborating on actual information products and coastal data resources, listening session participants wanted to ensure that USGS CMHRP CCH efforts to make coastal science more accessible and actionable, like the Coastal Data Delivery Listening Sessions they were actively participating in, would not overlap with identical efforts of other agencies. In several of the Coastal Data Delivery Listening Sessions, the first question posed to the facilitator after the introductory presentation was to ask how the USGS was coordinating with the NOAA on this effort to understand coastal data needs. As a resource manager explained, "I think it would be really, really helpful if we weren't all having separate conversations with each agency, but if we could all have one conversation together, and each agency could pull what they need to out of it, I would love to participate in that moving forward." (user type: resource manager)

In every listening session, participants expressed a need for agencies working on coastal hazards to communicate and collaborate. This corroborates the results of a recent needs assessment from the NOAA, which found that users can become confused when they perceive duplicative efforts across the NOAA, FEMA, and USGS (NOAA, 2022).

8. Summary

The demand to preserve recreational beaches, maintain infrastructure near the coast, and conserve coastal habitats and species will only increase as climate change affects the location of where the water meets land. Coastal land managers need relevant and actionable science to inform their management decisions. By considering the knowledge and expertise of coastal practitioners, the U.S. Geological Survey (USGS) can better deliver actionable assessments of coastal hazards and risk that help achieve resilient communities. The results of 10 listening sessions emphasize that coastal data user needs differ across user types and that coastal stakeholders experience many barriers and challenges to effective coastal data and information use.

One of the key challenges was the overabundance of similar tools, products, and sources for coastal information that users found difficult to keep track of and struggled to integrate. Similarly, coastal stakeholders, especially those in the local planner, State planner, and resource manager categories, lacked the capacity and staff needed to find relevant coastal information. Listening session participants also reported difficulties understanding how to apply data to make scientifically informed decisions and how to reconcile datasets from different sources. As the USGS Coastal and Marine Hazards and Resources Program (CMHRP) works to understand the barriers to data use that stakeholders experience, these lessons will provide actionable information to enable better access to CMHRP data. Addressing these challenges related to identifying and applying coastal data products would allow coastal stakeholders to spend more time and energy addressing complex coastal management issues, rather than resolving access issues internally or answering relatively simple questions from local communities.

When speaking about the USGS, participants described difficulties locating and downloading USGS coastal data and information. The result was further confirmed when the list of coastal data needs mentioned in the listening sessions were categorized, revealing that some of the data types that participants reported as a data gap were available to the public on USGS websites. This disconnect reveals a need for the USGS CMHRP to engage in a more effective outreach to ensure information reaches its intended users.

Alongside better data access, listening session participants reported that another key element hindering their ability to make scientifically supported decisions was a lack of accessible educational information on coastal change and coastal hazards. Participants felt that this was a role best suited for Federal science agencies because of their authority and the trust that they inspire in the public. When discussing Federal agencies, participants explicitly called for more collaboration and communication among coastal practitioners and agencies to provide better information sharing on coastal adaptation and management efforts across the United States.

9. Acknowledgments

Thank you to all the diverse listening session attendees for sharing their experiences and insights. Patrick Barnard, Kara Doran, Meaghan Emory, Sara Ernst, Donya Frank-Gilchrist, Kai Parker, Travis Sterne, Rae Taylor-Burns, and Legna Torres-Garcia provided technical assistance during the listening sessions, and Nicole Herman-Mercer contributed to the study design. Dawn Kotowicz, Patrick Barnard, and Meagan Eagle provided comments on earlier versions of this report. This research was conducted as part of the larger State of Our Nation's Coast project; thank you to the many Coastal and Marine Hazards and Resources Program (CMHRP) scientists who provided input as part of the larger effort, especially Meg Palmsten and Richard Snell. Thank you to the U.S. Geological Survey Risk Community of Practice and the CMHRP for funding staff time to support this project.

Introduction to Chapter #3

My second chapter illuminates the issues facing coastal decision-makers and shows that these stakeholders need more guidance in making scientifically informed decisions around coastal adaptation and environmental justice. One source of this guidance comes from coastal hazard scientists and Federal science agencies in the form of decision-support tools. However, as we learned in chapter two, these tools can often be overly complicated, redundant, and can create an even more confusing information space for decision-makers, especially those with limited bandwidth.

My third chapter builds upon the second and asks: What are the barriers to providing accessible and actionable scientific decision support? Here we expand the scope of the research to include decision-support tool creators from across the USGS. The lessons learned from the interview and survey data explored in this chapter can inform scientists and agencies that would like to make a decision-support tool but don’t know where to start.

Chapter #3: So, You Want to Build a Decision-Support Tool? Assessing Successes, Barriers, and Lessons Learned for Tool Design and Development

Abstract:

The purpose of this study is to increase understanding of how the U.S. Geological Survey (USGS) is developing decision-support tools (DSTs) by documenting successes and barriers across all levels of USGS scientific tool creation and outreach. These findings can help streamline future tool design and development processes. We provide a synthesis of lessons learned and best practices across a spectrum of USGS decision-support efforts to, A, provide guidance to future efforts and, B, identify knowledge gaps and opportunities for knowledge transfer and integration. We present this information as five guiding principles for those striving to create effective DSTs. These principles are: (1) use an adaptive, iterative design process, (2) collaborate across disciplines and organizations, (3) engage with the target users of the tool, (4) develop an empirical understanding of use and usability, and (5) plan for the tool's full life span. By providing guidance on how effective DSTs are realized at every phase of development (from planning to maintenance), these principles provide a starting point to improve the process of designing DSTs and thus help further the USGS mission of delivering actionable science.

1. Introduction

The U.S. Geological Survey (USGS) is the Nation's largest water, earth, and biological science and civilian mapping agency. Unlike other Federal Government agencies, the USGS has no land management mandate, and thus, outside of the role of Delaware River Master, has no decision-making authority. Rather, the USGS mission is to deliver actionable information at scales and timeframes relevant to decision makers at all levels, from individual landowners to Federal agencies. The core functions that the Bureau performs to accomplish its mission and support stakeholders include long-term data collection and monitoring, conducting research and assessments, and developing tools and applications. The USGS provides decision support through a range of products; in this report, we focused on decision-support tools (DSTs).

USGS-developed tools and applications take a range of forms—from simple web portals that provide access to real-time data, to map-based interfaces that display information from many datasets, to applications that allow users to adjust parameters via “knobs and levers” to explore a range of possible outcomes associated with specific decisions. Web-based applications or “web-tools” are an increasingly popular way to provide dynamic visualizations, analyses, and access to USGS data products. Across the USGS, tools and applications are proliferating, ranging from quick “off-the-shelf” data mock-ups (like R Shiny apps and other dashboards) to professional deployments built after years of investment (Chang and others, 2016). Regardless of format, these tools and applications share the underlying objective of providing actionable information to those who need it in order to make important decisions to prepare for or respond to natural hazards and to facilitate the management of biological, hydrological, energy, or mineral resources. The people to whom USGS provides information through these tools and applications similarly range widely, from policy makers to natural resource managers, to scientists, to recreationists, and many others. Thus, designing, developing, and maintaining tools and applications to provide actionable science to decision makers and other users is a core USGS function that crosses all levels of the organization (including Centers, Regions, and Mission Areas).

While decision support is a core piece of the USGS mission, the number of tools and the number of scientists creating tools appear to be growing both within the Bureau and among scientists more generally (Palutikof and others, 2019; Wong-Parodi and others, 2020; Keenan, 2021). This increasing focus on DSTs has several causes. Perhaps most important in recent years is the growing interest in making science—particularly Federal science—actionable for decision makers (Arnott and others, 2020; U.S. Geological Survey, 2021). Decision-support tools are seen as a logical and tangible way to make information actionable (Wong-Parodi and others, 2020). Interactive DSTs in particular hold great promise to provide tailored support to decision makers, making information available at the temporal or spatial scale needed for a particular decision. For example, DSTs can enable decision makers to quickly check the status of the quality of a body of water, facilitating the daily decisions needed to protect ecosystems. The USGS's Grand Canyon Monitoring and Research Center's "Discharge, Sediment, and Water Quality Monitoring" web application[2] provides the specific information on water quality and sediment loads that Federal decision makers need to support the Glen Canyon Dam Adaptive Management Framework.

Although the literature on DST development offers guidance, principles, and recommendations on how to develop DSTs within scientific organizations (for example: Loucks, 1995; Newman and others, 2000; Fleisher and others, 2014; Barnhart and others, 2018), the unique barriers and opportunities met by USGS employees had yet to be documented. Our research investigated experiences in initiating, designing, and implementing decision-support projects within USGS through both a survey and interviews of USGS employees.[3] Among the DSTs developed by USGS employees across the Bureau exist many compelling examples of successful tools. A small number of these are featured as example tools throughout this report. The information provided about each example tool was

[2] https://www. gcmrc.gov/discharge_qw_sediment/

[3] Data either are not available or have limited availability owing to restrictions (privacy concern). Contact Amanda Cravens at aecravens@usgs.gov for more information.

codeveloped with one of the USGS employees who worked to create the tool, and a quotation from that individual is included. Our investigations compiled lessons learned from successes and identified barriers that teams encountered. By analyzing how USGS scientists and technology professionals described their experiences and comparing those experiences with best practices as described in the wider literature, we offer five principles of successful DST design and development to consider before diving into DST creation. The synthesis of these lessons learned across the spectrum of USGS tools and applications is intended to inform future DST efforts. Specifically, this report is intended to be a resource for project managers, Bureau decision makers, programmers, and researchers considering building a DST.

2. Background

Advances in technology that facilitate near-real-time data collection and collaborative information sharing, coupled with computational advances such as machine learning and cloud computing services, have made it easier to develop sophisticated tools and have fostered a growing demand for such tools (Wong-Parodi and others, 2020; Heavin and Adam, 2022). This demand will likely continue to grow as the impacts of climate change are increasingly felt with natural hazards increasing in frequency and intensity as well as growing interest in providing applications that incorporate projections and forecasts (National Academies of Sciences, Engineering, Medicine, 2018).

The wider scientific literature examining the effectiveness of decision support testifies to how well-designed DSTs aid decision making (for example: Loucks, 1995; Newman and others, 2000; Shim and others, 2002; Uran and Janssen, 2003; Cravens and Ardoin, 2016; Grêt-Regamey and others, 2017; Barnhart and others, 2018). In one detailed examination of an interactive geospatial tool called MarineMap used to site marine protected areas along the coast of California, Cravens (2016) found that the DST shaped how users solved problems, negotiated trade-offs, and made mutually acceptable decisions in a collaborative setting[4]. In turn, the DST users were able to identify specific ways that the tool used in the California case performed these decision-support functions, including by creating a common language among participants, helping users understand the geography and scientific criteria in play during the process, aiding stakeholders in identifying shared or diverging interests, and facilitating joint problem solving.

Wong-Parodi and others (2020) investigated another coastal case, the Louisiana Coastal Master Plan Process and Planning Tool[5]. The authors analyzed how the tool's characteristics supported "high quality" decision making, noting that, "stakeholders must be able to understand the costs, benefits, and uncertainties of decision alternatives well enough to afford them the ability to make decisions that are in accordance with their values, beliefs and contexts" (Wong-Parodi and others, 2020, p.54). They conclude that DSTs are effective when they support the full process of making decisions, from defining goals to identifying and evaluating alternatives to monitoring outcomes.

Yet this same body of research on the effectiveness of decision support also offers caution: realizing the potential of DSTs is difficult. In too many cases, well-intentioned ideas, time, money, and enthusiasm do not result in effective tools (Moser, 2009; van der Molen and others, 2018; Stoltz and others, 2023). Documented barriers include the following:

- Insufficient resources of the development team (Dale and English, 1999).

---

[4] MarineMap no longer exists in the form that was used during the California Marine Life Protection Act (MLPA) Initiative planning process. The experience of developing and implementing MarineMap influenced subsequent projects by the development team, primarily a tool called SeaSketch (https://www.seasketch.org/).
[5] https://coastal.la.gov/our-plan/2017-coastal-master-plan/ planning-process/planning-process-planning-tool/

• Institutional constraints on the development process (Pearman and Cravens, 2022).

• Limited resources of users to vet the credibility of new tools; high transaction costs for users to switch from a known information source to a new tool; and difficulties keeping track and differentiating between tools with similar purposes (Cravens, 2018).

Usability can also be a significant barrier to the success of DSTs. Specific usability challenges for scientific information products include mismatches between the type or scale of information provided and the needs of users (for example: Wong-Parodi and others, 2020; Cravens, 2016; Cravens, 2018; Dilling and Lemos, 2011), users' perceptions of the usefulness and trustworthiness of the information or product (for example: Cash and others, 2006; Dunn and Laing, 2017; Jacobs and Buizer, 2016; White and others, 2010), and users' capacities to interpret and incorporate the information into decision making (for example: Dilling and Lemos, 2011; van der Molen and others, 2018). Information products may not adequately account for how users understand decision contexts; for example, Cravens (2018) described a manager who thought of their region (the Southern Rockies) in terrestrial as opposed to watershed terms and thus saw no relevance in a drought early warning system focused on the "Upper Colorado River" despite the overlapping geographies. More broadly, as technology becomes more sophisticated, user expectations of what applications should look and behave like also change, influencing expectations of government or scientific tools (Cravens, 2016). These persistent barriers have led to repeated calls for greater attention to evaluating the effectiveness of DSTs and learning from past successes and failures (for example: Moser, 2009; Cravens, 2016; Wong-Parodi and others, 2020).

Designing, developing, and maintaining tools and applications to provide actionable science to decision makers involves collaboration among (at minimum) subject matter experts, technology professionals, and the intended user community. For USGS's DSTs, projects are often initiated based on USGS research, and USGS data become the foundation of the DSTs. In terms of technology, many USGS researchers are familiar with specific programming languages as part of their research. However, software development is a broader professional field that requires knowledge and skills in addition to programming. For example, a full software development cycle might include the following stages: project planning, requirement definitions, design, prototyping, quality assurance, implementation, and maintenance (Ruparelia, 2010). Another aspect of software development is project management, which is often a dedicated role in larger projects or organizations. A typical project manager would have expertise in the areas of managing project scope, timeline, cost, quality, outreach, risks, and human resources (Project Management Institute, 2021).

A body of interdisciplinary research and professional expertise called human-computer interaction addresses the challenge of ensuring software programs like DSTs work effectively for their intended users and emphasizes the importance of considering the lived experience of the people who will use a tool (Rigby and Priest, 2023). Many would date the beginnings of human-computer interaction to 1983, when computer scientist Austin Henderson and anthropology Ph.D student Lucy Suchman put a video camera in the copy room at the Xerox Palo Alto Research Center and analyzed how the scientists at the research laboratory interacted with the early Xerox copier (PARC, 2016). Suchman's ethnography was pivotal in demonstrating that people rarely interact with technology in ways that designers expect (or hope) they will, and thus, it can be disadvantageous to make assumptions about what users will do without testing or observing "in the wild" (PARC, 2011). Human-computer interaction research and the associated profession is now commonly understood to be a sub-field of the overall "usability" discipline. By combing the findings contributed by a diverse set of disciplines, including engineering, cognitive science, and design, the "usability" discipline and its professionals aim to create human-computing experiences that are as efficient and effective as possible (Rubinstein and Hersh, 1984; Gould and Lewis, 1985; Nielsen, 1994). Within modern corporate software design teams, usability experts and design researcher positions have become common, illustrating the value that the corporate sector finds in understanding the experiences, motivations, and behavior of application users. Within the Federal Government, the value of this expertise is increasingly recognized and initiatives (such as Usability.gov) that focus on building capacity are increasingly common. However, the number of people with usability and empirical human-computer interaction expertise within USGS remains small.

Many software design frameworks emphasize the importance of iteratively developing an application in response to feedback and usability testing results from the target users. In general, a human-centered design (HCD) approach can be used to promote mindsets and techniques that help a design team approach problem solving in a way that places central focus on human experiences. Particularly, user-centered design (UCD) is a human-focused technology design methodology, "in which designers focus on the users and their needs in each phase of the design process" (Interaction Design Foundation, undated). The UCD process is generally depicted as a series of iterative stages by which a team develops increasing understanding of users' needs and a finer match of a tool's capacities with those needs. Figure 10 shows one common depiction of these stages.

While pilot projects at the USGS have adopted more human and user-centered approaches in recent years (see Box 1), this iterative approach is not yet widespread nor familiar across the Bureau.

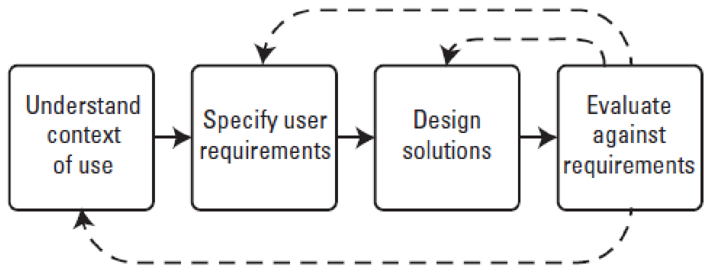


Figure 10. Diagram showing the user-centered design process. User-centered design is an iterative process that focuses on understanding users and their context in all stages of design and development. Modified from Interaction Design Foundation (undated).

3. Research Objectives and Methods

This project grew from the observations of the author team, each of whom played a role in supporting stakeholder engagement, decision-support design and development, or tool usability and evaluation for one or more USGS Mission Areas. In our respective roles, we realized that decision-support products of various types are increasingly common outputs across USGS, but that scientists and technology professionals working in different parts of the Bureau did not necessarily have access to lessons learned from the design and development process in other parts of the USGS community. This interest in capturing lessons learned and insights about best practices led to the USGS Community for Data Integration funding the current research.

The purpose of this study is to understand USGS experiences to help improve the DST design and development process. This report addresses four research questions:

- What can be learned from USGS employees' experiences with DST development?
- What principles would be beneficial for USGS tool developers to consider before building a DST?

• What barriers to success do USGS tool developers experience?

• What resources do tool designers believe would improve the design process?

The study was conducted in three steps described in the following sections.

Box 1. Human-Centered and User-Centered Design

Human-centered design (HCD) and user-centered design (UCD) processes both in general have, "phases throughout a design and development life-cycle all while focusing on gaining a deep understanding of who will be using the product" (Usability.gov, undated). Typically, four key phases are visited iteratively throughout an HCD or UCD process: (1) understanding target users and their context, including their needs; (2) defining user requirements, especially in relation to other types of requirements, such as technical and data requirements; (3) identifying design options and creating possible solutions; and (4) evaluating design options and possible solutions for best support for the users. More information on these key phases can be found at https://www.interaction-design.org/literature/topics/user-centered-design.

Examples

At the U.S. Geological Survey (USGS), decision-support tool (DST) developers are making strides in increasing the usability of their products. As discussed in this report, USGS DST projects address a wide range of scientific issues and decisions. Each project ideally would consider specifically how to improve its usability based its own unique context. However, the UCD is one that any project can use to integrate usability concepts and techniques into their lifecycle.

For example, the USGS State of Our Nation's Coast (SNC) project (https://www.usgs.gov/natural-hazards/coastal-marine-hazards-and-resources/science/state-our-nations-coast) decided to emphasize its DST development process on the first two phases of the UCD process (understanding target users and their context; defining user requirements). The SNC project aimed to improve the visibility of USGS coastal hazards science and prioritize science that meets stakeholder needs. In turn, the success of the SNC project's tool is dependent on how well its target users can use the project's science to support their coastal hazard mitigation activities. During the last three years, much can still be learned about the project's target users and their needs. By focusing on the first two phases of the UCD process, the SNC project ensured that user research and the resulting data are the foundation of their DST development decisions as the project moves forward with the other UCD phases.

Another example is the USGS Volcano Hazards Program (VHP) (https://www.usgs.gov/programs/VHP). The VHP has the goal to minimize social and economic disruption from volcano hazards, and the program's key mechanism for achieving its goal is by providing map-based risk and hazard-communication products. In order for these products to meet the target users' needs effectively, the target users must be able to understand the map-based information and apply the acquired knowledge about the risks to the associated hazards. However, unlike the SNC project, the VHP already has existing products, where the new designs will not only need to have an improved experience for the new users, but also provide continuity for the existing users. As a result, the VHP has focused on the latter two phases of the UCD process (evaluating the existing design; identifying the potential design improvements for the next iterations). By involving target users in usability studies of the current map-based risk and hazard-communication products, the VHP has established a baseline of the existing user experience. Subsequently, the VHP can determine the features and content to improve as well as to maintain in order to provide the desired usability for its target users as the program iterates over the other UCD phases.

Key Takeaways

HCD and UCD provide a framework to guide a team's process as it iteratively works with stakeholders to design a DST. Although a team may move iteratively through the phases and return to different phases of the process multiple times, the focus on user needs in both of these frameworks reminds teams to place user needs at the center of DST design.

3.1. Step 1: Literature Review

We reviewed the literature to identify papers describing best practices for DST design, development, and evaluation. Papers addressing the definition and functions of decision support were also considered. The goal of this literature review was to understand the state of the scientific literature regarding the process of building successful DSTs. The literature review was conducted in Google Scholar and Web of Science using the search terms "decision support," "decision support tool," "decision support product," "decisions support system," "usability," "user-centered design," "human-centered design," and "stakeholder engagement" both individually and in combination. We selected these terms because they are inclusive of the varied ways that DSTs are discussed within human-computer interaction and other scientific literatures that address them. Criteria for papers reviewed included whether they focused on one of the search terms or included a case study of a decision-support design process. Twenty-two papers were reviewed. The information collected in this literature review guided the design of both the survey and interview protocol used in this research and informed the principles that we present throughout this report.

3.2. Step 2: Web-Based Survey of USGS Employees

We designed a survey including a variety of open-ended and multiple-choice questions to understand how USGS scientists and developers create tools. The survey was distributed on November 30, 2020, in the weekly all-employee USGS newsletter "NeedToKnow" to maximize the awareness of the survey and advertise the opportunity to participate. All USGS employees who had been involved in initiating, designing, or implementing decision-support projects were encouraged to complete the survey[6]. The survey

[6] The original survey documents are available as a PDF file at https://doi.org/10.3133/sir20235076

was administered in Qualtrics[7] (and was open for four months,[8] during which 54 responses were collected across USGS Mission Areas (table 5) and Regions (table 6). Survey questions were informed by the literature review as well as our past experiences supporting USGS employees to develop DSTs.

We designed the survey to collect general information about DST creation experiences throughout USGS as well as to collect information that would guide the development of the interview protocol. Topics covered in the survey questions included respondents' definition of DSTs, their role in creating DSTs, details about past DST(s) created, and barriers to tool development. The survey also asked respondents to name up to five DSTs that they had been involved in creating. A total of 78 DSTs were named that spanned many different formats. Survey respondents were not required to provide identifiable information within the survey but were given the option of providing their contact information if they were interested in participating in an interview to further discuss their experiences with DST development.

Table 5. U.S. Geological Survey Mission Areas of survey respondents.

USGS Mission Areas of survey respondents	%	Count
Core Science Systems	17	9
Ecosystems	33	18
Energy and Minerals	0	0
Natural Hazards	15	8
Water Resources	35	19
Total	100	54

[7] https: //www.qualtrics.com/

[8] The survey administration fell over the winter holidays when many employees were out on leave, so the survey was left open over the entire time before and after the holidays.

Table 6. U.S. Geological Survey Regions of survey respondents.

USGS Regions of survey respondents	%	Count
Headquarters	20	11
Southeast	9	5
Midcontinent	20	11
Rocky Mountain	7	4
Southwest	17	9
Northwest - Pacific Islands	17	9
Alaska	4	2
Northeast	6	3
Total	100	54

3.3. Step 3: Interviews of USGS Employees

We developed our interview protocol based on both the literature review and information gleaned from the survey responses. We conducted two pilot interviews in January 2021 that resulted in improvements to the original interview protocol, such as including additional questions like, "What resources would have helped you in the DST design process?" and a reordering of questions for better interview flow. Appendix 3 shows the final interview protocol.

We sent requests for interviews via email to the survey respondents who indicated their interest in being interviewed in the web-based survey. We conducted interviews May through December 2021. At the end of each interview, interviewees were asked whether they knew of other USGS employees with DST experience who the research team could interview (called "snowball sampling"). All 25 USGS employees who agreed to the interview requests were able to participate in an interview. The interviews were conducted virtually using Microsoft Teams and designed to take no more than one hour each. The interviewees spanned four USGS Mission Areas (table 7) and came from a range of Regions (table 8).

Table 7. U.S. Geological Survey Mission Areas of interviewees.

USGS Mission Areas of interviewees	%	Count
Core Science Systems	16	4
Ecosystems	16	4
Energy and Minerals	0	0
Natural Hazards	28	7
Water Resources	40	10
Total	100	25

Table 8. U.S. Geological Survey Regions of interviewees.

USGS Regions of interviewees	%	Count
Midcontinent	32	8
Southeast	20	5
Southwest	16	4
Headquarters	16	4
Northeast	8	2
Rocky Mountain	4	1
Northwest—Pacific Islands	4	1
Alaska	0	0
Total	100	25

The 25 interviews were recorded on Microsoft Teams and professionally transcribed. The transcriptions were then uploaded to NVivo,[9] a qualitative data analysis software. Qualitative data analysis ("coding") was completed by one member of the author team. This analysis method means the researcher coded individual sentences or sections of text with descriptive labels that allowed for the rigorous identification of related content and themes across the data (Saldaña, 2016). We used a list of predefined codes based on the survey data and the interview protocol, a method known as deductive, concept-driven, or thematic coding (Guest, MacQueen, and Namey, 2012) Some example codes were "Resources Needed," "Barriers," and "Hindsight." The full codebook appears in appendix 4.

[9] 7NVivo, release 1.3, a product of Lumivero.

4. Decision Support and Decision-Support Products at USGS

4.1. How Do USGS Employees Define Decision Support?

The range of tools and applications created by USGS scientists and developers with the goal of delivering information to support decisions may broadly be referred to as "decision-support tools," "decision-support systems," or "decision-support products." Within the larger scientific literature, DSTs were classically defined narrowly as software systems that assist in solving unstructured problems for which there is not a mathematically optimal solution (Geoffrion, 1983). In 2009, the National Academies surveyed the landscape of decision support for climate change science and offered a definition of decision support as, "organized efforts to produce, disseminate, and facilitate the use of data and information in order to improve the quality and efficacy of climate-related decisions." (National Research Council [NRC], 2009, p. 2) and highlighted the improved efficacy of decision support when scientists and decision makers engage in mutual learning. Similarly, Wong-Parodi and others, (2020, p. 52) define DSTs as, "the array of computer-based tools developed to assist sound decision making, including the management of environmental risks and planning for impacts in different sectors and regions." Within the USGS, the definition of "decision support" and the understanding of what constitutes a "tool" varies across the Bureau, with programs, projects, and scientists using these terms in subtly but importantly different ways. Recognition of these differences was one of the motivations for this study.

Key to understanding the experiences of USGS employees who develop DSTs was understanding their definition of DSTs. Therefore, one of the first questions asked in both the survey and the interviews was how individual scientists and developers define DSTs. "Decision science," "decision-support tools," "decision-support frameworks," "decision-support systems," and even "decision-support system tools" are all terms used within USGS to describe data or applications that help a stakeholder make a decision. In the survey and interview protocols, for the sake of simplicity, we used the term "decision-support tool" (DST).

In the decision-support literature, definitions of DSTs range from narrow, to broad, to expansive. Some, like Fleisher and others (2014), limit their definition only to interactive software applications that structure a decision-making process. Others broaden the definition to include all software applications (Wong-Parodi and others, 2020). Others further expand the definition to a wide range of activities that support decision making (NRC, 2009). We provided three definitions based on these distinctions in the literature as response choices in the survey, then asked respondents to choose among them or to select "other" and fill in their own definition. Eighteen percent of our respondents defined DSTs as interactive software applications that structure a decision-making process (for example, modeling tools that allow users to explore different scenarios), 14 percent defined DSTs as any software application that supports user decision making (for example, data portals and modeling tools), 62 percent defined DSTs as any activity (software or other) that provides data or other types of information products that supports user decision making (like decision-maker outreach, infographics, data portals, and modeling tools), and 6 percent chose "other" and provided alternative definitions. When these answers were compared with individuals' Mission Areas, it became clear that most respondents (62 percent) trended towards choosing the broadest definition of DSTS (fig. 11).

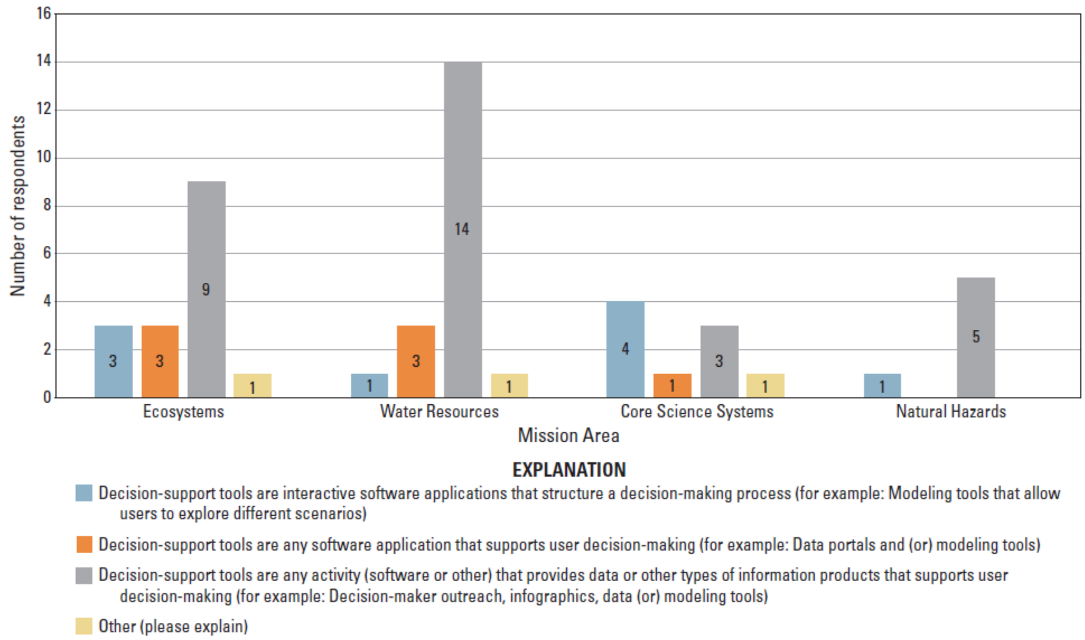


Figure 11. Survey respondents' definitions of "decision-support tool" by U.S. Geological Survey Mission Area.

In the interviews, we asked USGS employees to define decision support and some of their responses revealed an even broader definition. As one interviewee asserted:

I think decision support, lowercase, has been the main reason I'm here. If I didn't want to do decision support, I wouldn't be at the USGS because I would just get [National Science Foundation] funding and be an academic. I personally feel everything we [as a Bureau] do is decision support, or at least should be. (Interviewee 3)

This quote exemplifies how some USGS employees have adopted an even broader definition of DSTs than those that appear in the literature (which informed the multiple-choice options provided to them in the survey). This broad definition can include providing raw data and information to the public without an explicit focus on who will use it and how. This definition may come from the fact that USGS is not a decision-making Bureau, but rather a Bureau with a mission to provide quality science, information, and data that can be used by cooperators and other stakeholders to support decisions. It follows that some interviewees view this distinction as evidence that everything USGS does is decision support.

In essence, this broad (and, to our knowledge, unique to USGS employees) definition suggests that the activity of decision support is analogous to the USGS mission of making scientific information accessible. This sometimes results in a mentality that USGS employees could simply share data with those who need it rather than thinking about ways that they could enable and empower decision makers to use the data more effectively. As one interviewee explained:

> If someone still decides to build in a tsunami zone because of many other preexisting economic and social reasons, and political reasons, that's their call. It's not my job to say you can't build in a tsunami zone * * *. As long as they're letting us be at the table, and they say, “I'm glad you all were here for the conversation.” That's success. (Interviewee 3)

Alternatively, this belief that all USGS science is decision support can also lead to the creation of DSTs where a DST may not be necessary, and the decision maker simply needs streamlined data access. As an interviewee explained:

> There has been more than one example of building a tool that was not used because there was a misunderstanding, or we didn’t go the whole nine yards in terms of understanding the use case before creating something. (Interviewee 10)

Understanding when to build a DST is not always easy, and the desire to bring greater clarity to this question was one of the driving forces behind this research and the principles presented in this report.

4.2. Barriers to Successful Decision-Support Tool Development

The survey allowed respondents to answer the same group of questions for up to five different tools that they were involved in creating. One of these questions was, “What barriers did you and (or) the team face in building the DST?” Respondents were given eight options of barriers to choose from including “barriers in another category” and “did not experience any barriers". Respondents were able to select multiple options and could answer this question for up to five decision support tools. This question allowed us to gather information on what challenges USGS employees face when building a DST to both report on these challenges and offer potential solutions.

Survey responses revealed a multitude of barriers faced by DST designers within USGS (table 9). Notably, only one respondent indicated that they did not experience any barriers when building DSTs. The majority of respondents (98 percent) faced obstacles related to Department of the Interior (DOI) or USGS policies, funding, software, stakeholder engagement, tool usage, or staffing. Sixteen percent of responses were "barriers in another category" and respondents described specific barriers they or their team had faced including limited advertising and outreach, lack of tool maintenance, changes in operational requirements, no access to affordable programmers, lengthy and challenging hiring processes, lack of stakeholder engagement experience, difficulties meeting too many varied and opposing stakeholder needs in a single tool, difficulty tracking usage, and run time especially regarding tools with large datasets.

Table 9. Barriers to building decision-support tools.

Barriers to building decision-support tools	% of respondents	Total responses across all respondents
Barriers related to funding (for example, funding availability, contracts)	52	28
Barriers related to software (for example, approval of platform, cloud hosting)	48	26
Barriers related to stakeholder interactions (for example, understanding needs)	39	21
Barriers for tool usage (for example, low usage or not user-friendly)	33	18
Barriers related to staffing (for example, lack of IT capacity, shortage of usability experts)	30	16
Barriers related to DOI or USGS policies (for example, Paperwork Reduction Act, Fundamental Science Practices)	13	7
Did not experience any barriers when building this tool	11	6
Barriers in another category[1]	43	23
Total	n.a.	145

We asked our interviewees about the barriers they faced in building the DSTs, how these barriers were or were not overcome, and if there were any resources that would have helped them in the process (appendix 3). One survey respondent, who agreed to be interviewed, explained how multiple interacting barriers kept their tool from being successful:

> While substantial financial and technical resources were invested in building [the tool], there was never adequate * * * internal commitment behind consistently promoting it, ensuring timely development, [or] having the USGS set an example by meaningfully populating it with our own data. As a consequence, we built a great tool that was never used or adopted by the community. (Interviewee 18)

This quote demonstrates a range of barriers across development, project management, and deployment encountered by many research participants that the USGS could address.

4.3. Successful Decision-Support Tool Development at USGS

Before we asked the research participants whether they participated in creating tools that were successful, we asked them to share their definition of success. Several interviewees pointed to use of the DST as an indicator of success. Others, however, stated that use must be accompanied by informing decisions the tool was developed to support. These interviewees further pointed out that this kind of success could be in the form a small group of decision makers rather than a large number of total users. This is similar to the findings of Pearman and Cravens (2022) in which drought tool creators defined success to include producing tools that met defined needs and were used. Other interviewees felt that success could be measured by widespread use and adoption of a DST beyond the initial group of decision makers or cooperators that funded the tool's development. A growing audience over time, too, was an indication of success for these interviewees.

As is clear in these differing definitions of success, DST success can be measured in several ways, which was also stated by a handful of interviewees who maintained that success is different for every project and varies depending on the perspectives of the developer and the user (and, presumably, the funder). Some interviewees also pointed to "ease of use" of the tool as a metric of success. One interviewee stated that customer satisfaction was a way of identifying success, saying, "The fact that people keep coming back to us and asking us to [make another DST]. That's really our measure of success. People like what we make, and they come back and ask for more" (Interviewee 15).

Although barriers to DST development were consistently identified and described by both survey respondents and interviewees, many interviewees explained ways that these barriers were avoided or overcome, leading to successful DSTs with high numbers of users, media attention, and long-term support. The types and frequency of barriers identified by all survey respondents (table 9) were very similar to those types and frequency of barriers experienced in developing tools that are still in use today. However, all six of the tools that did not experience any barriers to their development are still in use today either in their original or a modified form. This finding points to the importance of adequate funding, staffing, software, and stakeholder engagement in building a successful tool with longevity.

Throughout the interviews, interviewees provided examples of successful DSTs they have been a part of and how they knew that the tool had become a success. Most examples related to media coverage of a tool, examples of users incorporating the tool into their decision-making process, or an uptick in the number of users and use by unexpected groups over time. While media coverage and direct relationships with decision makers are easy ways to tell if a tool is successful, many interviewees described the roundabout ways they learn about a tool's success and lamented the lack of quicker and more reliable avenues for obtaining this information. One interviewee described the Paperwork Reduction Act (PRA)[10] as a barrier to soliciting feedback from users:

> It would be great to send out a survey to 50 different people within [the geographic area] and say, "What do you think of our tool? Do you use it? Give us good examples of how it's changed your world." I can't easily do that without a 6-month process. (Interviewee 4).

Instead of soliciting direct feedback from users, interviewees described receiving feedback from users via emails that let them know in which ways the DST was succeeding and which areas needed improvement; Pearman and Cravens (2022) found the same widespread reliance on informal methods of feedback in their study of the experiences of drought tool creators across State and Federal agencies. According to the interviewees, when a DST is successful it can make complicated science easier to use by ensuring robust and repeatable outcomes to inform decisions, thereby saving time and money, improving decision making, and making the science more understandable.

5. Five Key Principles of Designing Effective Decision Support

The information collected from the surveys, interviews, and the literature on DST design and development was analyzed to identify best practices that apply both at USGS and more broadly. We present this information about best practices and lessons learned from successful tools as five main principles that contribute to effective DST development. These principles are: (1) use an adaptive, iterative design process, (2) collaborate across disciplines and organizations, (3) engage with the target users of the tool, (4) develop an empirical understanding of use and usability, and (5) plan for the tool's full life span. Considering these

[10] The Paperwork Reduction Act is a law governing how federal agencies collect information from the public. For more information see: https://pra.digital.gov/.

principles before and during tool design and development supports the USGS mission of delivering actionable science by providing guidance on how effective DSTs can be designed, as well as important considerations for USGS DST developers before they begin creating a DST.

5.1. Principle 1. Use an Adaptive, Iterative Design Process

The first principle is about giving equal consideration to the process by which tools are created rather than focusing exclusively on the intended products or information outputs. This principle includes the following best practices:

- Allow space for adaptation and learning
- Work iteratively

The importance of allowing space for adaptation and learning is a common tenet of human-centered design and user-centered design (defined in Box 1). Most, if not all, visualizations of the design process depict a cycle starting with understanding user needs and continuing through the other design stages (fig. 10). Equally important, these visualizations typically show the iterative nature of the process by using symbols, such as arrows, to signify that the stages feedback to one another. When describing successful tools, many research participants described the process of designing the tool as iterative, participatory, and inclusive of trial and error.

5.1.1. Allow Space for Adaptation and Learning

Allowing space for adaptation and learning ensures that the design team can stay flexible and open to changes regardless of when they occur in a project’s lifetime (Conboy, Fitzgerald, and Golden, 2005). However, any development process is inherently confined by resource allocation, such as funding and staff availability. To accommodate for unforeseen changes, a project manager would ideally strike a balance between creating time allocations for completing each project outcome and keeping planning to a minimum (Barnhart and others, 2018; Meso and Jain, 2006). Ideally, managers would not try to control the development process too rigidly in order to be more responsive to changes (Cusumano and Yoffie, 1999). This part of Principle 1 is about staying flexible and embracing uncertainty in a proactive and organized manner.

Interviewees described how decision-support projects at USGS often focus on creating a tool the same way many scientists think about publishing a scientific paper—as a finite goal to be completed as quickly as possible. However, many of the larger, more successful tools at USGS were created and improved over the span of multiple years. While some interviewees revealed that this process could be frustrating early on when there is messy exploration and ambiguity, respondents also explained how allowing adequate space for the design and development process would eventually result in better tools. One interviewee stated:

> Each time we have an improved capability, then we have something more to discuss. As we go along, we get a better idea what it is that users want, and so, we're able to put more information, either prototypes or ideas and so forth, into the conversation. (Interviewee 9)

Although essential to improving the tool, the iterative process described in this quote is time and resource intensive. Creating the space and time necessary for trial and error is essential for this process to occur. This can be achieved by having the team leaders monitor the team's progress at regularly scheduled review meetings where any issues or changes in requirements can be assessed and addressed by the next meeting (Grenning, 2001). When the development team is an adaptive organizational unit that is ready to tolerate the ambiguities of the design and development process, it allows for sufficient time to discuss the assumptions, needs, and limitations of approaches (Barnhart and others, 2018). Allowing space for the design and development process to unfold requires leadership and funders to have buy-in in the process (Lavery, 2018).

5.1.2. Work Iteratively

Successful DST development requires iteration (Newman and others, 2000); that is, successive rounds of refining designs based on user feedback. When focusing on iteration with user groups and prototype testing, some USGS tool development teams have enlisted expertise in this area by working with usability experts within USGS or contracting organizations like 18F,[11] a technology and design consultancy within the U.S. Government.

Respondents reported that without iteration, DST projects could miss the mark. One USGS software developer described the benefits of the Agile method of software design (a method described in Meso and Jain [2006] that includes constant iteration and stakeholder engagement throughout the design process). He stated what happens when iteration is not prioritized:

> One thing I've learned in nine years of doing software development, the other way of doing it which is generally called the waterfall method where you just say, “Okay, build this thing for us. Here's all the specs, and we'll see you in six months.” That does not work. It never leads to good outcomes. (Interviewee 19)

As the interviewee explains, development processes that lack iteration rarely led to good outcomes. It is important to note that iteration can occur during the development process as well as after the tool is created. Successful tools created by interviewees often resulted from long-term relationships between the tool’s creators and the tool’s users. Some

[11] https://18f.gsa.gov

interviewees reported attending meetings or workshops with the user group (sometimes meetings that were already regularly held for other purposes) in order to keep the DST relevant. For example, one interviewee stated:

> Periodically, [we had] presentations and engagements with the [users] over the course of a year or year and a half to update them on new pieces or getting their feedback on that usability, getting their feedback on suggested functionality. (Interviewee 10)

This quote demonstrates how, over time, the development team worked iteratively with their users to improve the tool after it was created. Iterative prototyping and evolving development processes are key contributors to successful DSTs (Newman and others, 2000).

Obtaining user feedback throughout a tool's lifetime is an ongoing operational task that improves a tool's uptake and usability. User feedback can be obtained through both qualitative methods, like emails from users or media coverage, or quantitative methods, such as web analytics. One interviewee explained how user feedback helps him to modify his tool:

> [I] understand what the users might want by paying attention to what sort of questions people [are] asking—when people do run into problems and contact me I [try] to see if there's something my program could do that would have made it so that they wouldn't have had to contact me… These user questions should not be viewed as a drag on the developer's time. They should be viewed as a resource to be mined for ideas. (Interviewee 21)

This quote explains why user feedback is key to any iterative tool development process and why the pathways for this feedback should be as accessible as possible. User feedback can sometimes also reveal uses for a tool that the tool's designers did not originally intend.

Example Tool 1. The Chesapeake Bay Watershed Data Dashboard

Design time.—3 years

Team lead(s).—John Wolf (USGS) and Emily Trentacoste (EPA).

Principle represented.—Use an adaptive, iterative design process

Decision makers or end users.—Environmental managers and planners in the Chesapeake Bay

Decision opportunity.—Watershed restoration plan development and implementation

Decision-support need.—Information on nontidal monitoring, tracking interventions, and best management practices

Tool description

The Chesapeake Bay Watershed Data Dashboard is an online tool that provides accessibility and visualization of data and technical information that can help guide water quality and watershed planning efforts. A large amount of scientific and technical information is available to environmental managers and planners at both State and local levels to inform restoration efforts. Much of this information has been updated or newly generated in recent years.

The Chesapeake Bay Watershed Data Dashboard is a collaborative project of the Chesapeake Bay Program Partnership, with input from the U.S. Environmental Protection Agency (EPA), the U.S. Geological Survey (USGS), and other science providers.

Quote

"We had the mindset of 'if you build it, they will come' [laughs], and so, occasionally, that worked if you happened to guess what was in their minds in advance. At this point, we're much more inclined to interact with the proponent, the sponsor, if you will, as well as the people they are trying to reach, and trying to do that in advance of actual tool construction. We have certainly evolved, I think, in a good way."

— John Wolf, team lead (USGS)

Key Takeaway

Focusing on the process rather than the product allowed tool development to be driven by the needs of the target users rather than the assumptions of tool developers.

For more information, go to https://www.usgs.gov/centers/lower-mississippi-gulf-water-science-center/science/chesapeake-bay-watershed-data-dashboard?qt-science_center_objects=0.

5.2. Principle 2. Collaborate Across Disciplines and Organizations

The second principle is to collaborate and build connections across disciplines and organizations. This principle includes the following best practices:

- Work with diverse teams
- Bring diversity into the team early
- Get everyone on the same page and speaking the same language

When interviewees described DST design processes that were successful, they often were the product of teams with diverse skillsets where the entire team convened from the beginning and was able to overcome differences in communication or starting assumptions to get on the same page.

5.2.1. Work with Diverse Teams

Human-centered and user-centered design approaches put a great emphasis on the composition of the development team and their talents, skills, perspectives, and knowledge (Meso and Jain, 2006). Multi-disciplinary teams have been shown to increase the success of DST development (Fleisher and others, 2014). This success may be due in part to the integration of plural perspectives which can create a more holistic process (Vennix, 1995) or due to the way that more diverse team composition enhances creativity (Ulibarri and others, 2019).

USGS respondents who believed their DST(s) were successful all spoke highly of their team members, especially those who brought experience and knowledge to the table that the respondents themselves did not have. One interviewee added that in addition to a mix of roles in a development team, it is good to have a mix of personalities and perspectives:

"You need a mix of roles and personalities in a group to make one of these [DSTs] effective * * *. Make sure you don't have everybody who thinks just like you and is from just your little group on your team" (Interviewee 9).

This interviewee went on to explain that the type of person who excels at the operational side of maintaining the tool and someone who is primarily interested in the initial creation of the tool are very different personality types, and that the development team needs both for the tool to be successful. Multidisciplinary design teams benefit from members that span a range of roles and expertise. Some of the roles and job titles that research participants identified as being valuable included fundraiser, spokesperson, social scientist, usability specialist, graphic designer, writer, coder, and project manager. It is important to note that some of these roles and job titles are scarce in the USGS and comprise skillsets that conventionally trained USGS natural scientists do not necessarily have. For example, out of more than 8,000 USGS employees, only 11 permanent employees hold the title social scientist, although other people with social science training may work under other job titles.[12] This lack of employees with specific expertise generally results in scientists backfilling these roles and shows that more training in those skillsets or hiring more employees who are trained in these skillsets could be beneficial for developing DSTs. As one interviewee explained (when referring to the hiring of usability experts), “There's people who are trained to do these skills. Appreciate them and realize the additional expertise that having someone who is trained and experienced can bring to the table as opposed to having a scientist [take on that task]” (Interviewee 18).

The mention of USGS scientists backfilling tool design roles outside of their expertise was common throughout the interviews. Having team members fulfill roles for which they do not have expertise is a tradeoff that can reduce costs, and sometimes design time, but that can also decrease the quality of aspects of the DST that may be crucial to its success such as graphic design or usability. However, human-centered design is inherently people focused and needed expertise can sometimes be found unexpectedly within teams. For example, some interviewees mentioned working with coders who also enjoyed graphic design. It is beneficial to recognize, use, and nurture the varied talents of all team members

[12] The DOI Position Locator provides statistics on the number of Federal employees working within DOI Bureaus under specific job titles and occupational series. The numbers reported here are based on accessing the DOI Position Locator on May 3, 2023, at http s://career s.doi.gov/ position- locator.

while seeking to develop a well-rounded team that can fill the roles required for successful DST development.

5.2.2. Bring Diversity into the Team Early

Managing diverse teams requires an open flow of communication that can benefit from early involvement of all team members. Katzenbach and Smith (1992) found teams performed more effectively when all the team members have a clear understanding of a team's goal from the beginning. This finding was supported by the interviews on successful DSTs in which the entire design team was brought together early in the design process. The data revealed that teams that did not initially convene with every part of the design team left some roles (developers, usability experts, and stakeholder engagement scientists, in particular) being brought in too late to be fully effective.

Every USGS coder or designer, usability expert, and social scientist who was interviewed preferred to be brought into a DST project early in the process. For example, a USGS employee explained that when the programming team joins a project in its early stages, they can help define what the tool could look like and how it could function:

> I think it's really important to have the programmer team involved in the beginning and involved with the people that actually have to use it on both sides. They'd come with me to these meetings with collaborators too * * * I think that's critical, because if they don't hear what the problems are firsthand, they're relying on one person to translate them, and that's a hot mess. (Interviewee 8)

The benefits of involving the programmer early in the process are twofold: (1) they learn about user needs firsthand, and (2) they can inform the design team of what is and is not possible based on their specific expertise. When interviewing USGS programmers, they confirmed that being involved early in the design process was helpful to them. This holds true for every member of the team essential to the tool's design. When team members are brought on to a project late in the game, it can be difficult for them to fix the problem that they were brought on to fix. A quote from a project manager explains how a tool would have benefitted from earlier involvement of a UX-UI expert, a term that refers to someone with expertise in user experience (UX) design and user interface (UI) design:

> [The tool] existed prior to us having a usability person, but we brought her in… So, the new [tool] looks completely different than the old [tool], and that's because of her presence. I brought in a [usability expert] because I knew [the tool] was kind of clunky. It worked, but it was clunky. Could have been fine, most things at the [Geological] Survey looked fine, but they're not great. I would love to have a hundred UX-UI experts instead of us geologists or seismologists thinking we can not only be experts in this science topic, but also are experts in tool development. (Interviewee 3)

Example Tool 2. The Great Lakes Coastal Wetland Restoration Assessment

Design time.—6–12 months per mapper

Team lead(s).—Kurt Kowalski and Chris Sanocki

Principle represented.—Collaborate across disciplines and organizations

Decision makers or end users.—Ecological managers and planners

Decision opportunity.—Coastal wetland habitat restoration planning

Decision-support need.—Information on which coastal wetlands have the greatest potential for habitat restoration

Tool description

The Great Lakes Coastal Wetland Restoration Assessment (GLCWRA) initiative is composed of multiple individual mappers that are described by a larger story map. The GLCWRA initiative uses principles of geodesign to identify coastal wetland areas that have the greatest potential for habitat restoration. The resulting composite index raster can be used by ecological managers and planners to assist with the identification and selection of wetlands for restoration initiatives. The GLCWRA team partnered with the New College of Florida and U.S. Geological Survey Wisconsin Informatics and Mapping group for their geographic information system (GIS) experience and hosting abilities and collaborated with stakeholders at the U.S. Fish and Wildlife Service (Wildlife Refuges), State agencies, Ducks Unlimited, the Nature Conservancy, and more.

Quote

"I value the partnerships and the ideas of other experts, so to me, it's better to engage collaborators [and] others in USGS who have that expertise and build off their expertise rather than trying to duplicate it within our center."

— Kurt Kowalski, team lead

Key Takeaway

When the decision-support tool development team lacks expertise in an area, collaborating with people who have that expertise benefits the tool development and implementation process.

For more information, go to https://glcwra.wim.usgs.gov/ or https://www.sciencebase.gov/catalog/item/56d862bfe4b015c306f6bdad.

5.2.3. Get Everyone on the Same Page and Speaking the Same Language

When building a DST, having a multidisciplinary team that can bring multiple perspectives to the development process is valuable (Fleisher and others, 2014). However, working with a multidisciplinary team can be challenging because software developers, natural scientists, social scientists, and usability experts all speak slightly different languages. When you add the users, stakeholders, and outside partners to this list, it takes a considerable amount of time and energy for everyone to get on the same page. Having a mutual understanding of the team's goals is essential for a development team to be effective because its members must be responsive, competent, and collaborative (Cockburn and Highsmith, 2001; Boehm, 2002). As one of the interviewees explained: "You end up with a better team if everybody understands all the parts of the team" (Interviewee 8).

The interviewee went on to describe how it took multiple interagency meetings for everyone involved in the tool's design to realize that they were talking past each other. For multiple days, these agencies were talking about the importance of delivering the data in "real time" without realizing that they all had different definitions of that term. For this tool, one agency defined "real time" as seconds, the USGS defined "real-time" as four hours, and another partner agency defined "real-time" as four to six hours. Then everyone turned to the primary collaborator and intended user of the tool, and asked what their definition of real time was, and they said that real-time for their organization is seven days. Once everyone realized that they had been talking past each other and that the worry of not being able to deliver data in seconds or four hours was not a key requirement, they could move forward and design a tool that worked for the primary organization's needs. Although every agency involved in these meetings was approaching the idea of real-time decision making differently, the goals ended up being achievable once they all got on the same page.

5.3. Principle 3. Engage with the Target Users of the Tool

The third principle is about defining the target users for the tool you are building and engaging with them throughout the tool design and development process. This practice can be considered a special case of the more general process of stakeholder engagement (Box 2). In the human-computer interaction discipline there is an important distinction between the terms, “stakeholder” and “user.” A stakeholder is defined as any group or individual who can affect or is affected by the achievement of the organization's objectives (Freeman, 2010). This means that while some stakeholders may not use a DST themselves, they may still benefit from its creation (Kelly, 2019). All users are stakeholders, but not all stakeholders are users. In the context of DST development, users are a special subset of stakeholders, and user engagement is key to ensuring that tools serve the decision processes they are built to support (Uran and Janssen, 2003). This principle includes three best practices:

- Define the target users of the tool
- Understand the decision context
- Adapt to evolving user needs and expectations

5.3.1. Define the Target Users of the Tool

Defining specifically who the target users are for a tool is one of the challenges of the DST development process (Loucks, 1995), and limited involvement of users in the development phase can lead to unsuccessful DSTs (Uran and Janssen, 2003). When users become part of the development process, scientific expertise and local knowledge are combined, maximizing the opportunities and benefits arising from the development of the tool (Oliver and others, 2017; Burnett, 2020), including mutual learning (NRC, 2009).

In the interviews, tools that had low usage were often developed without specific users in mind. Many of the interviewees explained that within USGS unsuccessful DSTs are often built without considering who the target users of the tool will be. One remarked: “That’s my pet peeve of the [U.S. Geological] Survey, is that we do tend to build tools that don’t have a [specific intended] audience… We track it for three years of use and it’s at 200 hits in its lifetime” (Interviewee 15).

The sentiment that some USGS DSTs are built without target users in mind was expressed in many of the interviews. Oftentimes interviewees explained a process in which a group of scientists discovered an intriguing problem that they thought they could solve by building a DST, without thinking about who would actually use the DST or how they would use it. As one interviewee stated:

> I think the [DSTs] that have user engagement have a lot more buy-in. Sometimes some of the things I've built it's much more of a ‘If you build it, they will come,’ mentality. * * * To be perfectly honest with you, sometimes these things do not get a lot of attention. They really don't. There might be 10 to 20 users who use it all the time, and that could be it, and then you get a few spikes here and there from time to time. Some of these probably hardly get seen at all after the initial year that they're a new thing, and then they might just fall by the wayside. (Interviewee 19)

Creating a tool in a vacuum, without identifying the target users of the tool, has led to the creation of DSTs that are not used over time and do not necessarily support the decisions they were built to support.

5.3.2. Understand the Decision Context

Once the target users of the DST are defined, one of the primary goals of user engagement is to understand the context of the decision(s) that the DST is built to support. Understanding the decision context means learning about how target users accomplish specific tasks, make decisions, and what they are trying to achieve or what problems they are trying to solve. Gathering this information enables the DST development team to meet user expectations and needs. As an interviewee explained:

> I try to outline who are the people using [the tool] before we just build it. * * * We write up these use cases where we get into what [the user's] pain points are. What are they trying to do? What decisions are they making without us? What decisions could they do better if they had us around? (Interviewee 3)

Understanding the decision context is important because too often the interactions between scientists and users are motivated by the interests and goals of scientists and scientific agencies rather than the needs of their users (Lavery, 2018). This creates a disconnect and can ignore the obstacles faced by users, including diverse data formats and low data literacy (Sandoval-Almazán and others, 2017; Restrepo-Osorio and others, 2022; Stoltz and others, 2023). The context in which a user makes a decision defines a set of constraints that needs to be analyzed and understood early in a tool development process as they are of crucial importance, especially when opinions of the project team differ (Wallach and Scholz, 2012). Structured user engagement is essential for increasing understanding of the complex social, economic, cultural, and political settings in which a decision is made (Carmona and others, 2013; Röckmann and others, 2012) because actual users' behavior tends to differ from the imagined behavior assumed by DST developers—especially regarding the importance of proposed features (Wallach and Scholz, 2012).

Box 2. Engaging with Stakeholders

Stakeholder engagement is a term applied to a variety of interactions that organizations (like the U.S. Geological Survey [USGS]) carry out with groups or individuals that have a stake in the activities of that organization. These interactions can range from public outreach (in which an organization communicates about an activity) to developing partnerships with stakeholders to undertake an activity together (Bamzai-Dodson and others, 2021). Fiorino (1990) notes that organizations may engage stakeholders for a variety of reasons, including the following:

- normative reasons, such as the inherent good associated with greater participation in decision making in democratic societies
- substantive reasons, such as bringing about better decisions through increased depth and breadth of information that can brought to bear on an issue when more perspectives are included
- instrumental reasons, such as increasing the legitimacy of a decision in the eyes of stakeholders when they feel ownership in the process

Structured stakeholder engagement is differentiated from unstructured stakeholder engagement, or the ongoing relationships that a USGS scientist or employee has with stakeholders that are characterized by unstructured interactions and other forms of public outreach. Structured stakeholder engagement requires rigorous social science methods and adherence to ethical standards like confidentiality.

Methods used in structured stakeholder engagement include the following:

- surveys, a method of collecting data in a consistent way such as a questionnaire (Young, 2015)
- semi-structured or open-ended interviews, which combine defined questions with unstructured exploration. This gives interviewees the opportunity to raise new issues that may not have been accounted for by the interviewer (Wilson, 2014)
- focus groups, which obtain data from a purposely selected group of individuals (Nyumba and others, 2018)

Stakeholder engagement methods can uncover the decision context when developing decision-support tools (DSTs). Although usability testing may also fall under the umbrella of stakeholder engagement, it occurs later in the tool development process, after the decision context has been understood. Usability testing is described in more detail in Principle 4.

While structured stakeholder engagement methods can be cost- and time-intensive (Oliver and others, 2017), they are essential for ensuring that DSTs serve the need(s) they were built to support (Oliver and others, 2017; Burnett 2020). All of the USGS interviewees spoke about the benefits that can be gained from both structured and unstructured stakeholder engagement. Some of these methods included long-lasting relationships with individuals in partner organizations (unstructured engagement) as well as arranging focus groups with targeted tool users (structured engagement). Several interviewees described tools that only achieved their goal after involving a collaborator with social science expertise:

> It's not even possible to evaluate how helpful it was to have [a social scientist] be part of the group. It would've been a completely different experience without her, and it's been very successful as a product because of her involvement in shaping it. (Interviewee 9)

Interviewees also emphasized the difference between stakeholder engagement focused on learning about user needs with outreach that takes place after a tool is built. Although outreach after a tool is made public is important, that tool may not meet the users' needs if the developers do not work to identify and understand those needs early in the development process.

One interviewee explained why it is important to ask potential tool users about their needs before asking what kind of product they want:

> If you take the time to do that, sometimes you'll go in a different direction, and that's great * * *. There's questions you can start to ask at the beginning that I think—and we're starting to do that now—could prevent some of the failings that we've seen [for] the future. (Interviewee 18)

This quote demonstrates how learning about the decision context of target users is essential to creating a usable tool. The kinds of questions that might be asked of target users include the following:

- What is a recent task that you need to accomplish in your role?
- What decisions are associated with achieving that task?
- How does this task support your organization's overall mission?
- How do you relate to others (either internal or external to your organization) in completing this task?
- What challenges do you face in completing this task?

Questions like these can guide the development team towards clearly defining the political, environmental, economic, social, and legal context of the decision, essential information that will allow the tool to support quality decision making (Wong-Parodi and others, 2020).

5.3.3. Adapt to Evolving User Needs

Engaging with users is a continuing process that ideally results in sustained relationships with users that begin before DST development and persist after a DST is launched. These relationships are important to maintain as the users' needs and decision contexts evolve over time. User engagement needs to be strategic and sustained to be successful; Pearman and Cravens (2022) found strong links between user engagement throughout the development process and their perceptions of tools as salient and credible.

Interviewees who described successful tools often described efforts to continue learning from and sharing information with users after the DST was created. These efforts included emailing users who participated in user engagement efforts to let them know the outcome of their involvement, sharing links to the finished tools, sending out newsletters with updates, providing trainings or workshops on how to use the tool(s), and creating new or using existing pathways for user feedback. One interviewee explained their process for maintaining relationships with users:

> I've spent some time just reaching out to these partners in the off season when we're not that busy and asking them what they like about the tool, what limitations they see, and sort of their wish list * * * so it's ongoing—we provide the data, and then we're there to support and answer questions as they interpret the data. (Interviewee 12)

When asked to reflect what they would have done differently in hindsight, some interviewees spoke about the importance of timing in managing relationships with users. Timing is important, and if user engagement occurs years before a tool is made available, the users' needs may have evolved, other tools to meet those needs might have become available, or there could be a loss of interest in the tool. Maintaining continuity of participation can also be an issue; after too much time, user interest in tool development may decrease (Newman and others, 2000). One interviewee explained how it can be challenging to get users back on board when they lose interest in a tool before it is complete:

> Management didn't push the developers to get things done, so we would promise a new functionality and it wouldn't come online for like a year and a half, and then people would be like, “Well, you guys are never going to get this done.” They'd lose faith in it. We didn't promote it. We didn't promote contributing to it. We didn't offer services to help people put data into it * * *. It just failed on all levels. (Interviewee 18)

This quotation explains how user engagement at the beginning of the development process is not enough to guarantee that the usership will be there once a tool is built. Additionally, sometimes tools built by the USGS are created because they anticipate a need that targeted users have yet to express. This assumption can be problematic for tool development. Users rarely have the time or resources to use new and unfamiliar tools (Barnhart and others, 2018), and tool users report that there can be significant opportunity costs to switching from a familiar tool to a new and untested one (Cravens, 2018), which makes the bar for adopting new tools high. As an interviewee explains:

> It takes a long time for the community to mature to be ready to handle the data, too. I think that's a key point. Sometimes we look at the science and we go, “I know you need this,” but you [don’t] wait long enough for your customer to mature, to be ready to be able to handle that decision. (Interviewee 8)

When developers do not bring their users along with them on the tool creation process, the users do not have investment in the tool being created or the chance to express preferences about how the tool is developed. Involving tool users throughout the development process can increase uptake and use.

Example Tool 3. USGS Operational Aftershock Forecasts

Design time.—2 years

Team lead(s).—Mike Blanpied, Jeanne Hardebeck, Andrew Michael, Sara McBride, Ned Field, Kevin Milner, Michael Barrall, and Eric Martinez

Principle represented.—Engage with the Target Users of the Tool

Decision makers or end users.—Federal Emergency Management Agency (FEMA) and the public

Decision opportunity.—Increasing the public's understanding of aftershocks

Decision-support need.—Probabilistic models that provided accessible information on the frequency and size of earthquake aftershocks.

Tool description

Using a probabilistic model, the U.S. Geological Survey (USGS) Operational Aftershocks Forecast provides a general understanding of the frequency and size of aftershocks that could occur given the mainshock magnitude. Communicating these probabilistic models presented many challenges such as communicating statistics to a diverse audience with various levels of knowledge. To address these challenges, the aftershock product presents the simplest information first and then expands in complexity as the user continues to browse. In contrast to previous products that were inaccurately reported in the media, this tool resulted in accurate media reports demonstrating that the forecast template was successful (Michael and others, 2020).

Quote

"We would present the kinds of information we could provide in these sorts of formats, in these sorts of timeframes and so forth, and then various user groups' representatives [would] talk to us about what would be useful, how they would use that, what they would like to have, what kind of information and so forth. We've also had a fair number of more targeted meetings with, for example, different FEMA representatives. We've talked to urban search-and-rescue groups and so forth, so really talking straight to the users * * *. If you happen to have a good, a really outreach-focused person in the project group, it's great, and then you can build and maintain those user relationships and engage users in product development and improvement and so forth over time."

— Mike Blanpied, team lead

Key Takeaway

A communication-focused social scientist conducted stakeholder engagement that increased the tool's successful uptake and the public's understanding of aftershocks.

For more information, go to https://earthquake.usgs.gov/data/oaf/overview.php.

5.4. Principle 4. Develop an Empirical Understanding of Use and Usability

Having an empirical understanding of the use and usability of the tool can help sustain a tool over its lifecycle and ensure that it meets user needs. This principle includes:

- Define metrics of success
- Analyze tool use trends
- Understand user experiences

5.4.1. Define Metrics of Success

Identifying success metrics at the onset of tool development can help tool developers avoid trying to fulfill too many requirements with a single tool. The scope of an individual DST development effort should be kept manageable (Newman and others, 2000). Stakeholders, technical experts, and scientists need to develop a shared understanding of the decision being supported before creating the DST, and explicit metrics of success should be identified and refined throughout the process (Barnhart and others, 2018).

Evaluating the success of a DST was an aspect of tool deployment that challenged USGS interviewees. Here is how one interviewee explained the challenge:

> Measuring the success is tricky. If we get good feedback, that's good, or if we get user feedback, that's good. It's difficult to find concrete examples of a decision that was made that was aided by a particular tool. We're always hungry for those examples, and when we find them, we treasure them. (Interviewee 9)

The challenge described by this interviewee is well documented in the wider literature on decision support and arises from three main sources. First, documenting the causal link between someone's use of a DST and improvements in their decision-making processes is challenging (Cravens, 2018). Scholars of knowledge use distinguish between conceptual information use (adding to a decision maker's general knowledge base) and instrumental information use (providing information that feeds into a specific decision) (NRC, 2012). Most DST developers associate instrumental use with success, but studies of how people make decisions indicate that a high percentage of the information that informs a given decision is conceptual rather than instrumental (Amara and others, 2004; van der Molen and others, 2018). Second, despite repeated calls for greater attention to and resources for evaluation, support for DST evaluation remains relatively rare (Moser, 2009; Cravens, 2016; Wong-Parodi and others, 2020). Finally, measuring success requires defining concrete metrics that correspond to developer and user objectives and then collecting empirical data to assess whether and how those objectives are being met (VanderMolen and others, 2019).

Metrics for DST evaluation may be broadly divided into two categories: (1) type and amount of use and (2) how individuals interact with a tool. When interviewees were asked to describe what makes a tool successful, they often said that a tool is successful if people use it. But when we asked whether the interviewees had usage expectations for the tools they had built in the past, the interviewees indicated that they often did not. In general, we found that USGS employees were not defining upfront what they wanted their tools to accomplish nor defining metrics that would let them know their objectives had been achieved. One interviewee expressed why defining success metrics is important:

> You can't just measure on one [success] metric alone. I think that's also something that should be defined in the beginning. If our metrics were set up that way * * * we could then say at the end whether or not it was successful. That should be set up the same time you set up how you're gonna pay for it. (Interviewee 8)

Evaluating a tool's performance is difficult without explicit metrics of success.

5.4.2. Analyze Tool Use Trends

One category of success metrics are measurements of tool use across users. This includes aggregated measures of numbers of users across time or space and automated counts of tool use using web analytics. Some interviewees also spoke about assessing success in terms of referrals, mentioning that some collaborators who worked with their design team thought the resulting DST was successful enough to continue making DSTs with them and to refer other groups to their design services.

Interviewees reported they primarily monitor usage using Google Analytics. Google Analytics is a web analytics service offered by Google that tracks and reports website traffic. Web analytics can be configured to track both simple counts (for example, number of total webpage views) as well as count actions that correspond to particular user behaviors that are important to a user's experience using a given application (for example, submit a form or click on a button). Highly sophisticated automated tracking of user behavior is common in the corporate sector, but such uses of web analytics remain rarer on scientific and government applications due to a combination of privacy regulations, data and software regulations, and likely concerns about public backlash (Cravens, 2014; Pearman and Cravens, 2022). Importantly, the ability for web analytics to measure particular behaviors is intimately related to the design and deployment of the application, which means that defining metrics before an application is built is important to ensuring the software will be designed in such a way that measurement of behaviors of interest is indeed possible (Cravens, 2014).

One interviewee described the nuances of what quantitative analytic metrics can and cannot provide and how analytics relate to tool architecture:

> From a quantitative standpoint, if you've got a web application, if you're getting what I guess you perceive is a good amount of traffic * * * those are numbers you can look at and understand * * *. You can just arbitrarily throw things out, but [you might not always know whether] 1,500 hits a day is really good. It's all relative, right? You might have an application that could be really important, but it's got a smaller subset of audience, a niche area. You're not going to get the general public going to it, but you're seeing consistent usage * * * I guess you hope to see it continue to increase. You'll naturally look at analytics compared to other, for us, applications [in our Mission Area]. There's a lot of nuances there when you look at those numbers. For instance, with a mapping application, the way analytics are tracked on a web map versus a normal web page... are quite a bit different. Someone could spend all day on the [web map], and it's going to show up as one event. If they're clicking around all kinds of different pages, each of those are going to be a separate hit. We're trying to refine the level of detail we collect. (Interviewee 16)

Notably, another interviewee reported that they erroneously believed USGS applications were not allowed to use Google Analytics and described this as a significant (perceived) barrier:

> We can't track people via the web * * *. We used to have Google Analytics [for our tool], but, now, all of our traffic goes through Reston or Denver I guess. [Reports] look like everybody's from Reston or Denver. Apparently, there are other mechanisms available, but they're not made available to [my team]. (Interviewee 7).

This comment illustrates the diversity of experiences with web analytics across regions and Mission Areas at USGS and, although only reflecting the experience of a single interviewee, may highlight a larger issue with employee understanding of resources available for monitoring tool use.

Example Tool 4. The Operational Total Water Level and Coastal Change Viewer

Design time.—10 months

Team lead(s).—Kara Doran, Richard Snell, Meg Palmsten, Li Erikson, and Alex Nereson

Principle represented.—Develop an empirical understanding of use and usability

Decision makers or end users.—Regional Weather service offices

Decision opportunity.—Responding to coastal hazards

Decision-support need.—Forecasts of wave-induced water levels

Tool description

The U.S. Geological Survey (USGS) National Assessment of Coastal Change Hazards team works with the National Weather Service and the National Centers for Environmental Prediction to combine wave predictions from the Nearshore Wave Prediction System with USGS-derived beach morphology to provide detailed forecasts of wave-induced water levels. The viewer includes predictions of the timing and magnitude of water levels at the shoreline and potential impacts to coastal dunes.

Quote

"On the Total Water Level Viewer, we have a button to submit a user story. Sometimes people submit a story of how they're using it or give us a suggestion for how to improve or something. I like that, too. It feels successful to me when we get feedback. It feels successful to me when it's easy to train someone how to add data and update things * * *. I have a monthly call with the weather forecasters nationwide that use the total water level forecast and just the wave model in general from [the National Oceanic and Atmosphere Administration]. Those partnerships have been really great."

— Kara Doran, team lead

Key Takeaway

Decision-support tools should be easy to use and include methods to obtain user feedback so that future tool improvements can be made.

For more information, go to https://www.usgs.gov/centers/spcmsc/science/operational-total-water-level-and-coastal-change-forecasts.

5.4.3. Understand User Experiences

Another broad category of DST evaluation metrics assesses the experience of users to understand the ways and extent to which a tool supports decision making. This category of metrics is usually assessed using a well-known evaluation technique from the usability discipline called usability testing. Many of the successful tools at USGS involved elements of usability testing, for example, observing target users using early prototypes to carry out actual work. Usability testing enables tool designers to know how well a tool works for the tool's intended users and, as necessary, make modifications in response to findings (Loucks, 1995).

In this report, we have focused on the usability testing technique because it allows a DST team to understand how a design meets the users' needs by directly involving the target users. For example, during a usability testing session, the users might be asked to think aloud while performing representative tasks with a DST. In turn, by staying as non-intrusive as possible, the DST team can gain insights into the users' experiences by listening to the users and observing their interactions with the tools. Jakob Nielsen (1994) defined five key quality components that a design team might learn about through usability testing:

- Learnability: How easy is it for users to accomplish basic tasks the first time they encounter the design?
- Efficiency: Once users have learned the design, how quickly can they perform tasks?
- Memorability: When users return to the design after a period of not using it, how easily can they reestablish proficiency?
- Errors: How many errors do users make, how severe are these errors, and how easily can they recover from the errors?
- Satisfaction: How pleasant is it to use the design?

As one tool designer explained:

"Early on, I would have a fairly strong vision about what the tool should look like, and then I would realize that the way [the users] see the tool and the way they want to use tool is not necessarily the way I have developed the tool" (Interviewee 7).

This quotation shows that one cannot assume how users use a tool, and that this information can only be obtained using empirical data collection methods such as usability testing. Many interviewees expressed how usability testing and sharing early prototypes with users revealed gaps and functionality issues that would not have been discovered otherwise. This process draws on aspects of the first principle (use an adaptive, iterative design process) because it requires space for trial and error. When asked what interviewees would have done differently in hindsight, several indicated that they would have done more usability testing earlier in the tool design process. Interviewees who had access to usability experts within USGS or were able to contract usability experts outside the Bureau reported that the added expertise in usability testing was key to their tool's success. Importantly, we note that usability testing is a formal discipline with trained professionals who caution against the dangers of "guerilla" usability testing; that is, casual and not rigorous application of their methods. However, rigorous usability testing study design does not imply large sample sizes; testing with as few as 5 to 10 users can often allow a team to identify most issues (Oakley and Daudert, 2016).

5.5. Principle 5. Plan for the Tool's Full Life Span

Last but certainly not least, Principle 5 is the need to understand and plan for a tool's full life span. This principle includes the need to

- Determine the full life span of the tool
- Invest in maintenance (for example, money and staff time)

According to the interviewees, sometimes finished tools are too complicated or not durable because of software and maintenance limitations. Despite fulfilling a need, they end up not being maintained due to a lack of resources. This can occur when a tool is designed without plans for long-term support and maintenance. Within the USGS, there are efforts to increase data stewardship, such as requirements for USGS projects to develop Data Management Plans and guidance for scientists to include support and maintenance considerations when developing DST projects in the Water Mission Area (Herman-Mercer and others, written commun., 2020). Developers of DSTs in the USGS should also work within USGS technology policy by working with the Chief Information Officer's (CIO's) office[13] in their planning.

5.5.1. Determine the Full Life Span of the Tool

The success of a DST can be constrained by resource limitations; thus, understanding what resources will be needed before embarking on tool development is essential (Dale and English, 1999). DSTs have a life cycle and require maintenance, funding, and staff time to keep them usable during their life span; thus, they can be thought of differently than a traditional research project that may have a distinct beginning and end.

DSTs are developed throughout the USGS to support a variety of decisions, some of which may change or evolve over time, while other decisions may be more stable. Some tools are developed to meet a specific cooperator's needs with the intention to turn tool maintenance over to the cooperator at a certain point while others may be maintained by USGS personnel over many years. These typologies of maintenance warrant consideration ahead of time to ensure the appropriate level of support and maintenance is provided.

An interviewee explained why sometimes they will not begin a project if there is not enough maintenance support:

[13] https://www.usgs.gov/associate-chief-information-officer

> We also have a big consideration of ongoing support, and we've been supporting this tool for eight years, nine years? So, you have to consider how much your team can do for the group, for the people who are asking for these tools, and I consider that a lot when we build things. Your tools are like children. Once they come out, you're stuck with it for the next, you know, 18 years, so you can't just toss it over the fence and think you're done. You have to provide support to whoever's using it, make updates as needed. So, I try to space that out for our team as well, "Are we going in over our heads? Are we taking on projects that are too big?" And sometimes [when] the researcher [asks] for something, I say "That's too big for our group. We can't build something like that, we can't maintain it." (Interviewee 22)

This quote describes why the tool's life span is best defined before tool development takes place. Supporting a tool, including scientifically, technically, or operationally, requires funding and ongoing resources. These resources are easier to acquire when the support requirements and request schedule are included in the planning process rather than retroactively. In addition to data management, technology changes rapidly, and software vulnerabilities occur. Planning in information technology (IT) for life cycle maintenance and support is critical to supporting a DST.

Example Tool 5. The Strategic Hazard Identification and Risk Assessment Project (SHIRA)

Development time.—3 years

Team lead(s).—Alice Pennaz and Nate Wood

Principle represented.— Plan for the tool's full life span

Decision makers or end users.—The Department of the Interior's Office of Emergency Management

Decision opportunity.—Hazard prioritization for a baseline operation plan

Decision-support need.—Data, tools, and training on how hazards could negatively affect assets across the Department of Interior

Tool description

The SHIRA project provides data, tools, and training exclusively for Department of the Interior (DOI) personnel to improve planning for realistic threats to DOI assets, resources, and people. The DOI is responsible for a diverse set of assets that include personnel; visitors to public lands; facilities; infrastructure; historic sites; and natural, cultural, and economic resources. Many natural and human-caused hazards could negatively impact any one of these assets. SHIRA tools are being developed to help DOI managers and senior leadership plan to prevent, protect against, mitigate, respond to, and recover from various hazards.

Quote

"From the very beginning of this project, we said, 'If you're going to invest all of this money and in all of these tools, you need to think about them in a long-term—who's going to be maintaining them? Who's going to be updating the data that are in them, *et cetera*?' Because they will become obsolete within a year, really, if that doesn't happen. The Office of Emergency Management heard us, and a request was made to the DOI working capital fund to maintain the tools and data over time."

— Alice Pennaz, team lead

Key Takeaway

Planning for a tool's full life span can engender the resources needed to support successful tools over time.

For more information, go to https://www.doi.gov/emergency/shira.

5.5.2. Invest in Maintenance

Some interviewees who experienced working on tools that fulfilled a need but were not maintained cited the inability to provide maintenance to the tool. The lack of maintenance can be due to a lack of funding to support IT staff and a dearth of programming expertise. This section of planning for the tool's life span focuses on the importance of acknowledging and planning for technical debt. Technical debt is a concept in software development that reflects the implied cost of reworking a tool caused by changes in technology (Tom and others, 2013). Updates may also cause security vulnerabilities. Although technical debt cannot always be avoided, it can be anticipated by staying proactive and diligent about future tool maintenance requirements. During one of the interviews, a USGS developer explained the concept of technical debt:

> Just like when your phone gets updates or your computer gets updates because of security stuff, it's the same way with the software packages that we build on. That's actually become an issue recently where an old software package is basically saying, "This is a security threat," or "It's a security problem." To replace it would mean breaking some stuff and then now all of a sudden you have to spend time to make that update, and the funding hasn't been there in years. Then you have to make a hard choice. "Well, is this thing going to come down?" Then the scientist says, "Wait, why are you taking my application down?" It's, "Well, because they don't have a permanent life span with one-time funding," is basically the answer. (Interviewee 19)

Many interviewees spoke about technical debt and changing technologies, and the need for time and staff to keep a tool running. One interviewee who lacks in-depth programming experience explained their team's way of overcoming this technological barrier:

> We have readily embraced off-the-shelf software that's more configuring applications as opposing to coding from scratch. When you're doing your own coding, it's not just building something. It's maintaining it as well, because there's nobody else that's going to come in and tell you how to fix your own product. It has been advantageous to leverage off-the-shelf software that's more configuration than programming. (Interviewee 10)

While this quotation demonstrates one way of skirting the barrier of technological debt, other interviewees spoke about contracting out programming experience or training in coding software. These solutions require support and resources, and interviewees had many suggestions for resources that would help them in the tool design process. Furthermore, it is important that DST team members work with their supervisors or respective regional or Mission Area administrative leadership and the USGS CIO to ensure their DST uses the correct IT capabilities and addresses Federal requirements. Coordinating early in your planning with those in USGS who set IT policy can avoid issues in the long run.

6. What Resources Do Interviewees Say They Need?

Throughout the interviews, interviewees discussed resources that could have made the process of DST development easier or helped their projects to be more successful. Many of these comments were drawn from the final question asked in each interview: "Are there any resources that you wish you had that would have helped during tool design and development?" The three categories of responses to this question mentioned most often were institutional support, funding, and staffing.

Institutional support includes comments about USGS leadership demonstrating a broader commitment to develop effective tools that support USGS stakeholders to make sound decisions. It also includes comments about support from supervisors, Programs, Mission Areas, and others in USGS leadership that allows project teams to meet the objectives of specific DST development efforts. For example, one interviewee described how a new Associate Director became a champion for their project: "He saw what we had * * * and he was really excited about the potential. [He] was the catalyst for pushing this into a much larger project." (Interviewee 23). As this quote demonstrates, support and advocacy from leadership is often necessary to obtain the investments needed to develop a successful DST or to scale a promising pilot into a larger-scale effort.

The second resource need discussed by interviewees was funding, including changes to funding models. One interviewee highlighted that DSTs represent "an investment," pointing out that, "if it's really worth doing and it's going to have a big impact, then it's going to have a big cost." (Interviewee 9). The topic of ongoing financial support, particularly for tool maintenance, often came up in interviews. One interviewee summarized the challenges of ongoing maintenance for tools that can "cost $20,000 a year to run":

> It's easy to build a tool. It's really hard to keep it going * * * You've got Cloud costs. You've got maintenance costs…patches…upgrades. It's not like publishing a report and then it just sits in Publications Warehouse, and you can check it out or read the PDF. A lot of people have still not wrapped their head around it. (Interviewee 15).

Interviewees also mentioned the challenge of meeting the needs of DST development within the constraints of year-to-year appropriated funding and not having access to working capital funds for tool operating costs like hosting.

Without adequate funding and institutional support, interviewees reported it can be difficult to ensure appropriate staffing within a project team. Research participants reported that they variously lacked access to programmers, usability experts, social scientists, graphic designers, and project managers to commit time to operational tasks. For example, one interviewee pointed out that USGS hiring processes are, "not well structured to handle the idea that usability is a thing." (Interviewee 3). Interviewees similarly described their need for more software expertise and explained that skills in Python, Javascript, and integrating statistical capabilities within a geographic information system (GIS) are in particularly short supply. Many participants mentioned challenges with Federal hiring in general, especially the time between identifying the need for a new position and filling that position. Beyond hiring, interviewees commented on the need to develop skills within the current USGS workforce related to coding, usability, and stakeholder engagement. While some interviewees identified a gradual and welcome evolution currently taking place in the Bureau's attitude toward these skillsets, others spoke of barriers to increasing their ubiquity, including other scientists' and leadership's awareness of their importance and performance criteria that do not necessarily value efforts to improve or measure the usability of tools.

Although not explicitly mentioned as resources needed, the way that participants framed barriers they face suggests a need for greater institutional guidance and potentially a common institutional framework for DST development across USGS. For example, confusion on USGS policy regarding use of Google Analytics to track tool traffic indicates that at least some developers are not receiving the information and tools they need to be successful and, in some cases, may be receiving inaccurate information. The PRA was explicitly identified as a barrier to understanding user needs by three interviewees. One interviewee communicated accurate information related to the PRA but seemed unaware of ways in which to collect information that could be useful to their DST that do not require approval under the PRA. This interviewee seemed to lack the support to complete the steps to receive approval through the PRA process to collect the information they sought. A broader framework outlining best practices (some of which have been outlined throughout this report) and resources available to USGS scientists and developers, including funding and staffing models, could improve overall DST development in the USGS.

7. Conclusion

U.S. Geological Survey (USGS) scientists and technology professionals have created a variety of successful decision-support tools (DSTs) that fulfill a range of user needs to enable scientifically informed decision making across USGS Mission Areas. This report distilled experiences from past DST projects to present general principles that contributed to tool success and provided best practices for USGS employees interested in building a DST. Of these best practices, these seven warrant particular consideration by USGS employees before building a tool:

- Clearly define the target users of the tool
- Decide how input from users will be acquired
- Understand the context of the decision(s) the tool will be built support

- Determine how tool success will be measured
- Plan for the life span of the tool
- Establish how the tool will be maintained and who will maintain it
- Calculate how much the tool will cost over time to maintain

Our study also compiled information about barriers to tool development. Knowledge gaps that interviewees revealed included needing information about available resources that can help with DST development, knowledge of which colleagues have experience building similar tools, and ways to connect with USGS employees who can answer their questions about DST development.

We focused on DST creation across Mission Areas and Regions to distill common experiences. However, USGS DSTs vary widely in formats and the needs that they fulfill, so the needs and resources covered in this report represent guiding principles and a starting point rather than an exhaustive list. We hope this research can provide the foundation to begin identifying aspects of DST design and development that are unique to Mission Areas or Regions.

The USGS has provided trusted science to the public for decades, and DSTs are an important way that the Bureau gets targeted scientific information into the hands of those who need it for real-world decisions. There are many successful examples of DSTs built by USGS scientists that have resulted in long-lasting relationships with users and enabled high-quality decision making, a small subset of which are highlighted in this report. DSTs help ensure that USGS science is actionable, but their effectiveness depends on the specifics of how tools are designed and developed. The principles presented in this report and the lessons learned from the experiences of employees across USGS improves the chances that every DST that the USGS chooses to invest in will be effective and used.

Acknowledgments:

This research was funded by the U.S. Geological Survey (USGS) Center for Data Integration. Thank you to Mike Duniway, Stephen Fick, Leslie Hsu, Karen Jenni, J.C. Nelson, Emily Read, and Nate Wood for providing input to the research design and to Paul Exter, Joseph Nielsen, and Jennifer Rapp for providing feedback on earlier versions of this report. The authors are grateful to all the USGS employees who participated in data collection for this project and to Michael Blanpied, Kara Doran, Kurt Kowalski, Alice Pennaz, and John Wolf for contributing the example tools that appear in the text. Thank you to our collaborators who worked with us on previous decision-support development and evaluation projects for shaping the ideas that appear in this guide, especially the members of the USGS Coastal and Marine Hazards and Resources Program's State of our Nation's Coast project team.

.

Introduction to Chapter #4

The second and third chapters of my dissertation outlined what coastal decision-makers need and what coastal scientists need to provide. My fourth chapter asks: What are the problems that coastal decision-makers face that cannot be addressed with more actionable and accessible science? The impetus for this chapter came from one of the local coastal planners in the listening sessions, who explained that the biggest barriers to making the "right" decisions are not information-based and include regulatory requirements, funding, coordination across coastal regions, and governance.

For this chapter, I reanalyzed the listening session data collected in chapter two and identified which barriers to the uptake of long-term, large-scale, and nature-based adaptation efforts were information-based and which are structural. These additional codes can be found in appendix 5. While information-based barriers, like a lack of data access and actionability, are widespread, solving them will not provide a panacea to the current crisis on our coasts. There exist equally entrenched barriers that cannot be alleviated by providing better science, like regulations that incentivize hard armoring over nature-based options. These barriers are often not the focus of efforts to support scientifically informed coastal decision-making despite that they, in many cases, are the cause of maladaptation. This chapter argues that systemic and transformational changes are necessary to meaningfully support scientifically informed coastal adaptation.

All the barriers mentioned in chapters 2 and 4 are interconnected, and managing them will require the alignment of organizations, agencies, and decision-makers across scales. While there have been several papers on the systemic changes that need to happen (e.g.., the need to restructure our permitting systems), this paper combines these recommendations and shows how they can help coastal decision-makers in the US avoid maladaptation and allow for the implementation of more desirable adaptation pathways.

Chapter #4 title: The Barriers to Long-term, Large-scale, and Nature-based Coastal Adaptation in the US

1. Introduction

Careful planning is essential to avoid the worst impacts of sea-level rise (SLR). However, coastal adaptation is a complex process where multiple, often conflicting, interests and processes must come together to reach effective and sustainable goals and outcomes. Many coastal adaptation scholars and climate change researchers have called for coastal adaptation that is long-term, large-scale, and nature-based, but these solutions are rare in practice (IPCC 2018). When adaptation efforts are short-sighted, they can lead to unintended consequences and potentially maladaptation. Efforts to prevent maladaptive coastal adaptation often focus on the need to provide more accessible and actionable science, but this alone will not alleviate the structural barriers that go beyond the science. This research investigates the factors that promote or hinder various coastal adaptation strategies in the US, such as shoreline armoring, nature-based solutions, and planned relocation.

Coastal planners, developers, and managers face many options for coastal planning that all have various tradeoffs. These options are often grouped into three categories: protect (e.g., seawalls), accommodate (e.g., raising roads), or relocation (e.g., managed retreat plans or buy-out programs) (Nicholls 2011). One of the primary "protect" approaches within coastal planning is shoreline armoring. There are two main kinds of shoreline armoring – hard armoring and soft armoring (McGuire 2013). Hard armoring is the construction of artificial structures, usually seawalls, that use concrete, boulders, or similar structures to provide a barrier between the ocean and the land. In contrast, soft armoring provides structures that often mimic the shoreline in its use of materials and are temporary by design (McGuire 2017). Hard armoring structures, such as seawalls and rock revetments, have been the most common response to coastal or shoreline erosion (Griggs 2022). Hard armoring may prevent SLR impacts on coastal communities by protecting the coast in the short term but can result in myriad negative consequences.

One of the consequences of hard armoring is ‘coastal squeeze’, a form of coastal habitat loss whereby intertidal habitat is lost due to the high-water mark being fixed by a structure and the low water mark migrating landwards in response to SLR (Pontee 2013). Protecting dynamic coastal habitats in their present position is not a viable option in many locations, and hard armoring prevents coastal features from migrating inland under long-term SLR (Doody 2013; McGuire 2017). Coastal ecosystems, such as coral reefs, kelp forests, and mangrove forests buffer the effects of phenomena such as erosion and wave impacts. The loss of such ecosystems will exacerbate the coastal hazards that already plague at-risk coastal areas (Arkema et al. 2013). A meta-analysis of the ecological consequences of shoreline hardening showed that seawalls supported 23% lower biodiversity and 45% fewer organisms than natural shorelines (Gittman et al. 2016). These intertidal habitats are not only important ecologically but can also be important economically, especially in the case of highly touristic sandy beaches (Schlacher et al. 2007; Dugan et al. 2008). For example, in Cape Town, South Africa, when private properties installed hard armoring in the form of sandbags along the bank, it resulted in a loss of beach area, reduced recreational value, and a loss of tourism and tourism-related revenue (Mangun 2016).

Hard armoring has also paradoxically contributed to greater erosion rates in some areas by reducing sources of sand supply that contribute to beach accretion down current from the hard armoring (Lester 2016). If property owners use hard armoring on their shorefront, the armoring and perpetuation of development will result in the eventual loss of beach area in many places. These impacts can negatively affect many who enjoy access to the coast, especially those whose livelihoods depend on access to marine resources and ocean-based tourism, presenting a significant environmental justice issue. Additionally, seawalls do not exist in isolation and can result in nuisance conditions for neighboring areas without seawalls, which may suffer increased flooding or erosion (Piggott-McKellar et al, 2020). Sometimes, property owners who are negatively impacted by a neighboring seawall will react by building their own seawall, perpetuating these effects and shifting the largest impacts to those locations and communities unable to armor as well (House 2020). Furthermore, seawalls provide a false sense of security, leading to more development in coastal areas (Betzold and Mohamed, 2017; Nunn et al. 2021). This may indicate that seawalls beget seawalls, leading to further coastal squeeze and erosion, thus exacerbating the issue (Schipper 2020).

In contrast to these hard armoring approaches, soft armoring approaches are nature-based methods that can include a range of options like living shorelines (Currin et al. 2009). Living shorelines capitalize on the natural ability of ecosystems to protect coastlines from coastal hazards while also providing benefits such as habitat, recreation areas, and the continuation or enhancement of ecosystem services (CCC 2018). Marsh restoration is a clear example of these efforts and can offer defense against SLR that would be lost if the marshes were drowned under rising seas. Many living shoreline projects are in the early phases of implementation, so their effectiveness and impacts will need additional monitoring (Smith et al. 2020). As such, it is difficult to comprehensively determine which nature-based efforts work best in which environments. While coastal managers may prefer soft armoring and nature-based methods to hard armoring methods because of their environmental or social benefits, there is limited information available to guide their planning efforts. Additionally, some critical infrastructure may require hard armoring or a combination of soft and hard armoring. More research is needed to understand where combining ecosystem-based and engineered approaches will be the most effective for reducing damage to human communities and marine ecosystems (Arkema et al. 2013).

Following “protect” strategies, the second category includes “accommodate” strategies. These strategies are often coupled with some form of coastal protection and include modifying existing infrastructures like raising roads or installing pumping systems. These efforts can be pursued by individuals or through broader policy, but in cases where homeowners are required to raise their homes, these expensive adaptations can price people out of coastal properties, adding to the growing issue of climate gentrification (Melix et al. 2023). Additionally, even in cases where homes and other permanent infrastructure are raised and can withstand storm surges and rising seas, there may still be issues with getting emergency vehicles into flooded areas when needed (Yin et al. 2017; Chang et al. 2010).

Efforts to accommodate or protect the coast from SLR are technically short-term solutions, as the only long-term response is to relocate communities away from the shoreline (Griggs 2024a). Relocating infrastructure located in hazardous areas away from the coast is a process known as planned relocation or managed retreat. Planned relocation is a proactive adaptation strategy based on an understanding of the key processes that structure the coastal ecosystem (CCC 2018). This adaptation method accepts the natural ranges of ecosystem variation allowing for long-term success, sustainability, and resilience (Neal et al. 2017; Holling and Meffe 1996). However, the process of planned relocation is complex (Griggs 2024b). Relocating structures and homes away from hazardous areas can be more cost-effective in the long term than other adaptation measures, but it is more challenging to implement (Abel et al. 2011; Alexander et al. 2012). Buy-out programs, in which cities purchase at-risk homes from their owners, can engender environmental justice concerns (Siders 2019). Coastal managers can be put in the difficult position of deciding which homes are worth protecting and who can afford, or continue, to live on the coast. Additionally, relocation of development alone will not ensure that beach and wetland formation or "living" shorelines will occur in its wake. These processes require time and additional management strategies to preserve coastal habitats and ecosystem services in the longer term (Alexander et al. 2012; Kochnower et al. 2015; Koslov 2016).

Proactive planning is essential to ensure that SLR adaptation actions are cost-effective, equitable, and do not adversely impact coastal resources. In the US, coastal planners and managers are challenged to make the best decisions to protect their coastal communities from rising seas while tackling issues related to equity, politics, justice, data availability and accessibility, uncertainty, and limited capacity. However, successful implementation of adaptation strategies that provide the most positive outcomes, ecologically, socially, and economically, are few and far between. If coastal armoring continues at its current rate, nearly one-third of the contiguous US coastline will be armored by 2100 (Gittman et al. 2015). Meanwhile, despite growing evidence for the effectiveness of nature-based solutions for risk reduction, uptake has remained surprisingly limited (Kelso et al. 2024).

Recently, the coastal planning community has used the term "maladaptation' to describe when an adaptation action results in conditions that are worse than those that the original strategies were trying to address (Schipper 2020). Maladaptation often occurs when adaptation efforts are focused on keeping coastal communities and their infrastructure static in the face of ecological transformation. The current use of the term maladaptation is effective because it puts adaptation on a continuum, where the outcomes range from an ideal transformation toward a climate-resilient pathway on the one side, to irreversibly higher vulnerability on the other (Juhola et al. 2016; Schipper 2020). However, Schipper writes that "poor planning is the primary cause of maladaptation" which places the onus on the decision-makers to make better plans for the future of our coasts (2020). In holding individual decision-makers solely responsible for coastal outcomes, we forego an understanding of the systems and structures that may incentivize maladaptation. This research asks, what are the information-based barriers that prevent scientifically informed decision-making, and which barriers may be structural?

2. Methods

To understand the barriers to scientifically informed coastal adaptation we conducted ten virtual listening sessions with coastal planning actors including coastal resource managers, consultants, local planners, State planners, and researchers from across US coastal regions. The US coastal regions included in this research were the Southeast (Including the Gulf and the Caribbean), Northeast (New England/Mid-Atlantic), and the West Coast. Alaska and US territories were not included in this research due to their unique coastal and institutional systems that differ greatly from those in the lower 48 states.

Potential listening session participants were identified by surveying USGS scientists who work within the USGS coastal change hazards programmatic focus. In the survey, we asked them to provide the names, emails, roles, and regions of stakeholders who fit into the category of resource manager, local planner, State planner, consultant, or non-USGS researcher. This resulted in 234 contacts. Invitations to participate in the virtual listening sessions were sent by email to 95 contacts including approximately 17-23 stakeholders of each category with the goal of having no more than 10 people from each role in the listening sessions to increase participation. Overall, 48 stakeholders (including one participant who opted for a one-on-one interview due to scheduling constraints) participated in the listening sessions (Table 3).

Each listening session was designed to include people with the same role from across regions. For example, one of the sessions included consultants from Florida, Washington State, California, and Massachusetts. This design allowed listening session participants to compare notes across regions and expedited data analysis because the differences and similarities between roles were clear in each session and did not need to be teased out after the data was collected.

In the listening sessions, participants introduced themselves with the coastal issue that "keeps them up at night," then went through a series of questions about the decisions or tasks they complete in their role, the data they use to make those decisions, and what barriers or challenges they face in the decision-making process. These listening sessions were based on a protocol for focus groups conducted by USGS scientists on water data delivery to support the Water Mission Area's development of a regional Integrated Water Availability Assessment (Restrepo-Osorio et al. 2022). For both projects, the protocol was guided by the key question following Cantor and others, 2018: Who needs what data in what format to make what decisions? Each listening session was approximately two hours long, and the recordings were professionally transcribed.

We comprehensively analyzed the verbal content of the transcripts using NVIVO (release 1.3; Lumivero, Denver, Colo.). The transcripts were coded both deductively and inductively (app. 1). The deductive codes were central to the main theme of the listening sessions and included codes such as Data Needs, Barriers and Challenges, and Tasks. The subcodes of these categories (e.g. Funding and Environmental Justice) were developed inductively, as the coding took place and themes emerged. The structural barriers were coded after the initial coding was completed (app. 5).

3. Results

In the listening sessions, research participants described wanting to enact coastal adaptation measures that were long-term, large-scale, and nature-based, but encountered barriers that in many cases, pushed them towards less sustainable, and potentially maladaptive, options. Some barriers, like data gaps, data accessibility, and insufficient guidance, described issues that were information-based, while other barriers were not related to data access or actionability (figure 12). The barriers that were not information-based include temporal scale mismatch, regulatory hurdles, economic costs, and fragmentation.

Many of the conversations about supporting coastal decision-makers are centered on providing more science and better guidance on how to integrate that science into decisions (Tribbia and Moser 2008; Hayes et al. 2018). This is an essential goal, as it would lessen the information-based barriers discussed below. However, developing an understanding of the structural barriers faced by those working towards sustainable coastal adaptation in the US is a less discussed, but arguably more critical exercise as maladaptive adaptation options are often not the result of a lack of guidance.

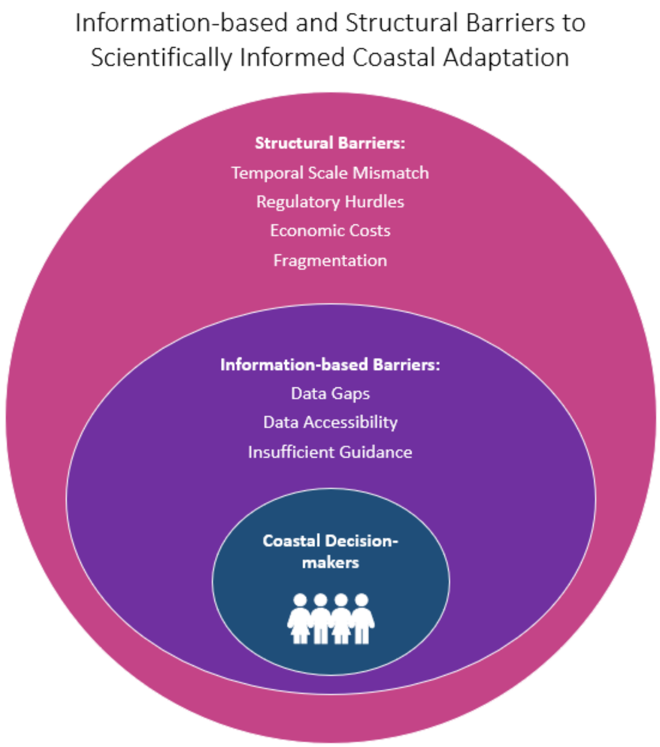


Figure 12. Information-based and structural barriers to scientifically informed coastal adaptation

3.1. Information-based Barriers

When asked about the barriers to scientifically informed decision-making on US coasts, research participants reported difficulties finding the information they need and once they found it, struggling with how to apply it to their work. These barriers were pervasive and included data accessibility, data gaps, and insufficient guidance.

3.1.1. Data Accessibility

Overall, research participants in the State planner, local planner, and resource manager categories expressed their inability to access reliable and trustworthy sources for scientific data. Being able to easily find coastal data and information is essential to making scientifically informed decisions on the coast. Research participant methods for locating scientific information, outside of contacting USGS scientists with whom they already have a working relationship, are often unfruitful. For example, participants in these roles mentioned using Google to search for data and remarked on how this pathway was insufficient and provided many results that did not suit their needs. As stated by a local planner,

"*I hate to admit it, but I go to Google just because when you enter a particular agency's site, they're all different. You don't know how to navigate. You don't know if you've even got the right agency*."

While reliable sources for coastal data do exist, like Federal science agency websites such as NOAA's Digital Coast, participants reported being confused by which agency's site to use and having difficulties navigating new sites. An example mentioned in multiple listening sessions was the multiplicity of online SLR viewers that all vary slightly in their estimations.

Often the most utilized path of scientific knowledge to the decision-maker (State planners; local planners; resource managers) was through hired consultants or researchers who are more familiar with how and where to acquire scientific data and information. While this pathway of information alleviates some of the capacity issues that prevent decision-makers from spending time seeking out scientific information, it also creates circumstances in which those less versed in finding data feel daunted by the landscape of agencies, organizations, websites, and tools all focused on providing answers to coastal change queries. This barrier can prevent decision-makers from finding the information they need on nature-based solutions and the efficacy of long-term, large-scale adaptation options.

Coastal researchers and consultants also reported struggling with data access, especially in cases of proprietary data or data that exists but has not yet been published. A researcher explained how even with expertise in locating data, they still worry about what they may have missed,

"*I would say the hardest part is knowing what's out there because there're so many different data repositories, different data owners, and publishers that I'm always finding out about new, potentially relevant data sets that I didn't know about before*."

Researchers were the most likely user type to reach out to their colleagues for more information on the location and existence of available data. However, this option is not widely available to most coastal stakeholders.

As a solution, research participants reported that they would like a “one-stop-shop” or an interactive data navigator for all their coastal data needs. Data navigators that provide more background on where and what data exists online are growing (see: The Coastal Science Navigator[14]; Gulf Tree[15]; Digital Coast’s guided search function[16]) but they remain siloed in different agency websites. The separation of these data sources is confusing for coastal practitioners and the desire for a single site that combines coastal data and information from across agencies is still needed. Efforts are currently underway to provide this central portal in the form of sealevelrise.gov.

3.1.2. Data Gaps

While locating coastal data and information comes with its challenges, in many cases, the necessary data to pursue more sustainable and just options are simply not available. This section describes the data gaps that may stymie long-term, large-scale, and nature-based adaptation. These include a dearth of information on socioeconomic impacts and long-term monitoring.

Understanding how coastal change will affect coastal populations requires socioeconomic data. However, research participants explained that there is a lack of socioeconomic data available. As a consultant explained,

[14] https://www.usgs.gov/apps/coastalsciencenavigator/
[15] http://www.gulftree.org/
[16] https://coast.noaa.gov/digitalcoast/tools/home.html

"With regard to socioeconomic data, we just don't have it. Beach use data… it's very spotty. It's probably not very accurate. The way it's collected in many cases is a visual survey by a lifeguard."

This quotation describes both a data gap and a reluctance to use socioeconomic data because of how it's collected. New technologies, including beach surveys carried out by drones, may help alleviate some of these barriers (Provost et al. 2019). Other socioeconomic data needs mentioned by participants included better information on where people live, data on current infrastructure, and information on marginalized populations who live near the coast. In some cases, the lack of this data is due to practical reasons. As explained by a researcher,

"Often when we're doing environmental monitoring, we place sensors where it's convenient or safe, won't get vandalized, won't get stolen, but that means we're frequently moving them away from where the people are. In thinking about the impacts and vulnerabilities, we want to know more where the people are, not where they're not."

This quotation shows a need to shift the way researchers think about coastal data. The shift from a purely ecological or geological focus to a human one is necessary to protect coastal populations from coastal hazards, especially those that are the most vulnerable. While the listening session moderator did not ask any questions related to environmental justice, concerns about environmental justice were mentioned in six listening sessions, across every participant type. In one listening session, a researcher explained their concerns about equity,

"How can we make this adaptation plan equitable? How do we not leave the people behind that need the most help?"

Examples of coastal communities that have been "left behind" are becoming more and more numerous (Stoltz et al. 2024 (In Review)). Most recently, the farmworker community of Pajaro, California, was displaced by coastal flooding despite local officials' knowledge that the levee would not protect the area from future storms (Rust 2023). While more information about at-risk, underserved communities will not by itself create just outcomes, it is essential for better informing current adaptation efforts.

Other barriers to collecting socioeconomic data, especially information on marginalized groups, may be more perceived than actual. Researchers talked about the difficulties of "getting a marginalized community to take an online survey" but did not mention alternate pathways to acquiring that information such as more participatory, collaborative, or qualitative methods. The resulting data gap is common in the environmental justice literature as mentioned in the discussion section of chapter 1. Studies have shown that engaging environmental justice communities in coastal planning can create important educational opportunities and develop the trust necessary for implementation (Douglas et al. 2012).

Another data gap mentioned by participants was the lack of long-term monitoring data on the economic benefits and ecological efficacy of nature-based solutions. As explained by a resource manager,

> "*Having more and more data that says [nature-based solutions are] better than a sea wall… will be very helpful in continuing to push the natural infrastructure approaches… a lot of times they are more economically feasible than a sea wall. A sea wall, if it gets destroyed, it's really expensive to rebuild. Having the financial piece of that, I think, would be helpful.*"

In the listening session with State planners, participants explained that living shorelines are going to require a lot of monitoring to prove their viability. One State planner explained that there may be a lot of gray literature on successful living shoreline projects but that the data is not being communicated more broadly in scientific publications. They went on to say that as they look to living shorelines as an answer to coastal change, they need more long-term monitoring data that can show the benefits of these solutions from reliable, trustworthy sources. While some of these studies exist, like Reguero et al.'s cost-effectiveness study of nature-based adaptation on the Gulf Coast (2018), more research is needed.

3.1.3. Insufficient Guidance

Research participants in the local planner, State planner, and resource manager categories explained that once they found the coastal data or information they were looking for, they often struggled with how to interpret and use it in their planning. Coastal planners and managers need more support in making scientifically informed decisions on the coast than they have been previously provided. One example of needing more guidance has to do with beach renourishment efforts and sediment management, a common theme throughout the listening sessions. As a State planner explained,

"*Most of the design guidance for nourishment is all sand. The lack of technical information and design guidance for mixed sediment systems, cobble dunes, and cobble nourishment is a significant challenge.*"

Decision-makers who are interested in pursuing nature-based solutions need accessible and usable design guidance. Providing more accessible guidance on how to use coastal data and information is especially important given the limited capacity of coastal decision-makers. As a resource manager explained,

"Managers do not have time to read technical data at all. A true resource manager has about enough time to read two bullet points and skim at a very high level. Getting information to the hands of managers to be able to be used in decision-making is insanely challenging because of how limited in capacity they are, and how overextended in bandwidth."

The need for more guidance is especially tangible when planners are accounting for uncertainty in the data. Overall, research participants wanted uncertainty to be communicated upfront and made clear to non-scientists. Local and State planners need to be able to account for uncertainty to make time-sensitive decisions and those in the researcher and consultant category need accessible metadata that can help them understand the limitations of the data they input their analyses.

Participants across categories also reported difficulties applying data due to differing formats or methodologies that make some data sets incompatible with each other. Difficulties combining information from different sources were mentioned throughout the listening sessions, especially in the case of attempting to combine information from different systems to better understand multi-hazards. For example, research participants reported difficulties understanding how coastal flooding and riverine flooding will interact during a hurricane.

3.2. Structural Barriers

Barriers to scientifically informed coastal adaptation go beyond the information-based barriers outlined above and are a result of the current structures of our social systems. Oftentimes, coastal scientists will focus their efforts on alleviating the information-based barriers (e.g., pushes for more science communication and outreach) and ignore the non-information-based barriers that are more frequently the cause of maladaptation. This may be because alleviating information-based barriers is more achievable than dismantling or retooling the systems that incentivize maladaptation. A local planner described the systemic barriers to their work that do not receive enough attention,

"The things that come up less frequently end up being the bigger systemic changes; the changing of regulatory requirements, the lobbying for legislation and funding, coordination on skills that extend beyond just us as a county or as a jurisdiction, and the bigger issues around governance and how we manage and plan in a way that makes logical sense given sea level rise."

The local planner expressed a fear shared by many working to protect their communities as shorelines change and coastal hazards intensify, that our current adaptation efforts will not be enough to counter the long-term negative impacts of climate change on our coasts. This quotation touches on several interconnected issues for coastal decision-makers that cannot be solved with more science or better guidance. We describe these non-information-based barriers in the following sections: temporal scale mismatch, regulatory hurdles, economic costs, and fragmentation.

3.2.1. Temporal Scale Mismatch

SLR is a long-term problem that will require long-term solutions, however, many of the proposed and enacted solutions suffer from short-termism. This mismatch of temporal scales is sometimes referred to as “scale mismatch” in the natural resource management literature, a term that refers to the mismatch between the spatial or temporal scale of management actions and the scales of the ecological problem that needs to be solved (Lee 1993; Young 2002; Cumming et al. 2006).

However, matching the scale of the problem to the scale of the solutions is difficult because of the structures of our current systems. Difficulties planning for SLR within the confines of political and regulatory timelines were brought up by research participants who shared the user type of local planner, State planner, resource manager, and consultant. Those in the researcher category did not mention any temporal scale mismatches as a barrier in their work. In this section, we explore the temporal mismatches that complicate long-term planning for SLR.

Scientific communication and outreach centered on SLR often provide estimates of SLR by 2050 or 2100. However, these dates are 26 to 76 years in the future which does not match with the timelines of our current systems of decision-making. Local and state planners may be incentivized to make decisions that may be politically popular in the short term but do not provide long-term benefits. This mismatch can prevent local and state planners from implementing long-term solutions on the coast.

Mayors, who often serve 4-year terms before needing to seek reelection, are disincentivized from proposing coastal adaptation measures that conflict with the community's current wants and needs. This is especially tangible on California coasts that have seen efforts to introduce managed retreat as an adaptation strategy. Some mayors who have recommended managed retreat plans have lost their community's support, and in at least one case, were ousted from their office (Bragg et al. 2021).

Local planners must try to balance their community's short-term preferences with pursuing efforts that mostly pay off in the long term. For example, a local planner tasked with upkeeping waterfront facilities, explained difficulties getting buy-in for a new pier system to account for rising seas,

"*Looking toward the future resiliency is important, but dealing with the realization that you've still got to implement it and have people buy into it in the short-term is a challenge.*"

They went on to explain that most of the fishermen in their district are only considering the functionality of the pier for the next five years and are not concerned with the state of the pier in twenty or thirty years when they will no longer be fishing. This quotation reveals the tension between planning for future resiliency and meeting present needs. Convincing stakeholders about the importance of issues that may occur in the future is a difficult process that requires careful community engagement. Additionally, the stakeholders who are the most actively engaged in coastal management issues and have the time to attend community meetings often tend to be older, and more invested in maintaining the community as they know it than investing in forward-looking options that will have more benefits for the next generation.

Achieving buy-in can be further complicated when state guidance, in hopes of encouraging long-term solutions, provides guidelines that go far beyond the lifespans of community members. A local planner explained how the mismatch between California State guidance affects their ability to plan for the future,

> "*We're conflicted with State guidance that's telling us to plan for 3 and a half feet by the middle of the century and up to 10 feet by the end of the century, depending on risk tolerance for what you're protecting. We're having communities and engineers design adaptation measures that meet these recommendations and then community members who don't want to see that much change that fast. They're short-term planning… They're on 30-year mortgages. On average, the folks who are engaging with us probably don't necessarily have 50-year lifespans that they're planning for.*"

Private property owners are often not planning for 50 years in the future. The mismatch between solutions that meet the scale of the problem and solutions that benefit the local community in the next four years are in conflict, making political timelines another source of scale mismatch and a barrier to long-term adaptation.

While State and local planners are concerned about their ability to get buy-in from their communities to pursue more sustainable solutions, they encounter not only barriers related to political timelines and private property ownership but also timelines related to permitting and regulation. When working to enact nature-based adaptation strategies, permits can take many years to acquire partly because of the uncertainties associated with the performance and longevity of these strategies (Leo et al. 2019; Howarth et. al 2024). This delay can push decision-makers into choosing more maladaptive options that are quicker to enact. The issue of regulations as barriers to SLR planning, particularly regarding nature-based solutions, is a common problem. Across the US, it is less costly and less time-intensive to get a permit for hard armoring than it is to acquire permits for nature-based solutions, incentivizing coastal armoring over more sustainable options (Ulibarri et al. 2017; Brandon 2016). Sometimes the permitting delays associated with nature-based solutions take so long, that the original problem they were designed to solve has changed in nature. As a local planner expressed in the listening session, "*The [natural] systems […] are changing so rapidly that the time frames are on different paths, the regulatory time frame, the design and engineering [time frame], the funding time frame. By the time those may be in place, the problem's already somewhere else.*"

Acquiring permitting for living shoreline projects involves a convoluted review process that can work against these multi-beneficial projects (Talton 2017). A consultant explained the policy and jurisdictional hurdles that go along with nature-based adaptation strategies,

"*It goes beyond economics… I can get a permit for a bulkhead in 10 minutes online, but it's going to take me 10 years to get a permit for a living shoreline project.*"

This quotation shows that consultants working to enact nature-based solutions in communities can face regulatory hurdles that can delay a project long enough to make the project unfeasible. This pushes consultants and decision-makers away from nature-based solutions and toward potentially maladaptive options that have quicker permitting timelines such as seawalls and bulkheads. The fear that coastal planners won't be able to meaningfully adapt the coast before coastal hazards become more dangerous was common in the listening sessions. As explained by a local planner,

"*It takes us 10 to 15 years to be able to build a project, fund one, design one, permit one … One of my big fears, one of the things that keeps me up at night, is [whether] we're ever going to be able to build anything before the sea levels rise so much that all that work, all that money, all that planning is just going to be for naught because we're going to be too late?*"

The finding that, in some cases, it can take over a decade to acquire a permit for nature-based adaptation is problematic, as SLR is increasing exponentially, and the odds of extreme coastal flooding double approximately every 5 years (Taherkhani et al. 2020). Over time, some locations can lose natural flood buffering capacity leaving shoreline hardening as the only viable option (Oppenheimer et al. 2019; Temmerman et al. 2013). Delaying SLR preparations will result in lost opportunities and higher economic costs. However, long timelines for permitting nature-based solutions to coastal change is not the only issue that listening session participants mentioned regarding regulations. More on how regulations can stymie nature-based efforts is outlined in the next section, Regulatory Hurdles.

3.2.2. Regulatory Hurdles

Regulatory hurdles were mentioned in six of the listening sessions as being a barrier to enacting long-term, large-scale, and nature-based solutions; these mentions were across all roles. As a local planner explained,

"The living shoreline topic is growing nationwide … It's a tough sell in some cases. You really [need] the right location to have the right kind of approach. Even when you do, there are still some regulatory hurdles. Even though you're trying to do the right thing, regulations as they are set up often don't allow you to do the right thing."

State planners also discussed regulatory barriers to enacting nature-based adaptation options. These conversations often centered on marsh restoration, which has been shown to reduce flood risks (Taylor-Burns et al. 2024). A consultant who does a lot of permitting and environmental review pointed out that restoration projects, especially those that involve the reuse of dredged sediment, are a barrier to adaptation "just by the virtue of time, and the expense". A State planner from Mississippi explained how permits impact their ability to redirect dredge material into marsh restoration or nature-based features,

"The last permit the state received for a large sort of geomorphic or marsh-type restoration project was January of 2013, and this is in a state that's losing an average of over 200 acres a year of coastal land and islands… We're losing a lot of ground, literally, and just trying to figure out how to decomplicate the process of not throwing [away] valuable material—not dragging it 40 miles offshore and letting it go."

Coastal decision-makers expressed frustration about the duality of needing more sediment for beach nourishment and marsh restoration projects, but not being able to use available dredged sediment because of permitting barriers. The above quotation also speaks to the issue of mismatched temporal scales, in that permitting for these types of projects often takes years to acquire. Zooming out to a regional level, resource managers described issues with permitting because of their inherent spatial requirements. As a resource manager explained,

"Permitting tends to focus on individual parcels. A reasonable way of managing a coastal resource is to look at the size of the resource. Is it a coastal dune or a barrier system? Manage that as a whole unit rather than on a parcel basis."

This is an example of spatial scale mismatch, in which the spatial scale of the problem does not match the spatial scale of the solution. Projects that involve marsh restoration or living shorelines call for large-scale intervention, across politically determined state lines and parcel boundaries. More barriers to large-scale adaptation are described in the section on fragmentation.

3.2.3. Economic Costs

Lack of funding is a well-documented barrier to coastal adaptation efforts, but our findings reveal that barriers related to funding mechanisms are more complex than simply needing more resources. These findings indicate that some economic barriers may be systemic. In the US, funding opportunities for protecting coastal communities are at a high, including 2.6 billion available through President Biden's Inflation Reduction Act for coastal resilience efforts (DOC 2023), but acquiring funding for coastal adaptation projects is still a difficult process. As a local planner explained,

"*You don't get funding typically for an issue that has not arisen yet, even though you think it might arise down the road because you're still fighting for the limited funding to get to the current problem."*

The issue of getting funding to solve future problems conflicts with scientific guidance that asks coastal managers to prepare for future SLR. Furthermore, some solutions, like planned relocation, require buy-out programs that are extremely expensive upfront. As a resource manager explained,

"*If we were to complete a full retreat from the coastline, we don't have the money to buy everybody out.*"

Despite that managed retreat is heralded as an adaptation option that will cost less economically in the long run than building and maintaining seawalls (Abel et al. 2011; Alexander et al. 2012), some research participants believed that they will never have enough funding to pursue this option and so they do not investigate it as a potential pathway.

The economic barriers to pursuing more sustainable adaptation options also elicit environmental justice concerns. A coastal researcher explained how acquiring the funding necessary to pursue just adaptation was a roadblock,

"The wharfs have been there for generations and the amount of money it would take to raise these to be impervious to SLR is just not a possibility and so we're seeing a turnover of a lot of our working waterfront real estate to developers and people coming for second homes who have deeper pockets than our fishermen do… We have a fund to grant money to help do the assessing and the initial phases of understanding risk, but like I said, the amount of money necessary to go to the next level of actually implementing the change is where we hit a roadblock."

While the differences in permitting timelines can incentivize hard armoring over nature-based solutions, the cost of completing the necessary monitoring to achieve permits for more sustainable solutions is also a barrier. Participants explained that there are limited resources to design and implement long-term monitoring of social and environmental triggers along adaptation pathways.

State planners, local planners, and resource managers who work on coastal issues all struggle with a lack of capacity. This most often was discussed in terms of needing more staff, especially those with expertise in engineering and GIS, and lacking the funding to hire people long-term. This means that instead of having local employees who live and work in the same area for many years, these offices are hiring outside consultants for 1–3-year periods. Participants reported that these consultants often come in with limited knowledge of that area or the existing local data/studies/tools that are currently being used. In one such case, a resource manager explained how a contractor hired to work on a project needed to use an internal National Parks Service viewer to understand coastal vulnerability but was unable to access the data as an outside contractor. In a Canadian study, issues with outsourcing engineering expertise to consultants did not result in best-fit solutions because the local government staff did not have the engineering expertise necessary to accurately communicate context-specific requirements (Sauvé et al. 2020).

Long-term and nature-based adaptation strategies can be impeded by a temporal mismatch across state institutions, regulations, and economic costs. An overlapping issue is fragmentation, which prevents holistic and large-scale adaptation.

3.3.4. Fragmentation

Large-scale adaptation is important because coastal planning should reflect the scale at which natural processes affect shorelines. However, barriers to large-scale coastal adaptation were mentioned in every listening session. Our current systems are not set up to handle large-scale adaptation and there are no formal systems of collaboration and communication between coastal stakeholders, including scientists and Federal organizations that are coast-wide. This fragmentation can prevent large-scale adaptation strategies and ensure that coastal adaptation efforts remain piecemeal, leading to mixed results for coastal inhabitants. As a researcher described,

"*There's a lot of Band-Aids being put out, and I worry that the Band-Aids can give a false sense of security, as well as possibly cause problems down the coast. I'm really interested in, what're the ways we can do this on a big-enough scale to help us address the issues of climate change and sea-level rise?"*

Piecemeal solutions to coastal change are not only ineffective but can result in maladaptation by pushing negative impacts elsewhere instead of protecting the entire coast, engendering environmental justice concerns described in Chapter 1. Research participants explained that one of the issues that leads to non-uniform adaptation is the presence of private shorelines. Addressing issues that affect the entire coast would require a refute of American Individualism. As explained by a resource manager,

"*One of the challenges is that property owners and towns tend to act individually. When towns can act in concert or different neighborhoods can act together to address a common thread or problem, then that's a great advantage."*

They went on to explain that scientific products should provide information at multiple spatial scales, creating more opportunities for collaboration across those working at State or regional levels and those working at the local or parcel scale. In some States, the challenge of private property ownership on the coast is more of a challenge than in others. As a resource manager explained,

"*I know that Massachusetts and Maine and maybe one other state are different from the rest of the country in how property is owned. That we allow, amazingly, property ownership to mean low water. That gets in the way of … trying to manage the resource… what happens here is it's managed parcel by parcel… it's a huge barrier to managing our coastal resources in a meaningful way*."

When the coast is managed parcel by parcel, it complicates efforts that need to be holistic in nature to be successful, such as allowing natural marsh migration. A local planner from Cape Cod explained that when property owners harden the shoreline on their property it impacts coastal processes. They went on to say that the strict regulatory climate of Cape Cod attempts to prevent shoreline hardening, but that it still occurs. As they work to accommodate marsh migration into adjoining lower elevated areas, they often find that those areas don't exist, they're privately owned, or they are already hardened or floodproofed, preventing marsh migration.

Continuing down this path of individualism where only the people who can afford to adapt are able to stay on our changing coastlines, will not only result in the loss of the marsh and the failure of efforts to protect coastal ecological systems, but create a myriad of environmental injustices. Already, small, under-served, and under-funded communities are abandoned by the political systems meant to ensure their health and safety on the coast.

4. Discussion

This research shows that barriers to long-term, large-scale, and nature-based coastal adaptation in the US are interconnected and that preventing maladaptation requires alignment of organizations, agencies, and decision-makers across scales. While many of these barriers are information-based, coastal decision-makers need more than data and guidance to choose the most sustainable options. Many of the barriers that incentivize maladaptation are structural and our current systems need to be altered to provide better pathways to resilience. Here we recommend several potential solutions that could lessen the challenges voiced by research participants.

More socioeconomic and long-term monitoring data is essential for supporting coastal communities that choose to pursue nature-based adaptation. Outreach and education on the benefits of more sustainable coastal solutions can provide coastal planners and managers with reliable and trustworthy sources of information to share with their stakeholders. Building public support for these options can help sway public discourse, allowing for more political leadership. Other options, like economic incentives and building a shared community identity, have been shown to increase the uptake of nature-based solutions by waterfront homeowners (Leo et al. 2019; Scyphers et al. 2020; Bragg et al. 2021).

For scale mismatch, both spatially and temporally, scientists should work to provide actionable scientific products that match the timelines and spatial scales ingrained in our current systems. Products that provide spatial data need to include the same information across scales (e.g., at a parcel scale as well as a regional scale) to allow decision-makers at different levels to be on the same page and work together. Scale mismatch can be overcome by better understanding the decision-making context of coastal actors, as detailed in the recommendations section of Chapter 2 and the "Understand the Decision Context" section of Chapter 3. For example, scientific guidance on SLR and future storm risk often provides data or estimates 50-75 years in the future, however, coastal practitioners often need to know about how coastal systems will change in the next 1-10 years, or ten-year increments as part of a 50-year plan.

To address the institutional issues with permitting and regulations, these systems should be analyzed and retooled to better meet the challenges of our time (Reiblich et al. 2019; Marshall et al. 2011; Rahman et al. 2023). There should be more opportunities to acquire funding for forward-looking efforts, monitoring programs, and regional adaptation efforts that account for environmental justice outcomes. Other methods of shortening permitting timelines for nature-based solutions include more cross-agency coordination during permit development and stronger collaborative governance (Howarth & Berkowitz 2024; Ulibarri et al. 2017). There have also been calls to repeal or amend Nationwide Permit 13, a permitting exception created by the US Army Corps of Engineers that excludes the private hard armoring of coastlines from permitting requirements under certain conditions (McGuire 2018; Army Corps of Engineers 2012).

To resolve the issues that have led to fragmentation in our coastal spaces, we need more communication and collaboration between the people, organizations, and Federal agencies who are working on these topics. Increasing collaboration and communication will allow coastal practitioners with limited capacity to take advantage of information gained from successful adaptation efforts in other communities. Efforts to create more spaces for information exchange are underway, like the Coastal Inundation Community of Practice[17], but have not yet proven to eliminate barriers to collaboration and communication across US coasts.

Coastal practitioners lack capacity. This issue requires more sustained economic support for local and State coastal planning offices so that they can hire full-time, permanent staff. It also requires more hands-on guidance and cooperative learning for science agencies hoping to support decisions on the coast. Federal science agencies are uniquely positioned to provide trustworthy, reliable coastal data and information, and should be doing so on the most accessible level possible and in multiple languages.

Transformational change on the coast has been recommended by the Fifth National Climate Assessment and others (Jurjonas and Seekamp 2020; Portman 2012; Nobel et al., 2014; Mimura et al., 2014; Mycoo 2014; Middelbeek et al. 2014; Dedekorkut 2010) but much of the required progress is hindered by the current structure of our systems (May et al. 2023).

5. Conclusion

Nature-based shorelines and planned relocation efforts are seen as favorable by environmentalists, and marine resource users who have studied the negative impacts of hard armoring. However, this interest in and intent to invest in nature-based shorelines and other long-term solutions is hindered by multiple, sometimes structural barriers including data accessibility, data gaps, insufficient guidance, temporal scale mismatch, regulatory hurdles,

[17] https://adaptationprofessionals.org/coastal-inundation-community-of-practice/

economic costs, and fragmentation. These findings challenge the assertion that "poor planning is the primary cause of maladaptation" (Schipper 2020) and reveal how less visible factors, like permitting timelines, can favor maladaptive options over others, despite what planners and managers may think is the best solution for their community and context. In other words, unless we can name and dismantle the systemic factors that encourage short-term adaptation strategies over more sustainable and long-term adaptation strategies, we will continue to see an increase in maladaptation despite growing enthusiasm and support for more long-term, large-scale, and nature-based methods of adaptation.

Conclusion to the Dissertation

My dissertation explores decision-making and environmental justice on our changing coasts through four interrelated chapters. In each chapter I recommend a version of the following reflection: As our coastal ecosystems undergo irreversible ecological transformation, so should our social systems (Table 10). Maintaining the status quo, and continuing our current path, will lead to myriad negative consequences, some of which will be worse than the original problem. In other words, adapting our coasts to climate change is a wicked problem that will only be solved through strategic coordination and systemic transformation.

Table 10. Recommendations from the Dissertation

Chapter Title	Summary	Recommendations
Chapter #1: Environmental Justice of Coastal Hazards: A Systematic Literature Review	The first chapter of my dissertation is a systematic review of scientific literature that focuses on environmental justice in coastal systems.	For coastal hazard researchers we recommend, 1. that future environmental justice research on the coast more comprehensively engages with historical systems of oppression, 2. that studies should acknowledge the limitations of using census data, and 3. that proposed solutions to environmental justice issues on the coast should consider avenues for decreasing specific vulnerabilities to hazards as well as approaches to addressing the structural conditions that increase or maintain these vulnerabilities. Our four policy recommendations for improving the state of coastal environmental justice are to, 1. take account of social groups that are likely to be excluded without intentional action when planning for coastal hazards, 2. improve the collection and accessibility of data and information related to underserved communities,

		3. create spaces for marginalized social groups to participate in decision making procedures, and 4. address the systemic and structural drivers that render certain groups marginal and more vulnerable to coastal hazards.
Chapter #2: User Engagement to Improve Coastal Data Access and Delivery	My second chapter explores the needs and challenges faced by coastal decision-makers who are concerned about environmental justice and are working towards more resilient coastlines.	For Federal Science Agencies working to support coastal decision-makers we recommend that they, 1. consider the knowledge and expertise of coastal practitioners, 2. engage in a more effective outreach to ensure information reaches its intended users, and 3. provide spaces for better collaboration and communication among coastal practitioners and agencies across the United States.
Chapter #3: So, You Want to Build a Decision-Support Tool? Assessing Successes, Barriers, and Lessons Learned for Tool Design and Development	My third chapter looks at the challenge of supporting scientifically informed decision-making in the face of climate change from the opposite viewpoint and asks how USGS scientists understand their role in decision-support and how they work to create decision-support tools.	We present this information about best practices and lessons learned from successful tools as five main principles that contribute to effective DST development. These principles are: 1. use an adaptive, iterative design process, 2. collaborate across disciplines and organizations, 3. engage with the target users of the tool, 4. develop an empirical understanding of use and usability, and 5. plan for the tool's full life span.
Chapter #4: The Barriers to Long-term, Large-scale, and Nature-based Coastal Adaptation in the US	My fourth chapter explores the barriers that push decision-makers away from adaptation options that are long-term, large-scale, and nature-based.	To decrease the barriers to long-term, large-scale, and nature-based coastal adaptation we recommend: 1. increasing the availability of socioeconomic and long-term monitoring data,

		2. providing more outreach and education on the benefits of more sustainable coastal solutions, 3. working to ensure scientific products match the timelines and spatial scales ingrained in our current systems, 4. retooling permitting and regulatory systems so that they better meet the challenges of our time, 5. creating opportunities for more communication and collaboration between the people, organizations, and Federal agencies who are working on these topics, and 6. providing more sustained economic support for local and State coastal planning offices so that they can hire full-time, permanent staff.

Sea-level rise may be a long-term directional trend, but that doesn't mean we have time to waste. Coastal areas that may benefit from the forward-looking and holistic forms of adaptation described in this dissertation will not always have these options available to them. As we look towards 2100 and beyond, we look towards a coast with seawalls instead of beaches, where coastal adaptation becomes a code word for redlining. That's not the future that I'm working towards.

The work presented here focuses on flipping this script and imagining just futures where people are not priced out of the benefits of coastal resources and where "resilience" means transformation. While many of the problems mentioned in this dissertation seem daunting, the goal of providing coastal decision-makers with the information they need is in reach. These chapters have already inspired my colleagues in academia and Federal science to create Tribal Engagement working groups, push for Federal agency coordination on sea-level rise, and think critically about what role they can play in the climate crisis and the pursuit of environmental justice.

Appendix 1. Coastal Data Delivery Listening Session Protocol

Block 0: Logistics

"I want to thank you all for taking the time to be here today. My name is X and I will be facilitating the listening session today and with me is X who will be taking notes and generally helping out. If you have a logistic or Microsoft Teams related question, please type it into the chat box and X will help you out. Here is our agenda for the listening session today. First, I want to welcome all of you. The goal of these listening sessions is to get a better understanding of your needs as U.S. Geological Survey (USGS) coastal hazards stakeholders."

- Housekeeping: Explain basics about Teams, use of data, and obtain consent to record
- Introductions
- 5-minute presentation about the State of our Nation's Coast project
- Question segment: Tasks
- 10-minute break
- Question segment: Data needs
- Question segment: Format

Block 1: Introductions

"Now we are going to go around the room and introduce ourselves. You will notice that while everyone here has a similar position, you are all from different regions, with different coastal concerns, and unique challenges. Throughout these listening sessions, we are interested in these regional differences as well as the similarities between your goals, tasks, and the obstacles you face in making scientifically supported decisions."

1. Round robin introductions. Each person will introduce themselves with their name, title, organization, location, and the coastal issue that keeps you up at night.

Block 2: Presentation

"Thanks everyone. Now I'm going to give a short presentation on the goals of this listening session to give us context for our discussion about your data needs."

- Background on the State of our Nation's Coast project, the geonarritives, and the portal
- Why USGS wants to learn more about how you use data and web tools
- The goal of these listening sessions is to be able to answer this question,

  "Who needs to complete what tasks with what data or information in what format"

  - Answering this question will help us develop use cases that we can feed to our technical team of software developers to give them some objectives and functional requirements to meet. It also enables USGS to learn more about how to support your needs as coastal stakeholders.
  - Does anyone have any questions before we jump in to our first segment of this discussion?

Block 3: Tasks

"Now we are going to go around the room and each explain a recent goal and/or task that you want to accomplish in your position and what decisions are associated with achieving that task."

1. Does anyone have a task that we haven't talked about yet?

2. Help me understand why this task is important - what is the [political, environmental, legal] context? How does this task support your organization's overall mission?
3. How often are you completing this task? [daily, monthly, quarterly, seasonally, annually] – TIME/SCOPE
4. Who else is on your team?
5. What challenges did you face in completing this task?
6. What are the issues your organization is worried about? Are there issues that you think are important that are currently not part of your work function?

Block 3.5: 10-Minute Break

"Now we are going to take a 10-minute break. While we are on break, I would like each of you to think about the types of data or information that you use to complete your tasks and inform the decisions you make in your position. When we come back, we will start with another round robin and I will ask that each of you explain a recent experience you had finding information and/or accessing data to complete your tasks."

Block 4: Data or Information Needs

"Let's start with another round robin. We are going to go around the room and each talk about a recent experience you had accessing information or data to achieve one of your goals."

1. What kinds of information are you accessing topic-wise? What ocean or coastal hazards do you need data or information on?
2. For those of you who use spatial or map-based data - what spatial scale is the data that you're using? For example, parcel/meters/etc?
3. What temporal scale is the data that you are using? [For example, historical (how far back)? Daily? Forecasts of real time estimates?]
4. Where are the data from? How do you locate it? Do any of you use data portals? Do you go to different sources to locate different kinds of data?
5. How do you find information? For example, do you find information yourself or do you get it from others on your team?

Block 5: Format

"Now we're going to move on to talk about the format of the information that you're using and what works best with your workflow."

1. What format is the data in? [For example, raw data, modeled, estimated, time series, interpreted data like infographics, plots, charts, tables]
2. What kind of hardware/software do you use? For example, computer/phone/field/office?
3. Do any of you use web-based tools like decision support tools or dashboards? Explain an experience you had recently using a web tool to access coastal data and what made it effective or not.
4. What level of uncertainty are you comfortable with in estimated or modeled data?

    a. Do you consider the uncertainty in a data product before incorporating it into your workflow?

b. How do you determine what level of uncertainty is acceptable when using data?

c. How do you prefer the uncertainty or reliability of the data be communicated?

d. How do you communicate uncertainty to others when sharing the results of your tasks?

5. Are you able to get data in the format you need it in currently?
6. Thinking back to the recent experience you all described earlier accessing data, what challenges/issues did you encounter?
7. For those of you using USGS data, do you think USGS does a good job of taking your needs into account in our science? Is there anything you wish USGS did differently?

Block 6: Wrap Up

"Thank you all for spending your time today helping USGS support your needs as coastal stakeholders. Does anyone have anything else they would like to add before we sign off?"

Appendix 2. Codebook for Chapter #2

Code name	Code definition	Number of mentions by listening session participants
Barriers and challenges	Barriers or challenges faced by listening session participants in their roles	399
Access	Data access	50
Capacity/funding	Capacity and/or funding needs	37
Education/outreach	A need for more education and outreach	11
Format	Data/information is not available in the participant's preferred format	16
How to use data	Difficulties understanding how to use data	46
Multihazards	Difficulties evaluating how multiple processes affect hazards at a single location	7
Uncertainty	Difficulties understanding/communicating uncertainty	32
Data needs	Data needs of listening session participants	102
Dredging/sediment	Data associated with sediment management	10
Historical	Historical data gaps	10
Imagery	Imagery/lidar data	4
Interplay	Data concerning the interplay among multiple water bodies or issues concerning groundwater	7
Monitoring	Long-term monitoring data	6
Natural shoreline	Information that can aid in natural shoreline projects and research	3
Other	Other data gaps	24
Real-time	Real-time data	3
Scale	Data are available but not at the preferred spatial scale	6
Socioeconomic	Socioeconomic data/information	5
Value	Ecosystem services	12
Format of data	Mentions of preferred types of data formats	56
Introductions	Participant introductions including their name, location, role, and the coastal issue that keeps them up at night	48
Data for decision making	In response to what coastal issue keeps them up at night: having accurate and accessible data for decision making	7
Funding	In response to what coastal issue keeps them up at night: funding needs	2
Habitat	In response to what coastal issue keeps them up at night: information about coastal habitats	3
Hurricane/tsunami	In response to what coastal issue keeps them up at night: hurricanes or tsunamis	7
Environmental justice	In response to what coastal issue keeps them up at night: environmental justice and advocacy	2
Sediment	In response to what coastal issue keeps them up at night: sediment data needs	1
SLR	In response to what coastal issue keeps them up at night: sea-level rise and associated effects	26
Location of data	Mentions of where data were located	127
Spatial scale	The spatial scale requirements of participants	41
Tasks	Example work tasks provided by participants	201
Temporal scale	The temporal scale requirements of participants	40
Types of data used	The types of data used by participants	122
USGS	Comments about USGS	171
USGS data used	USGS data that participants use	48
USGS needs	Participant suggestions for USGS	44

Web tools	Comments on web tools	39

Appendix 3. Interview Protocol for Chapter #3

Introduction: The Community for Data Integration project that we are working on is called, "So you want to build a decision support tool? Successes, barriers, and lessons learned for tool design and development."

We are interviewing U.S. Geological Survey (USGS) employees to understand how the USGS creates tools that shape how users' problem solve and make decisions. We are working to understand what researchers should consider before diving into tool design and development. We would like to interview you about your experience in designing, initiating, or implementing decision support projects. Any question that you do not feel comfortable answering you do not need to answer. Please feel free to end the interview at any time by letting me know or just closing your browser. This interview will not take more than one hour to complete and will be recorded with your consent. Do you consent to recording this interview? If you do not consent to a recording, we can still continue with the interview, and I will take notes. Your contact information will not be shared beyond the research team and will only be used to initiate follow-up communication with you if needed.

Do you consent to participate in this interview?

Have interviewee introduce themselves.

Block 1. Their understanding of DSTs

- How do you define Decision Support Tools? Why?
- What role do DSTs play in your larger scientific research agenda?
- How many DSTs have you been involved in creating?

Block 2. DST Project Information—Ask generally OR tool specific if only have designed one tool. Ask for examples.

- What type of decision(s) was the tool(s) built to support and why?
- How was this decision identified?
- How does the tool support the decision?

Block 3. Stakeholder/User Engagement

- Who was the intended audience for the tool(s)?
- How was this audience chosen?
- How did you engage with members of this audience? When?
  - Why did you choose these methods of engaging with the potential audience?
  - Have these relationships been maintained?

Block 4. Designing and Building

- What was your role in creating the tool(s)? What did the rest of the team look like?
- Who was your software developer and what role did they play in your team?
- How did you find the developer? When did they join your team?
- How did you/your team choose the software/algorithms/coding frameworks? What criteria were included/how conscious was this choice? If this person wasn't you, who was responsible for this decision?

- Was anyone from outside USGS involved? Why?

Block 5. Measuring Success

- How do you define success for decision support?
- Was/is the tool successful? How do you know?
- What were your expectations for tool usage? Were they met?
- Is it maintained? How? By Whom?

Block 6. Barriers—Ask about barriers in general, across multiple tools

- What barriers did you and your team face in building the tool?
- How were these barriers overcome (or not)?
- How would you have done this process differently in hindsight?
- Were there any resources you wish you had that would help the process?

Block 7. Anything else?

Thank you for your time today. Is there anything else you would like to add or anyone else you think it would be useful to reach out to?

Appendix 4. Codebook for Chapter #3

Code name	Code definition	Number of mentions by interviewees
Analytics	Information related to Google analytics or other methods of tool use evaluation	20
Barriers	Barriers to creating a DST	84
Decisions Supported	Discrete decisions supported by DSTs	32
Hindsight	Interviewee responses to the question: Are there things you would have done differently in hindsight?	65
Maintained	Interviewee responses to the question of whether the DST is/was maintained	49
Process	Information related to the overall process of building a DST	26
Iterative	Information from interviewees who describe using an iterative process	10
Quotations	Quotations from interviewees across all codes to be added to the report	46
Resources Needed	Interviewee responses to the question: Are there any other resources that you wish you had that would've helped in the process of building this tool?	65
Software	Interviewee responses that spoke specifically to different types of software used in DST design and development	36
Success Definition	Interviewee definitions of DST success	26
Successful	DSTs that interviewees identified as successful	49
Team	Information related to the DST design and development team including project roles and when different roles were added to the team	64
User Engagement	Quotes related to user engagement that took place during, before, or after DST development	86
Users	Information about the intended end users of a described DST	38

Appendix 5. Codebook for Chapter #4

Code name	Code definition	Number of mentions by listening session participants
Non-information-based barriers	Barriers or challenges to long-term, large-scale, or nature-based adaptation that go beyond the science	29
Economic	Economic barriers to making scientifically informed decisions	10
Fragmentation	Barriers to large-scale adaptation	13
Regulations	Regulatory barriers to large-scale, long-term, and nature-based adaptation	11
Timeline	Temporal barriers to large-scale, long-term, and nature-based adaptation	11

Bibliography

Adegun OB (2023a) Flood-related challenges and impacts within coastal informal settlements: a case from LAGOS, NIGERIA. International Journal of Urban Sustainable Development 15:1–13

Adegun OB (2023b) Climatic disasters within a flood-prone coastal slum in Lagos: coping capacities and adaptation prospects. International Journal of Disaster Resilience in the Built Environment 14:212–228

Adelman, K., and Adelman, G., 2002, Welcome to the California Coastal Records Project, an aerial photographic survey of the California Coastline, accessed June 12, 2023, at https: //www.cali forniacoas tline.org/ .

Adelman, L., 1992, Evaluating decision support and expert systems: New York, Wiley, 232 p.

Ahmed S, Eklund E (2021) Climate Change Impacts in Coastal Bangladesh: Migration, Gender and Environmental Injustice. Asian Affairs 52:155–174

Ahmed S, Kiester E (2021) Do gender differences lead to unequal access to climate adaptation strategies in an agrarian context? Perceptions from coastal Bangladesh. Local Environment 26:650–665

Ajibade I (2019) Planned retreat in Global South megacities: disentangling policy, practice, and environmental justice. Climatic Change 157:299–317

Ajibade I, Armah FA, Kuuire VZ, et al (2015) Assessing the bio-psychosocial correlates of flood impacts in coastal areas of Lagos, Nigeria. Journal of Environmental Planning and Management 58:445–463

Ajibade I, McBean G, Bezner-Kerr R (2013) Urban flooding in Lagos, Nigeria: Patterns of vulnerability and resilience among women. Global Environmental Change-Human and Policy Dimensions 23:1714–1725

Allen T, Behr J, Bukvic A, et al (2021) Anticipating and Adapting to the Future Impacts of Climate Change on the Health, Security and Welfare of Low Elevation Coastal Zone (LECZ) Communities in Southeastern USA. Journal of Marine Science and Engineering 9:1196. https://doi.org/10.3390/jmse9111196

Amara, N., Ouimet, M., and Landry, R.É., 2004, New Evidence on Instrumental, Conceptual, and Symbolic Utilization of University Research in Government Agencies: Science Communication, v. 26, no. 1, p. 75–106, accessed January 5, 2021, at https://doi.org/ 10.1177/ 1075547004267491.

Apelberg BJ, Buckley TJ, White RH (2005) Socioeconomic and racial disparities in cancer risk from air toxics in Maryland. Environ Health Perspect 113:693–699. https://doi.org/10.1289/ehp.7609

Arnott, J.C., Mach, K.J., and Wong-Parodi, G., 2020, Editorial overview—The science of actionable knowledge: Current Opinion in Environmental Sustainability, v. 42, p. A1–A5, accessed January 5, 2021, at https://doi.org/ 10.1016/ j.cosust.2020.03.007.

Aune KT, Gesch D, Smith GS (2020) A spatial analysis of climate gentrification in Orleans Parish, Louisiana post-Hurricane Katrina. Environmental Research 185

Babanawo D, Mattah PAD, Agblorti SKM, Aheto DW (2023) Perspectives on factors that influence local communities? vulnerability to coastal floods in Ketu South Municipality of Ghana. International Journal of Disaster Risk Reduction 90

Bamzai-Dodson, A., Cravens, A.E., Wade, A., and McPherson, R.A., 2021, Engaging with stakeholders to produce actionable science—A framework and guidance: Weather, Climate, and Society, accessed May 4, 2023, at https://doi.org/ 10.1175/ WCAS- D-21- 0046.1.

Barbier EB (2015) Climate change impacts on rural poverty in low-elevation coastal zones. Estuarine Coastal and Shelf Science 165:A1–A13

Barnett J, Breakwell GM (2001) Risk Perception and Experience: Hazard Personality Profiles and Individual Differences. Risk Analysis 21:171–178. https://doi.org/10.1111/0272-4332.211099

Barnhart, B.L., Golden, H.E., Kasprzyk, J.R., Pauer, J.J., Jones, C.E., Sawicz, K.A., Hoghooghi, N., Simon, M., McKane, R.B., Mayer, P.M., Piscopo, A.N., Ficklin, D.L., Halama, J.J., Pettus, P.B., and Rashleigh, B., 2018, Embedding co-production and addressing uncertainty in watershed modeling decision-support tools—Successes and challenges: Environmental Modelling & Software, v. 109, p. 368–379, accessed January 6, 2021, at https://doi.org/ 10.1016/ j .envsoft.2 018.08.025.

Bautista E, Hanhardt E, Osorio JC, Dwyer N (2015) New York City Environmental Justice Alliance Waterfront Justice Project. Local Environment 20:664–682

Bernard, H.R., 2018, Research methods in anthropology—Qualitative and quantitative approaches (6th ed.): Lanham, Md., Rowman & Littlefield, 728 p.

Bertana A (2020) The role of power in community participation: Relocation as climate change adaptation in Fiji. Environment and Planning C-Politics and Space 38:902–919

Betzold C, Mohamed I (2017) Seawalls as a response to coastal erosion and flooding: a case study from Grande Comore, Comoros (West Indian Ocean). Reg Environ Change 17:1077–1087. https://doi.org/10.1007/s10113-016-1044-x

Black R, Bennett SRG, Thomas SM, Beddington JR (2011) Migration as adaptation. Nature 478:447–449. https://doi.org/10.1038/478477a

Blanks J, Abuabara A, Roberts A, Semien J (2021) Preservation at the Intersections: Patterns of Disproportionate Multihazard Risk and Vulnerability in Louisiana's Historic African American Cemeteries. Environmental Justice 14:1–13

Boehm, B., 2002, Get ready for agile methods, with care: Computer, v. 35, no. 1, p. 64–69, accessed January 5, 2021, at https://doi.org/ 10.1109/ 2.976920.

Bordner AS, Ferguson CE, Ortolano L (2020) Colonial dynamics limit climate adaptation in Oceania: Perspectives from the Marshall Islands. Global Environmental Change 61:102054. https://doi.org/10.1016/j.gloenvcha.2020.102054

Brackel L (2021) Continuous Negotiation in Climate Adaptation: The Challenge of Co-Evolution for the Capability Approach to Justice. Sustainability 13

Bragg WK, Gonzalez ST, Rabearisoa A, Stoltz AD (2021) Communicating Managed Retreat in California. Water 13:781. https://doi.org/10.3390/w13060781

Brandon TO (2016) Nationwide Permit 13, Shoreline Armoring, and the Important Role of the U.S. Army Corps of Engineers in Coastal Climate Change Adaptation. Envtl L 46:537–584

Brodie M, Weltzien E, Altman D, et al (2006) Experiences of Hurricane Katrina evacuees in Houston shelters: Implications for future planning. American Journal of Public Health 96:1402–1408

Brown S, Jenkins K, Goodwin P, et al (2021) Global costs of protecting against sea-level rise at 1.5 to 4.0 °C. Climatic Change 167

Buchanan MK, Kulp S, Cushing L, et al (2020) Sea level rise and coastal flooding threaten affordable housing. Environmental Research Letters 15

Bullard RD (1993) Race and Environmental Justice in the United States Symposium: Earth Rights and Responsibilities: Human Rights and Environmental Protection. Yale J Int'l L 18:319–336

Bullard RD, Wright B Race, Place, and Environmental Justice After Hurricane Katrina: Struggles to Reclaim, Rebuild, and Revitalize New Orleans and the Gulf Coast

Burger J, Gochfeld M (2017) Perceptions of severe storms, climate change, ecological structures and resiliency three years post-hurricane Sandy in New Jersey. Urban Ecosystems 20:1261–1275

Burger J, Gochfeld M, Pittfield T, Jeitner C (2017) Responses of a vulnerable Hispanic population in New Jersey to Hurricane Sandy: Access to care, medical needs, concerns, and ecological ratings. Journal of Toxicology and Environmental Health-Part a-Current Issues 80:315–325

Burghardt M (2013) Common frailty, constructed oppression: tensions and debates on the subject of vulnerability. Disability & Society 28:556–568. https://doi.org/10.1080/09687599.2012.711244

Burnett, C.M., 2020, Incorporating the participatory process in the design of geospatial support tools—Lessons learned from SeaSketch: Environmental Modelling & Software, v. 127, p. 104678, accessed January 7, 2021, at

California Coastal Management Program, 2018, State of California sea-level rise guidance, accessed June 12, 2023, at ht tp://www.o pc.ca.gov/ webmaster/ ftp/ pdf/ agenda_ items/ 20180314/ Item3_ Exhibit- A_ OPC_ SLR_ Guidance- rd3.pdf.

Campbell J, Barnett J (2010) Climate Change and Small Island States: Power, Knowledge and the South Pacific. Routledge, London

Cantor, A., Kiparsky, M., Kennedy, R., Hubbard, S., Bales, R., Pecharroman, L. C., Guivetchi, K., McCready, C., and Darling, G, 2018, Data for water decision making—Informing the implementation of California's Open and Transparent Water

Data Act through research and engagement: University of California Berkeley, Berkeley Law, accessed December 15, 2020, at https ://eschola rship.org/ uc/ item/ 9x62x0g2.

Cape Cod Commission, 2019, Cape Cod coastal planner, accessed June 12, 2023, at http s://www.ca pecodcommi ssion.org/ our- work/ cape- cod- coastal- planner/ .

Carmona, G., Varela-Ortega, C., and Bromley, J., 2013, Supporting decision making under uncertainty—Development of a participatory integrated model for water management in the middle Guadiana river basin: Environmental Modelling & Software, v. 50, p. 144–157, accessed January 5, 2021, at https://doi.org/ 10.1016/ j .envsoft.2 013.09.007.

Cash, D.W., Adger, W.N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., and Young, O., 2006, Scale and Cross-Scale Dynamics—Governance and Information in a Multilevel World: Ecology and Society, v. 11, no. 2, at https://doi.org/ 10.5751/ ES- 01759- 110208.

Cash, D.W., and Belloy, P., 2020, Salience, credibility and legitimacy in a rapidly shifting world of knowledge and action: Sustainability, v. 12, no. 18, article 7376, 15 p., accessed February 5, 2021, at https://doi.org/ 10.3390/su12187376.

Chacowry A, McEwen LJ, Lynch K (2018) Recovery and resilience of communities in flood risk zones in a small island developing state: A case study from a suburban settlement of Port Louis, Mauritius. International Journal of Disaster Risk Reduction 28:826–838

Chakraborty J, Collins TW, Montgomery MC, Grineski SE (2014) Social and Spatial Inequities in Exposure to Flood Risk in Miami, Florida. Natural Hazards Review 15

Chakraborty L, Rus H, Henstra D, et al (2022) Exploring spatial heterogeneity and environmental injustices in exposure to flood hazards using geographically weighted regression. Environmental Research 210

Chakraborty L, Thistlethwaite J, Scott D, et al (2023) Assessing social vulnerability and identifying spatial hotspots of flood risk to inform socially just flood management policy. Risk Analysis 43:1058–1078

Chandra A, McNamara KE, Dargusch P, et al (2017) Gendered vulnerabilities of smallholder farmers to climate change in conflict-prone areas: A case study from Mindanao, Philippines. Journal of Rural Studies 50:45–59. https://doi.org/10.1016/j.jrurstud.2016.12.011

Chang H, Lafrenz M, Jung I-W, et al (2010) Potential Impacts of Climate Change on Flood-Induced Travel Disruptions: A Case Study of Portland, Oregon, USA. Annals of the Association of American Geographers 100:938–952. https://doi.org/10.1080/00045608.2010.497110

Chang, W., Cheng, J., Allaire, J.J., Xie, Y., and McPherson, J., 2016, Web application framework for R.

Cherry KE, Sampson L, Nezat PF, et al (2015) Long-term psychological outcomes in older adults after disaster: relationships to religiosity and social support. Aging & Mental Health 19:430–443

Choudhary BK, Tripathi AK, Rai J (2019) Can `poor' cities breathe: Responses to climate change in low-income countries. Urban Climate 27:403–411

Coastal and Marine Hazards and Resources Program [CMHRP], 2020, Coastal Change Hazards, U.S. Department of the Interior, 2022, accessed June 1, 2021, at h ttps://www.usgs.gov/ programs/ cmhrp/ science/ coastal- change- hazards.

Cockburn, A., and Highsmith, J., 2001, Agile software development, the people factor: Computer, v. 34, no. 11, p. 131–133, accessed January 5, 2021, at https://doi.org/ 10.1109/ 2.963450.

Coleman N, Esmalian A, Lee C-C, et al (2023) Energy inequality in climate hazards: Empirical evidence of social and spatial disparities in managed and hazard-induced power outages. Sustainable Cities and Society 92

Collins TW, Grineski SE, Chakraborty J (2018) Environmental injustice and flood risk: a conceptual model and case comparison of metropolitan Miami and Houston, USA. Regional Environmental Change 18:311–323

Colten CE (2007) Environmental justice in a landscape of tragedy. Technology in Society 29:173–179. https://doi.org/10.1016/j.techsoc.2007.01.006

Conboy, K., Fitzgerald, B., and Golden, W., 2005, Agility in information systems development—A three-tiered framework, in Business Agility and Information Technology Diffusion, IFIP TC8 WG 8.6 International Working Conference

[Atlanta, Ga.], May 8–11, 2005, p. 35–49, accessed January 20, 2021, at https://doi.org/ 10.1007/ 0- 387- 25590- 7_ 3.

Corburn, J., 2003, Bringing local knowledge into environmental decision making—Improving urban planning for communities at risk: Journal of Planning Education and Research, v. 22, no. 4, p. 420–433, accessed February 5, 2021, at https://doi.org/ 10.1177/ 0739456X03022004008.

Covi MP, Brewer JF, Kain DJ (2021) Sea level rise hazardscapes of North Carolina: Perceptions of risk and prospects for policy. Ocean & Coastal Management 212

Cravens, A.E., 2014, Evaluating software in environmental conflict resolution—The role of MarineMap in coastal planning and decision making in California: Stanford, Ca., Stanford University Ph.D. dissertation, 214 p. [Also available at https:// stacks.sta nford.edu/ file/ druid:pz784gq9221/ Cravens_ FinalDissertation_ Aug2014-augmented.pdf.]

Cravens, A.E., 2016, Negotiation and Decision Making with Collaborative Software—How MarineMap ‘Changed the Game’ in California’s Marine Life Protected Act Initiative: Environmental Management, v. 57, no. 2, p. 474–497, accessed January 5, 2021, at https://doi.org/ 10.1007/ s00267- 015- 0615- 9.

Cravens, A.E., 2018, How and why Upper Colorado River Basin land, water, and fire managers choose to use drought tools (or not): U.S. Geological Survey Open-File Report 2018–1173, 70 p., accessed February 1, 2021, at https://doi.org/ 10.3133/ ofr20181173.

Cravens, A.E., and Ardoin, N.M., 2016, Negotiating credibility and legitimacy in the shadow of an authoritative data source: Ecology and Society, v. 21, no. 4, p. art30, accessed January 5, 2021, at https://doi.org/ 10.5751/ ES- 08849- 210430.

Cusumano, M.A., and Yoffie, D.B., 1999, Software development on Internet time: Computer, v. 32, no. 10, p. 60–69, accessed January 5, 2021, at https://doi.org/ 10.1109/ 2.796110.

Cutter SL, Boruff BJ, Shirley WL (2003) Social Vulnerability to Environmental Hazards. Social Science Quarterly 84:242–261

Dale, V.H., and English, M.R., eds., 1999, Tools to aid environmental decision making: New York, Springer, accessed January 5, 2021, at https://doi.org/ 10.1007/ 978- 1- 4612-1418- 2.

Day JW, Gunn JD, Burger JR (2021) Diminishing Opportunities for Sustainability of Coastal Cities in the Anthropocene: A Review. Frontiers in Environmental Science 9

de Koning K, Filatova T (2020) Repetitive floods intensify outmigration and climate gentrification in coastal cities. Environmental Research Letters 15

de Koning K, Filatova T, Need A, Bin O (2019) Avoiding or mitigating flooding: Bottom-up drivers of urban resilience to climate change in the USA. Global Environmental Change-Human and Policy Dimensions 59

Dedekorkut A, Mustelin J, Howes M, Byrne J (2010) Tempering growth: planning for the challenges of climate change and growth management in SEQ. Australian Planner 47:203–215

Dilling, L., and Lemos, M.C., 2011, Creating usable science—Opportunities and constraints for climate knowledge use and their implications for science policy: Global Environmental Change, v. 21, no. 2, p. 680–689, accessed January 5, 2021, at https://doi.org/ 10.1016/ j.g loenvcha.2 010.11.006.

Dixon J, Ramutsindela M (2006) Urban resettlement and environmental justice in Cape Town. Cities 23:129–139. https://doi.org/10.1016/j.cities.2005.08.003

Dorkenoo K, Scown M, Boyd E (2022) A critical review of disproportionality in loss and damage from climate change. Wiley Interdisciplinary Reviews-Climate Change 13

Douglas EM, Kirshen PH, Paolisso M, et al (2012) Coastal flooding, climate change and environmental justice: identifying obstacles and incentives for adaptation in two metropolitan Boston Massachusetts communities. Mitig Adapt Strateg Glob Change 17:537–562. https://doi.org/10.1007/s11027-011-9340-8

Douglass K, Cooper J (2020) Archaeology, environmental justice, and climate change on islands of the Caribbean and southwestern Indian Ocean. Proceedings of the National Academy of Sciences of the United States of America 117:8254–8262

du Bray MV, Wutich A, Larson KL, et al (2017) Emotion, Coping, and Climate Change in Island Nations: Implications for Environmental Justice. Environmental Justice 10:102–107

Dunn, G., and Laing, M., 2017, Policy-makers perspectives on credibility, relevance and legitimacy (CRELE): Environmental Science & Policy, v. 76, p. 146–152, accessed January 5, 2021, at https://doi.org/ 10.1016/ j.envsci.2017.07.005.

Eakin H, Parajuli J, Yogya Y, et al (2021) Entry points for addressing justice and politics in urban flood adaptation decision making. Current Opinion in Environmental Sustainability 51:1–6

Eghdami S, Scheld AM, Louis G (2023) Socioeconomic vulnerability and climate risk in coastal Virginia. Climate Risk Management 39

Ferre IM, Negron S, Shultz JM, et al (2019) Hurricane Maria's Impact on Punta Santiago, Puerto Rico: Community Needs and Mental Health Assessment Six Months Postimpact. Disaster Medicine and Public Health Preparedness 13:18–23

Fiorino, D.J., 1990, Citizen Participation and Environmental Risk—A Survey of Institutional Mechanisms: Science, Technology & Human Values, v. 15, no. 2, p. 226–243, accessed January 20, 2021, at https://doi.org/ 10.1177/ 016224399001500204.

Fitrinitia IS, Matsuyuki M (2022) Role of social protection in coping strategies for floods in poor households: A case study on the impact of Program Keluarga Harapan on labor households in Indonesia. International Journal of Disaster Risk Reduction 80

Fleisher, L., Ruggieri, D.G., Miller, S.M., Manne, S., Albrecht, T., Buzaglo, J., Collins, M.A., Katz, M., Kinzy, T.G., Liu, T., Manning, C., Charap, E.S., Millard, J., Miller, D.M., Poole, D., Raivitch, S., Roach, N., Ross, E.A., and Meropol, N.J., 2014, Application of best practice approaches for designing decision support tools—The preparatory education about clinical trials (PRE-ACT) study: Patient Education and Counseling, v. 96, no. 1, p. 63–71, accessed January 5, 2021, at https://doi.org/ 10.1016/ j.pec.2014.04.009.

Flores AB, Castor A, Grineski SE, et al (2021a) Petrochemical releases disproportionately affected socially vulnerable populations along the Texas Gulf Coast after Hurricane Harvey. Population and Environment 42:279–301

Flores AB, Collins TW, Grineski SE, et al (2021b) Environmental Injustice in the Disaster Cycle: Hurricane Harvey and the Texas Gulf Coast. Environmental Justice 14:146–158

Flores AB, Collins TW, Grineski SE, et al (2023) Federally overlooked flood risk inequities in Houston, Texas: Novel insights based on dasymetric mapping and state-of-the-Art flood modeling. Annals of the American Association of Geographers 113:240–260

Freeman, R.E., 2010, Strategic management—A stakeholder approach: Cambridge, Cambridge University Press, accessed January 6, 2021, at https://doi.org/ 10.1017/ CBO9781139192675.

Geoffrion, A.M., 1983, Can MS/OR Evolve Fast Enough?: Interfaces, v. 13, no. 1, p. 10–25, accessed January 5, 2021, at https://doi.org/ 10.1287/ inte.13.1.10.

Golub A, Kelley J (2010) Exploring Potential Inequities Between Burdens and Benefits of Climate Change Abatement Policies. Transportation Research Record 65–72

Gould, J.D., and Lewis, C., 1985, Designing for usability—Key principles and what designers think: Communications of the ACM, v. 28, no. 3, p. 300–311, accessed January 5, 2021, at https://doi.org/ 10.1145/ 3166.3170.

Graham S, Barnett J, Mortreux C, et al (2018) Local values and fairness in climate change adaptation: Insights from marginal rural Australian communities. World Development 108:332–343

Grenning, J., 2001, Launching extreme programming at a process-intensive company: IEEE Software, v. 18, no. 6, p.27–33, accessed January 6, 2021, athttps://doi.org/ 10.1109/ 52.965799.

Grêt-Regamey, A., Sirén, E., Brunner, S.H., and Weibel, B., 2017, Review of decision support tools to operationalize the ecosystem services concept: Ecosystem Services, v.26, p. 306–315, accessed January 5, 2021, athttps://doi.org/ 10.1016/ j.ecoser.2016.10.012.

Griggs G, Reguero BG (2021) Coastal Adaptation to Climate Change and Sea-Level Rise. Water 13:2151. https://doi.org/10.3390/w13162151

Griggs GB (2024) The California Coast and Living Shorelines—A Critical Look. Journal of Marine Science and Engineering 12:199. https://doi.org/10.3390/jmse12020199

Guerry AD, Silver J, Beagle J, et al (2022) Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise. npj Urban Sustain 2:1–12. https://doi.org/10.1038/s42949-022-00056-y

Guest, G., MacQueen, K.M., and Namey, E.E., 2012, Applied thematic analysis: Thousand Oaks, Calif., SAGE Publications, 320 p. [Also available at https://doi.org/ 10.4135/ 9781483384436.]

Hardy RD, Milligan RA, Heynen N (2017) Racial coastal formation: The environmental injustice of colorblind adaptation planning for sea-level rise. Geoforum 87:62–72

Hauer ME, Fussell E, Mueller V, et al (2020) Sea-level rise and human migration. Nat Rev Earth Environ 1:28–39. https://doi.org/10.1038/s43017-019-0002-9

Haushofer J, Shapiro J (2016) THE SHORT-TERM IMPACT OF UNCONDITIONAL CASH TRANSFERS TO THE POOR: EXPERIMENTAL EVIDENCE FROM KENYA. Q J Econ 131:1973–2042. https://doi.org/10.1093/qje/qjw025

Hayes AL, Heery EC, Maroon E, et al (2018) The role of scientific expertise in local adaptation to projected sea level rise. Environmental Science & Policy 87:55–63. https://doi.org/10.1016/j.envsci.2018.05.012

Heavin, C., and Adam, F., 2022, From Decision Support to Analytics: Oxford Research Encyclopedia of Business and Management, accessed May 3, 2023, at https://doi.org/ 10.1093/ acrefore/ 9 7801902248 51.013.255.

Heberger M, Cooley H, Herrera P, et al (2011) Potential impacts of increased coastal flooding in California due to sea-level rise. Climatic Change 109:229–249

Hirabayashi Y, Mahendran R, Koirala S, et al (2013) Global flood risk under climate change. Nature Clim Change 3:816–821. https://doi.org/10.1038/nclimate1911

Hobbie SE, Grimm NB (2020) Nature-based approaches to managing climate change impacts in cities. Philosophical Transactions of the Royal Society B-Biological Sciences 375

Howarth M, Berkowitz J (2024) Perspectives on Permitting and Environmental Review of Nature-Based Solutions. 393–408. https://doi.org/10.1061/9780784485477.035

Howe, A.T., 2011, The U.S. National Ocean Policy—One small step for national waters, but will it be the giant leap needed for our blue planet?: Ocean and Coastal Law Journal, v. 17, no. 1, p. 65–102, accessed January 20, 2021, at https://core.ac.uk/ download/ pdf/ 234108852.pdf.

Hu P, Zhang Q, Shi P, et al (2018) Flood-induced mortality across the globe: Spatiotemporal pattern and influencing factors. Science of The Total Environment 643:171–182. https://doi.org/10.1016/j.scitotenv.2018.06.197

Hutcheon E, Lashewicz B (2014) Theorizing resilience: critiquing and unbounding a marginalizing concept. Disability & Society 29:1383–1397. https://doi.org/10.1080/09687599.2014.934954

Ikeme J (2003) Equity, environmental justice and sustainability: incomplete approaches in climate change politics. Global Environmental Change 13:195–206. https://doi.org/10.1016/S0959-3780(03)00047-5

Ilbeigi M, Jagupilla SCK (2020) An Empirical Analysis of Association between Socioeconomic Factors and Communities' Exposure to Natural Hazards. Sustainability 12

Interaction Design Foundation, [undated], User centered design: Interaction Design Foundation website, accessed January 20, 2021, at http s://www.in teraction-design.org/ literature/ topics/ user- centered- design.

Jacobs F (2019) Black feminism and radical planning: New directions for disaster planning research. Planning Theory 18:24–39

Jacobs, K.L., and Buizer, J.L., 2016, Building community, credibility and knowledge—The third US National Climate Assessment: Climatic Change, v. 135, no. 1, p. 9–22, accessed January 5, 2021, at https://doi.org/ 10.1007/ s10584- 015- 1445- 8.

Johansson-Sköldberg, U., Woodilla, J., and Çetinkaya, M., 2013, Design thinking—Past, present and possible futures: Creativity and Innovation Management, v.22, no. 2, p. 121–146, accessed January 16, 2021, athttps://doi.org/ 10.1111/ caim.12023.

Jurjonas M, Seekamp E (2020) `a Commons Before the Sea:' Climate Justice Considerations for Coastal Zone Management. Climate and Development 12:199–203

Jurjonas M, Seekamp E, Rivers L III, Cutts B (2020) Uncovering climate (in)justice with an adaptive capacity assessment: A multiple case study in rural coastal North Carolina. Land Use Policy 94

Katzenbach, J., and Smith, D.K., 1992, The wisdom of teams—Creating the high-performance organization: New York, Harvard Business Review Press, 304 p.

Keenan, P.B., 2021, Thirty years of decision support—A bibliometric view, in Papathanasiou, J., Zaraté, P., Freire de Sousa, J., eds., EURO Working Group on DSS, Integrated Series in Information Systems: Springer, Cham, accessed May 3, 2023, at https://doi.org/ 10.1007/ 978- 3- 030- 70377- 6_ 2.

Kelly, A., 2019, Customers, users, and stakeholders, in Kelly, A., ed., The art of agile product ownership—A guide for product managers, business analysts, and entrepreneurs: Berkeley, Calif. Apress, p. 45–48, accessed January 20, 2021, at https://doi.org/ 10.1007/ 978- 1- 4842- 5168- 3_ 6.

Kelso MA, Stovall AE, Reguero BG, et al (2024) Nature-Based Solutions & Risk Management: Recommendations for Integrating Nature into Risk Science & Insurance

Khan AE, Scheelbeek PFD, Shilpi AB, et al (2014) Salinity in drinking water and the risk of (pre) eclampsia and gestational hypertension in coastal Bangladesh: a case-control study. PLoS One 9:e108715

Khedun CP, Singh VP (2014) Climate Change, Water, and Health: A Review of Regional Challenges. Water Quality Exposure and Health 6:7–17

Kraan CM, Hino M, Niemann J, et al (2021) Promoting equity in retreat through voluntary property buyout programs. Journal of Environmental Studies and Sciences 11:481–492

Kraushar ML, Rosenberg RE (2015) A Community-Led Medical Response Effort in the Wake of Hurricane Sandy. Disaster Medicine and Public Health Preparedness 9:354–358

Krueger, R.A., 1989, Focus groups—A practical guide for applied research: Beverly Hills, Calif., SAGE Publications, 200 p.

Kuhl L, Kirshen PH, Ruth M, Douglas EM (2014) Evacuation as a climate adaptation strategy for environmental justice communities. Climatic Change 127:493–504

Kumar A, Nagar S, Anand S (2021) 1 - Climate change and existential threats. In: Singh S, Singh P, Rangabhashiyam S, Srivastava KK (eds) Global Climate Change. Elsevier, pp 1–31

Lavery, J.V., 2018, Building an evidence base for stakeholder engagement: Science, v. 361, no. 6402, p. 554–556, accessed January 5, 2021, at https://doi.org/ 10.1126/ science.aat8429.

Lentz, E., Andrews, B., Brothers, L., Ernst, S., Ganju, N., Gonneea, M., Himmelstoss, E., and Defne, Z., 2020, Our coasts, accessed February 20, 2021, at https://geonarrative.usgs.gov/ cch- ourcoasts/ .

Leo KL, Gillies CL, Fitzsimons JA, et al (2019) Coastal habitat squeeze: A review of adaptation solutions for saltmarsh, mangrove and beach habitats. Ocean & Coastal Management 175:180–190. https://doi.org/10.1016/j.ocecoaman.2019.03.019

Li J, Spidalieri K (2021) Home is where the safer ground is: the need to promote affordable housing laws and policies in receiving communities. Journal of Environmental Studies and Sciences 11:682–695

Liddell JL, Mckinley CE, Lilly JM (2021) Historic and Contemporary Environmental Justice Issues among Native Americans in the Gulf Coast Region of the United States. Studies in Social Justice 15:1–24

Lieberknecht K, Mueller EJ (2023) Planning for Equitable Climate Relocation: Gaps in Knowledge and a Proposal for Future Directions. Journal of Planning Literature 38:229–244

Lloyd SJ, Kovats RS, Chalabi Z, et al (2016) Modelling the influences of climate change-associated sea-level rise and socioeconomic development on future storm surge mortality. Climatic change 134:441–455

Lo AY, Liu S, Cheung LTO (2019) Socio-economic conditions and small business vulnerability to climate change impacts in Hong Kong. Climate and Development 11:930–942

Loucks, D.P., 1995, Developing and implementing decision supoort systems—A critique and a challenge: JAWRA Journal of the American Water Resources Association, v.31, no. 4, p. 571–582, accessed January 6, 2021, athttps://doi.org/ 10.1111/ j.1752-1688.1995.tb03384.x.

Lumbroso DM, Suckall NR, Nicholls RJ, White KD (2017) Enhancing resilience to coastal flooding from severe storms in the USA: international lessons. Natural Hazards and Earth System Sciences 17:1357–1373

MacDonald G (2020) Climate, Capital, Conflict: Geographies of Success or Failure in the Twenty-First Century. Annals of the American Association of Geographers 110:2011–2031

Madajewicz M (2020) Who is vulnerable and who is resilient to coastal flooding? Lessons from Hurricane Sandy in New York City. Climatic Change 163:2029–2053

Maldonado A, Collins TW, Grineski SE, Chakraborty J (2016) Exposure to Flood Hazards in Miami and Houston: Are Hispanic Immigrants at Greater Risk than Other Social Groups? International Journal of Environmental Research and Public Health 13

Marshall A, Robinson L, Allen Owens M (2011) Coastal construction trends in response to coastal erosion: an opportunity for adaptation. J Coast Conserv 15:61–72. https://doi.org/10.1007/s11852-010-0120-5

Martin JA, Gray S, Aceves-Bueno E, et al (2019) What is marine justice? Journal of Environmental Studies and Sciences 9:234–243

Martinich J, Neumann J, Ludwig L, Jantarasami L (2013) Risks of sea level rise to disadvantaged communities in the United States. Mitigation and Adaptation Strategies for Global Change 18:169–185

May CL, Osler MS, Stockdon HF, et al (2023) Coastal effects. In: Crimmins AR, Avery CW, Easterling DR, et al. (eds) Fifth National Climate Assessment. U.S. Global Change Research Program, Washington, DC, USA

Mazumder LT, Landry S, Alsharif K (2022) Coastal cities in the Southern US floodplains: An evaluation of environmental equity of flood hazards and social vulnerabilities. Applied Geography 138

McGuire CJ (2018) Examining legal and regulatory barriers to climate change adaptation in the coastal zone of the United States. Cogent Environmental Science 4:1491096. https://doi.org/10.1080/23311843.2018.1491096

McLeman R (2019) International migration and climate adaptation in an era of hardening borders. Nature Climate Change 9:911–918

Meixler MS, Piana MR, Henry A (2023) Modeling present and future ecosystem services and environmental justice within an urban-coastal watershed. Landscape and Urban Planning 232

Melix BL, Jackson A, Butler W, et al (2023) Locating Neighborhood Displacement Risks to Climate Gentrification Pressures in Three Coastal Counties in Florida. The Professional Geographer 75:31–43. https://doi.org/10.1080/00330124.2022.2087695

Meso, P., and Jain, R., 2006, Agile Software Development—Adaptive Systems Principles and Best Practices: Information Systems Management, v. 23, no. 3, p. 19–30, accessed January 5, 2021, at https://doi.org/ 10.1201/ 1078.10580530/ 46108.23.3.20060601/ 93704.3.

Michael, A.J., McBride, S.K., Hardebeck, J.L., Barall, M., Martinez, E., Page, M.T., van der Elst, N., Field, E.H., Milner, K.R., and Wein, A.M., 2020, Statistical Seismology and Communication of the USGS Operational Aftershock Forecasts for the 30 November 2018 Mw 7.1 Anchorage, Alaska, Earthquake: Seismological Research Letters, v.91, no. 1, p. 153–173, accessed January 6, 2021, athttps://doi.org/ 10.1785/ 0220190196.

Middelbeek L, Kolle K, Verrest H (2014) Built to last? Local climate change adaptation and governance in the Caribbean - The case of an informal urban settlement in Trinidad and Tobago. Urban Climate 8:138–154

Miller Hesed CD, Ostergren DM (2017) Promoting climate justice in high-income countries: lessons from African American communities on the Chesapeake Bay. Climatic Change 143:185–200

Minovi D (2021) Toxic Floodwaters on the Gulf Coast and Beyond: Commentary on the Public Health Implications of Chemical Releases Triggered by Extreme Weather. Environmental Justice 14:105–109

Molloy M, Nost E, Bledsoe M (2023) Is adaptation planning effective and for whom? The case of Louisiana’s 2017 Comprehensive Master Plan for a Sustainable Coast. Environmental Hazards-Human and Policy Dimensions

Montgomery MC, Chakraborty J (2013) Social Vulnerability to Coastal and Inland Flood Hazards: A Comparison of GIS-Based Spatial Interpolation Methods. International Journal of Applied Geospatial Research 4:58–79

Montgomery MC, Chakraborty J (2015) Assessing the environmental justice consequences of flood risk: a case study in Miami, Florida. Environmental Research Letters 10

Morgan, D., 1997, Focus groups as qualitative research: Thousand Oaks, Calif., SAGE Publications, 88 p. [Also available at https://doi.org/ 10.4135/ 9781412984287.]

Morse, R. (2008). Environmental justice through the eye of Hurricane Katrina (pp. 7-9). Washington, DC: Joint Center for Political and Economic Studies, Health Policy Institute.

Moser, S., 2009, Making a difference on the ground—The challenge of demonstrating the effectiveness of decision support: Climatic Change, v. 95, no. 1-2, p. 11–21, accessed January 5, 2021, at https://doi.org/ 10.1007/ s10584- 008- 9539- 1.

Mycoo MA (2014) Autonomous household responses and urban governance capacity building for climate change adaptation: Georgetown, Guyana. Urban Climate 9:134–154

National Academies of Sciences, Engineering, and Medicine, 2018, Future water priorities for the Nation—Directions for the U.S. Geological Survey Water Mission Area: Washington, D.C., The National Academies Press, accessed January 21, 2021, at https://doi.org/ 10.17226/ 25134.

National Oceanic and Atmospheric Administration [NOAA], 2022, Coastal flooding in the face of climate change—Understanding constituent needs—A needs assessment funded by the NOAA Water Initiative: National Oceanic and Atmospheric Administration, accessed August 26, 2022, at https: //www.naut icalcharts .noaa.gov/ hsrp/ meetings/ 2022/ fall/ docs/ 11+Final+Report_ OCM+CO-OPS+Needs+Assessment_ 508.pdf.

National Research Council [NRC], 2009, Informing decisions in a changing climate: Washington, D.C., The National Academies Press, 188 p. [Also available at https://doi.org/ 10.17226/ 12626.]

National Research Council [NRC], 2012, Using science as evidence in public policy: Prewitt, K., Schwandt, T.A., Straf, M.L., eds., Washington, D.C., The National Academies Press, 110 p. [Also available at https://doi.org/ 10.17226/ 13460.]

Newman, S., Lynch, T., and Plummer, A.A., 2000, Success and failure of decision support systems—Learning as we go: Journal of Animal Science, v. 77, E-Suppl, p. 1, accessed January 20, 2021, at https://doi.org/ 10.2527/ jas2000.77E- Suppl1e.

Nguyen TTX, Woodroffe CD (2016) Assessing relative vulnerability to sea-level rise in the western part of the Mekong River Delta in Vietnam. Sustainability Science 11:645–659

Nicholls R, Wong P, Burkett V, et al (2007) Coastal systems and low-lying areas. Faculty of Science - Papers (Archive)

Nicholls RJ, Cazenave A (2010) Sea-Level Rise and Its Impact on Coastal Zones. Science 328:1517–1520. https://doi.org/10.1126/science.1185782

Nicholls RJ, Tol RSJ (2006) Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 364:1073–1095. https://doi.org/10.1098/rsta.2006.1754

Nielsen, J., 1994, Usability inspection methods, in Plaisant, C., ed., CHI '94—Conference companion on human factors in computing systems—ACM Conference on Human Factors in Computer Systems, Boston, Mass., April 24–28, 1994: New York, N.Y., Association for Computing Machinery, p. 413–414, accessed January 5, 2021, at https://doi.org/ 10.1145/ 259963.260531.

Nishiura O, Tamura M, Fujimori S, et al (2020) An Assessment of Global Macroeconomic Impacts Caused by Sea Level Rise Using the Framework of Shared Socioeconomic Pathways and Representative Concentration Pathways. Sustainability 12

NOAA Office for Coastal Management American Community Survey Five-Year Estimates. https://coast.noaa.gov/digitalcoast/data/acs.html. Accessed 25 Apr 2024

Norman, D.A., 2013, The design of everyday things: Cambridge, Mass., MIT Press, 368 p.

Norman, D.A., and Draper, S.W., 1986, User centered system design—New perspectives on human-computer interaction: Boca Raton, Fla., Lawrence Erlbaum Associates, 540 p. [Also available at https://doi.org/ 10.1201/ b15703.]

Nunn PD, Campbell JR (2020) Rediscovering the past to negotiate the future: How knowledge about settlement history on high tropical Pacific Islands might facilitate future relocations. Environmental Development 35:100546. https://doi.org/10.1016/j.envdev.2020.100546

Nunn PD, Klöck C, Duvat V (2021) Seawalls as maladaptations along island coasts. Ocean & Coastal Management 205:105554. https://doi.org/10.1016/j.ocecoaman.2021.105554

Nyumba, T.O., Wilson, K., Derrick, C.J., and Mukherjee, N., 2018, The use of focus group discussion methodology—Insights from two decades of application in conservation:

Methods in Ecology and Evolution, v. 9, no. 1, p. 20–32, accessed insert date, at https://doi.org/ 10.1111/ 2041- 210X.12860.

O'Donnell T (2022) Managed retreat and planned retreat: a systematic literature review. Philosophical Transactions of the Royal Society B-Biological Sciences 377

Oakley, N.S., and Daudert, B., 2016, Establishing Best Practices to Improve Usefulness and Usability of Web Interfaces Providing Atmospheric Data: Bulletin of the American Meteorological Society, v. 97, no. 2, p. 263–274, accessed May 4, 2023, at https://doi.org/ 10.1175/ BAMS- D- 14- 00121.1.

Office of Personnel Management, [undated], What is human-centered design?, HCD discovery Concept Guide: Office of Personnel Management, The Lab at OPM website, accessed November 1, 2022, at https://the- lab- at- opm.github.io/ HCD-Discovery- Concept- Guide/ whatisHCD/ .

Ojomo E, Bartram J (2016) Adapting drinking-water systems to coastal climate change: evidence from Viet Nam and the Philippines. Regional Environmental Change 16:2409–2418

Olajide O, Lawanson T (2014) . Climate change and livelihood vulnerabilities of low-income coastal communities in Lagos, Nigeria. International Journal of Urban Sustainable Development 6:42–51

Oliver, D.M., Bartie, P.J., Heathwaite, A.L., Pschetz, L., and Quilliam, R.S., 2017, Design of a decision support tool for visualising E. coli risk on agricultural land using a stakeholder-driven approach: Land Use Policy, v. 66, p. 227–234, accessed January 6, 2021, at https://doi.org/ 10.1016/ j.la ndusepol.2 017.05.005.

Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321-445. https://doi.org/10.1017/9781009157964.006.

Orbach MK, Miller ML (2022) How Have the US Coasts Changed (and How Are They Going to Change) as Cultural and Policy Spaces? An Example from California. Coastal Management 50:79–91

Palutikof, J.P., Street, R.B., and Gardiner, E.P., 2019, Decision support platforms for climate change adaptation—An overview and introduction: Climatic Change, v. 153, no. 4, p. 459–476, accessed May 3, 2023, at https://doi.org/ 10.1007/ s10584- 019- 02445- 2.

PARC, 2011, Busting the myth of the giant green button: UX Magazine, accessed January 20 2021, at https://uxmag.com/ articles/ busting- the- myth- of- the- giant- green- button.

PARC, 2016, Ethnography and the PARC Copier, PARC, the Xerox Company video, 00:01:30, recorded in 1983, posted December 22, 2016, accessed November 2, 2021, at http s://www.yo utube.com/ watch? v= DUwXN01ARYgandt= 16s.

Parthasarathy D (2018) Inequality, uncertainty, and vulnerability: Rethinking governance from a disaster justice perspective. Environment and Planning E-Nature and Space 1:422–442

Pearman, O., and Cravens, A.E., 2022, Institutional barriers to actionable science—Perspectives from decision support tool creators: Environmental Science & Policy, v. 128, p. 317–325, accessed January 10, 2023, at https://doi.org/ 10.1016/ j.envsci.2021.12.004.

Pereira Santos A, Rodriguez-Lopez JM, Chiarel C, Scheffran J (2022) Unequal Landscapes: Vulnerability Traps in Informal Settlements of the Jacui River Delta (Brazil). Urban Science 6

Perez VW, Egan J (2016) Knowledge and Concern for Sea-Level Rise in an Urban Environmental Justice Community. Sociological Forum 31:885–907

Portman ME (2012) Losing Ground: Mediterranean Shoreline Change from an Environmental Justice Perspective. Coastal Management 40:421–441

Project Management Institute, 2021, A guide to the project management body of knowledge (PMBOK guide)—Seventh edition and the standard for project management: Newtown Square, Pa., Project Management Institute, 756 p.

Provost EJ, Butcher PA, Colefax AP, et al (2019) Using drones to quantify beach users across a range of environmental conditions. J Coast Conserv 23:633–642. https://doi.org/10.1007/s11852-019-00694-y

Pulcinella JA, Winguth AME, Allen DJ, Gangadhar ND (2019) Analysis of Flood Vulnerability and Transit Availability with a Changing Climate in Harris County, Texas. Transportation Research Record 2673:258–266

Qiang Y (2019) Disparities of population exposed to flood hazards in the United States. Journal of Environmental Management 232:295–304

R Core Team (2023) R: A Language and Environment for Statistical Computing

Rahman H, Manuel P, Sherren K, et al (2023) Characterizing social barriers to nature-based coastal adaptation approaches. Nature-Based Solutions 4:100099. https://doi.org/10.1016/j.nbsj.2023.100099

Rahman MM, Ahmad S, Mahmud AS, et al (2019) Health consequences of climate change in Bangladesh: An overview of the evidence, knowledge gaps and challenges. Wiley Interdisciplinary Reviews-Climate Change 10

Raker EJ, Lowe SR, Arcaya MC, et al (2019) Twelve years later: The long-term mental health consequences of Hurricane Katrina. Social Science & Medicine 242

Reiblich J, Hartge E, Wedding LM, et al (2019) Bridging climate science, law, and policy to advance coastal adaptation planning. Marine Policy 104:125–134. https://doi.org/10.1016/j.marpol.2019.02.028

Restrepo-Osorio, D.L., Stoltz, A.D., and Herman-Mercer, N.M., 2022, Stakeholder engagement to guide decision-relevant water data delivery: Journal of the American Water Resources Association, v. 58, no. 6, p. 1531–1544, accessed January 7,2021, at https://doi.org/10.1111/1752-1688.13055.

Rigby, J.M., and Preist, C., 2023, Towards user-centered climate services—the role of human-computer interaction, in Schmidt, A., Väänänen, K., Goyal, T., Kristensson, P.O., Peters, A., Mueller, S., Williamson, J.R., and Wilson, M.L., eds., CHI '23—Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, Hamburg, Germany, April 23–28, 2023, p. 1–14, accessed May 4, 2023, at https://doi.org/ 10.1145/ 3544548.3580663.

Röckmann, C., Ulrich, C., Dreyer, M., Bell, E., Borodzicz, E., Haapasaari, P., Hauge, K.H., Howell, D., Mäntyniemi, S., Miller, D., Tserpes, G., and Pastoors, M., 2012, The added value of participatory modelling in fisheries management – what has been learnt?: Marine Policy, v. 36, no. 5, p. 1072–1085, accessed January 5, 2021, at https://doi.org/ 10.1016/ j.marpol.2012.02.027.

Roy S, Vinayak P, Von Stroh D (2022) Modeling Demographic Relocation in Response to Climate Risk Factors and Gentrification Displacement Pressures. Transportation Research Record 2676:688–703

Rubinstein, R., and Hersh, H., 1984, The human factor—designing computer systems for people (excerpt), in Design principles and methodologies, chap. 11 of Beacker, R.M. and Buxton, W.A.S., eds., Human-computer interaction—A multidisciplinary approach: San Mateo, Calif., Morgan Kaufman Publishers, Inc., 1987, p. 502–507.

Ruparelia, N.B., 2010, Software development lifecycle models: Software Engineering Notes, v. 35, no. 3, p. 8–13, accessed January 20, 2021, at https://doi.org/ 10.1145/ 1764810.1764814.

Rust S (2023) Before disastrous flood, officials knew Pajaro River levee could fail but took no action. In: Lookout Santa Cruz. http://lookout.co/pajaro-river-flooding-levee-breach-before-disastrous-flood-officials-knew-pajaro-river-levee-could-fail-but-took-no-action/. Accessed 3 May 2024

Sadai S, Spector RA, DeConto R, Gomez N (2022) The Paris Agreement and Climate Justice: Inequitable Impacts of Sea Level Rise Associated With Temperature Targets. Earths Future 10

Saldaña, J., 2016, The coding manual for qualitative researchers (3rd ed.): London, Sage Publications.

Sandoval-Almazán, R., Luna-Reyes, L.F., Luna-Reyes, D.E., Gil-Garcia, J.R., Puron-Cid, G., and Picazo-Vela, S., 2017, Introduction, in Sandoval-Almazán, R., Luna-Reyes, L.F., Luna-Reyes, D.E., Gil-Garcia, J.R., Puron-Cid, G., and Picazo-Vela, S., eds., Building digital government strategies—Principles and practices: London, Springer International Publishing, p. 1–5, accessed January 5, 2021, at https://doi.org/ 10.1007/ 978- 3- 319- 60348- 3_ 1.

Sansom GT, Kirsch KR, Casillas GA, et al (2021) Spatial Distribution of Polycyclic Aromatic Hydrocarbon Contaminants after Hurricane Harvey in a Houston Neighborhood. Journal of Health and Pollution 11

Sauvé P, Bernatchez P, Glaus M (2020) The role of the decision-making process on shoreline armoring: A case study in Quebec, Canada. Ocean & Coastal Management 198:105358. https://doi.org/10.1016/j.ocecoaman.2020.105358

Scyphers SB, Beck MW, Furman KL, et al (2020) Designing effective incentives for living shorelines as a habitat conservation strategy along residential coasts. Conservation Letters 13:e12744. https://doi.org/10.1111/conl.12744

Seffah, A., Gulliksen, J., and Desmarais, M.C., 2011, Human-centered software engineering—Integrating usability in the software development lifecycle: Springer, 421 p.

Shammi M, Rahman MM, Bondad SE, Bodrud-Doza M (2019) Impacts of Salinity Intrusion in Community Health: A Review of Experiences on Drinking Water Sodium from Coastal Areas of Bangladesh. Healthcare 7:50. https://doi.org/10.3390/healthcare7010050

Shim, J.P., Warkentin, M., Courtney, J.F., Power, D.J., Sharda, R., and Carlsson, C., 2002, Past, present, and future of decision support technology: Decision Support Systems, v. 33, no. 2, p. 111–126, at https://doi.org/ 10.1016/ S0167- 9236(01)00139- 7.

Shim, J.P., Warkentin, M., Courtney, J.F., Power, D.J., Sharda, R., and Carlsson, C., 2002, Past, present, and future of decision support technology: Decision Support Systems, v.33, no. 2, p. 111–126, accessed Janurary 7, 2021, athttps://doi.org/ 10.1016/ S0167- 9236(01)00139- 7.

Siders AR (2019) Social justice implications of US managed retreat buyout programs. Climatic Change 152:239–257

Siders AR, Ajibade I (2021) Introduction: Managed retreat and environmental justice in a changing climate. Journal of Environmental Studies and Sciences 11:287–293

Smith CS, Rudd ME, Gittman RK, et al (2020) Coming to Terms With Living Shorelines: A Scoping Review of Novel Restoration Strategies for Shoreline Protection. Front Mar Sci 7:. https://doi.org/10.3389/fmars.2020.00434

Spears E (2021) Reconceptualizing Social Vulnerability in Brunswick, Georgia: Critical Physical Geography and the Future of Sea-Level Rise. Southeastern Geographer 61:357–380

Stoltz AD, Shivlani M, Glazer R (2021) Fishing Industry Perspectives on Sea-Level Rise Risk and Adaptation. Water 13:1124. https://doi.org/10.3390/w13081124

Stoltz, A.D., Cravens, A.E., Lentz, E., and Himmelstoss, E., 2023, User engagement to improve coastal data access and delivery: U.S. Geological Survey Scientific Investigations Report 2023–5081, 29 p., accessed July 2023, at https://doi.org/10.3133/sir20235081.

Sun J, Chow ACH, Madanat SM (2021) Equity concerns in transportation infrastructure protection against sea level rise. Transport Policy 100:81–88

Supekar S (2019) Equitable Resettlement for Climate Change-Displaced Communities in the United States. Ucla Law Review 66:1290–1328

Tadgell A, Doberstein B, Mortsch L (2018) Principles for climate-related resettlement of informal settlements in less developed nations: a review of resettlement literature and institutional guidelines. Climate and Development 10:102–115

Taherkhani M, Vitousek S, Barnard PL, et al (2020) Sea-level rise exponentially increases coastal flood frequency. Sci Rep 10:6466. https://doi.org/10.1038/s41598-020-62188-4

Talton T (2017) Corps Eases Living Shoreline Permit Process. In: Coastal Review. https://coastalreview.org/2017/01/corps-eases-living-shoreline-permit-process/. Accessed 5 May 2024

Talukder MRR, Rutherford S, Huang C, et al (2017) Drinking water salinity and risk of hypertension: A systematic review and meta-analysis. Archives of Environmental & Occupational Health 72:126–138. https://doi.org/10.1080/19338244.2016.1175413

Tansel B, Zhang K (2022) Effects of saltwater intrusion and sea level rise on aging and corrosion rates of iron pipes in water distribution and wastewater collection systems in coastal areas. Journal of Environmental Management 315:115153. https://doi.org/10.1016/j.jenvman.2022.115153

Tauzer E, Borbor-Cordova MJ, Mendoza J, et al (2019) A participatory community case study of periurban coastal flood vulnerability in southern Ecuador. Plos One 14

Taylor DE (2011) Introduction: The Evolution of Environmental Justice Activism, Research, and Scholarship. Environmental Practice 13:280–301. https://doi.org/10.1017/S1466046611000329

Taylor J, Levine NS, Muhammad E, et al (2022) Participatory and Spatial Analyses of Environmental Justice Communities' Concerns about a Proposed Storm Surge and Flood Protection Seawall. International Journal of Environmental Research and Public Health 19

Taylor-Burns R, Lowrie C, Tehranirad B, et al (2024) The value of marsh restoration for flood risk reduction in an urban estuary. Sci Rep 14:6856. https://doi.org/10.1038/s41598-024-57474-4

Tedesco M, Hultquist CG, de Sherbinin A (2022) A New Dataset Integrating Public Socioeconomic, Physical Risk, and Housing Data for Climate Justice Metrics: A Test-Case Study in Miami. Environmental Justice 15:149–159

Temmerman S, Meire P, Bouma TJ, et al (2013) Ecosystem-based coastal defence in the face of global change. Nature 504:79–83. https://doi.org/10.1038/nature12859

Tom, E., Aurum, A., and Vidgen, R., 2013, An exploration of technical debt: Journal of Systems and Software, v. 86, no. 6, p. 1498–1516, accessed January 5, 2021, at https://doi.org/ 10.1016/ j.jss.2012.12.052.

Tribbia J, Moser SC (2008) More than information: what coastal managers need to plan for climate change. Environmental Science & Policy 11:315–328. https://doi.org/10.1016/j.envsci.2008.01.003

Triboan D, Obonyo EA, Ayesh A, et al (2021) A Transdisciplinary Framework for AI-driven Disaster Risk Reduction for Low-income Housing Communities in Kenya. In: 2021 IEEE International Conference on Systems, Man, and Cybernetics (SMC). pp 188–193

Tubridy F, Lennon M, Scott M (2022) Managed retreat and coastal climate change adaptation: The environmental justice implications and value of a coproduction approach. Land Use Policy 114

Turan Z (2018) Finding the "local green voice"? Waterfront development, environmental justice, and participatory planning in Gowanus, NY. Urbani Izziv-Urban Challenge 29:79–94

U.S. Department of Commerce (2023) Biden-Harris Administration Announces $2.6 Billion Framework Through Investing in America Agenda to Protect Coastal Communities and Restore Marine Resources. https://www.commerce.gov/news/press-releases/2023/06/biden-harris-administration-announces-26-billion-framework-through. Accessed 4 May 2024

U.S. Environmental Protection Agency, 2023, EJScreen—Environmental justice screening and mapping tool: U.S. Environmental Protection Agency, accessed June 12, 2023, at https://www.epa.gov/ ejscreen.

U.S. Geological Survey [USGS], 2021, U.S. Geological Survey 21st-Century Science Strategy 2020–2030: U.S. Geological Survey Circular 1476, 20 p., accessed October 15, 2022, at https://doi.org/ 10.3133/ cir1476.

Ueland J, Warf B (2006) Racialized Topographies: Altitude and Race in Southern Cities. Geographical Review 96:50–78

Ulibarri N, Cain BE, Ajami NK (2017) A Framework for Building Efficient Environmental Permitting Processes. Sustainability 9:180. https://doi.org/10.3390/su9020180

Ulibarri, N., Cravens, A.E., Svetina Nabergoj, A., Royalty, A., and Kernbach, S., 2019, Creativity in research—Cultivate clarity, be innovative, and make progress in your research journey: Cambridge, England, Cambridge University Press, 328 p.

Uran, O., and Janssen, R., 2003, Why are spatial decision support systems not used? Some experiences from the Netherlands: Computers, Environment and Urban Systems, v. 27, no. 5, p. 511–526, accessed January 6, 2021, at https://doi.org/ 10.1016/ S0198-9715(02)00064- 9.

US EPA O (2015) Learn About Environmental Justice. https://www.epa.gov/environmentaljustice/learn-about-environmental-justice. Accessed 25 Apr 2024

Usability.gov, [undated], User-centered design basics: U.S. General Services Administration webpage, accessed January 5, 2021, at https: //www.usab ility.gov/what- and- why/ user- centered- design.html.

Van de Molen, K., Wall, T.U., and Daudert, B., 2019, A Call for the Evaluation of Web-Based Climate Data and Analysis Tools: Bulletin of the American Meteorological Society, v. 100, no. 2, p. 257–268, accessed May 3, 2023, at https://doi.org/ 10.1175/ BAMS- D- 18- 0006.1.

Van der Molen, F., Swart, J.A.A., and van der Windt, H.J., 2018, Trade-offs and synergies in joint knowledge creation for coastal management—Insights from ecology-oriented sand nourishment in the Netherlands: Journal of Environmental Policy and Planning, v. 20, no. 5, p. 564–577, accessed January 5, 2021, at https://doi.org/ 10.1080/ 1 523908X.20 18.1461082.

Vennix, J.A.M., 1995, Building consensus in strategic decision making—System dynamics as a group support system: Group Decision and Negotiation, v. 4, no. 4, p. 335–355, accessed January 5, 2021, at https://doi.org/ 10.1007/ BF01409778.

Voorhees CCW, Vick J, Perkins DD (2007) Came Hell and High Water: The intersection of Hurricane Katrina, the news media, race and poverty. Journal of Community & Applied Social Psychology 17:415–429

Vredenburg, K., Ji-Ye Mao, Smith, P.W., and Carey, T., 2002,A survey of user-centered design practice, in Proceedings of the Special Interest Group on Computer-Human Interaction (SIGCHI) Conference on Human Factors in Computing Systems, April 20–25, 2002, Minneapolis, Minn.,: Association for Computing Machinery, p. 471–478, https://doi.org/ 10.1145/ 503376.503460.

Walker G, Burningham K (2011) Flood risk, vulnerability and environmental justice: Evidence and evaluation of inequality in a UK context. Critical Social Policy 31:216–240. https://doi.org/10.1177/0261018310396149

Wallach, D., and Scholz, S.C., 2012, User-centered design—Why and how to put users first in software development, in Maedche, A., Botzenhardt, A., and Neer, L., eds., Software for people: Berlin, Heidelberg, Springer, p. 11–38, accessed January 5, 2021, at https://doi.org/ 10.1007/ 978- 3- 642- 31371- 4_ 2.

Walling, E., and Vaneeckhaute, C., 2020, Developing successful environmental decision support systems—Challenges and best practices: Journal of Environmental Management, v. 264, article 110513, 16 p., accessed January 1, 2021, at https://doi.org/ 10.1016/ j .jenvman.2 020.110513.

Warren Pinnacle Consulting, Inc., 2017, SLAMM—Sea level affecting marshes model: Warren Pinnacle Consulting, Inc., accessed June 12, 2023, at https:/ /warrenpin nacle.com/ prof/ SLAMM/ index.html."

White, D.D., Wutich, A., Larson, K.L., Gober, P., Lant, T., and Senneville, C., 2010, Credibility, salience, and legitimacy of boundary objects—Water managers' assessment of a simulation model in an immersive decision theater: Science & Public

Policy, v. 37, no. 3, p. 219–232, accessed January 20, 2021, at https://doi.org/ 10.3152/ 030234210X497726.

Wilson M, Lane S, Mohan R, Sugg M (2020) Internal and external validation of vulnerability indices: a case study of the Multivariate Nursing Home Vulnerability Index. Nat Hazards 100:1013–1036. https://doi.org/10.1007/s11069-019-03837-4

Wilson MJ, Sugg MM, Lane SJ (2019) Identifying multivariate vulnerability of nursing home facilities throughout the southeastern United States. International Journal of Disaster Risk Reduction 36:101106. https://doi.org/10.1016/j.ijdrr.2019.101106

Wilson, C., 2014, Semi-structured interviews, chap. 2 of Wilson, C., ed., Interview techniques for UX practitioners—A user-centered design method: Boston, Mass. Morgan Kaufmann, p. 23–41, accessed January 5, 2021, at https://doi.org/ 10.1016/ B978- 0- 12- 410393- 1.00002- 8.

Wolsko C, Marino E (2016) Disasters, migrations, and the unintended consequences of urbanization: What's the harm in getting out of harm's way? Population and Environment 37:411–428

Wong-Parodi, G., Mach, K.J., Jagannathan, K., and Sjostrom, K.D., 2020, Insights for developing effective decision support tools for environmental sustainability: Current Opinion in Environmental Sustainability, v. 42, p. 52–59, accessed January 7, 2021, at https://doi.org/ 10.1016/ j.cosust.2020.01.005.

Wunas S (2019) The disaster resolving on tourism settlements in small islands. 1st International Conference on Global Issue for Infrastructure, Environment & Socio-Economic Development 235

Xie W, Meng Q (2023) An Integrated PCA-AHP Method to Assess Urban Social Vulnerability to Sea Level Rise Risks in Tampa, Florida. Sustainability 15

Yin J, Yu D, Lin N, Wilby RL (2017) Evaluating the cascading impacts of sea level rise and coastal flooding on emergency response spatial accessibility in Lower Manhattan, New York City. Journal of Hydrology 555:648–658. https://doi.org/10.1016/j.jhydrol.2017.10.067

Young, T.J., 2015, Questionnaires and surveys, chap. 11 of Hua, Z. ed., Research methods in intercultural communication—A practical guide: Hoboken, N.J., John Wiley & Sons Inc, p. 163–180, accessed January 7, 2021, at https://doi.org/ 10.1002/ 9781119166283.ch11.