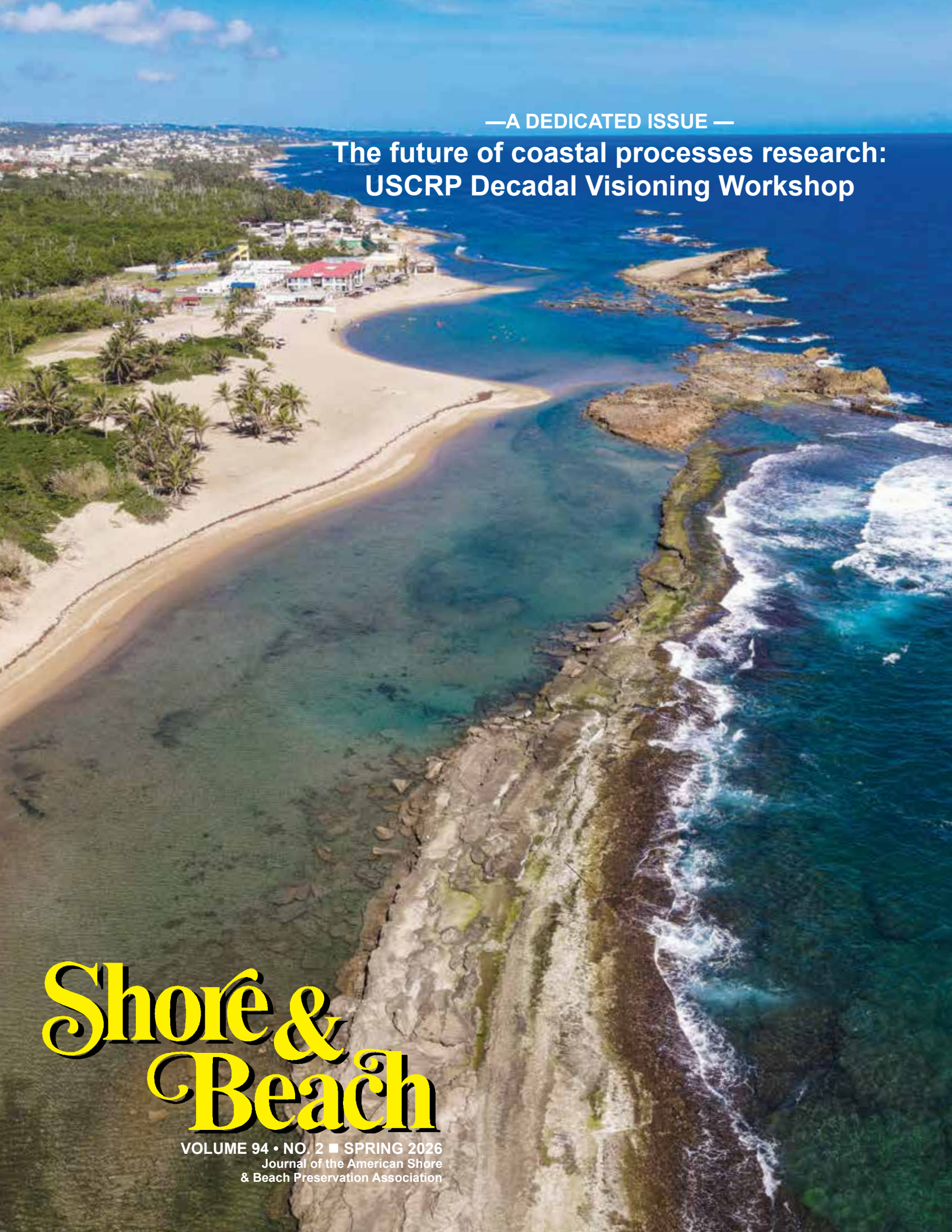

—A DEDICATED ISSUE —

The future of coastal processes research: USCRP Decadal Visioning Workshop

Shore & Beach

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Tropical treasure: Aerial view of the coastline of Punta Maracayo Hatillo, Puerto Rico. Image taken by Kevián Augusto Pérez Valentín, with a DJI Mavic Air 2 on 29 June 2021.

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FROM THE GUEST EDITORS' DESK:

Successes and challenges in coastal research, applications, and advancements

By

Julie Dean Rosati, Ph.D., P.E., and Tracie Sempier, Ph.D.

The papers presented in this dedicated issue document outcomes of the June 2024 Decadal Visioning Workshop (above) convened by the U.S. Coastal Research Program (USCRP). Papers synthesize advancements since the previous workshop in 2014 — which led to formation of the USCRP in 2015 — and highlight priorities for the future decade. The emphasis is to identify the key coastal management challenges and science gaps required to increase coastal community resilience and to focus research needed to address decadal priorities.

These papers represent a significant milestone for the USCRP and the nearshore community in several ways, by:

• Documenting the impact of the USCRP in coalescing funding towards priority community-driven coastal needs;

• Providing a resource for decision-makers, practitioners, educators and researchers in their distinct and intersecting roles driving future coastal solutions; and

• Documenting the power of our diverse nearshore community when working together to communicate national coastal priorities.

Elko and Stockdon's Coastal Forum briefly reviews the history of U.S. nearshore coastal workshops that have convened the national coastal community and summarizes the 2024 workshop. A comprehensive visioning process included more than 200 coastal experts to gather information prior to, during, and after the workshop, design the workshop format, prioritize outcomes, and include input from those unable to join the workshop during the meeting to best represent national challenges, priorities, and perspectives. This paper provides the foundational framework and context for articles in this dedicated issue.

The next two papers summarize the main findings from the workshop. In Part 1, Stockdon *et al.* present a vision for community-driven coastal science by first identifying the knowledge gaps and research needed to address these issues and then discussing the applied research necessary to achieve useful solutions, all informed through the decadal workshop. The authors introduce key research questions and recommended actions for a set of priority topics identified during the workshop which include:

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coastal flooding, morphodynamics and sediment transport, and ecosystem change and health. In order to make meaningful progress on advancing science and building coastal resilience, a multidisciplinary, co-developed, and stakeholder driven approach is essential. Additionally, a commitment to long-term data sets, cross-sector collaboration, and focus on translating scientific knowledge into action is necessary to create a strong foundation of research that supports science-based implementation and long-term resilience strategies.

In Part 2, Dusek *et al.* discuss the state of the science examining how coastal science advances are translated into operational tools and decision support applications for coastal managers. The rise of artificial intelligence and machine learning have transformed our ability to forecast coastal change with improved hazard modeling and enhanced environmental predictions. New innovations such as low-cost sensors have paved the way for higher-frequency and broader spatial coverage for coastal observations. Keeping pace with these new technologies and recognizing the integrated nature between scientific advancement and practical applied coastal management are essential for ensuring the science is robust, relevant, and useful to stakeholders.

Next, we turn to Briggs *et al.* for an update on the future of training coastal scientists and engineers. This comparative study provides an update from the

2018 assessment in terms of graduate programs, graduate student demographics, training, research funding, and workforce development. Using an online survey distributed in 2018, 2024, and again in 2025 through a coastal newsletter mailing list, the authors describe a changing landscape for the next generation of coastal scientists and engineers. Most academic institutions continue to report fewer funding opportunities that have impacted or will impact their ability to support graduate student research. The earlier 2018 data suggested most research conducted was basic while the 2024-2025 data showed higher amounts of applied research being conducted. Survey data from 2025 indicates that fundamental science and engineering courses are being taught less frequently. Despite a decrease in funding availability, academia-agency partnerships continue to be successful. The authors call for a coordinated effort between academia, federal agencies and industry to determine future workforce needs.

Valentine *et al.* discuss a theme heard throughout the 2024 workshop: the need for co-production research that engages inclusively across disciplines and communities from inception to delivery of transformational solutions. Their specific focus is on barriers that may be experienced by early-career researchers in participating in this type of work. In particular, early-career scientists may be new to organizations and/or geographic regions and under pressure to rapidly meet career path milestones (e.g., meeting goals for peer-review publications). Because co-production research is inherently founded on relationships and trust established across disciplines and communities, and the long-term nature in developing and transitioning solutions, early career researchers have experienced barriers to doing this type of work. The authors offer several practical mitigation strategies to engage newer career scientists and to highlight the critical nature of co-production work in closing the gap between research, policy action and actionable solutions.

Together, papers in this dedicated issue benchmark the present status and provide a trajectory for the future to advance coastal science and engineering research and solutions. We encourage readers to refer to this issue in identifying research priorities, future workforce development opportunities, and ideas relating to co-production solutions across disciplines and communities. The guest editors thank ASBPA staff for supporting this dedicated issue, as well as authors, workshop organizers, presenters and the broad coastal community who provided expertise summarized herein.

Julie Dean Rosati, Ph.D., P.E., is a coastal engineer with expertise in beaches, inlets, and barrier islands. In September 2025, she retired from the U.S. Army Engineer Research and Development Center's Coastal & Hydraulics Laboratory after a 44-year career. In June 2025, she joined the University of Florida as an Adjunct Lecturer to teach Littoral Processes. Rosati has a B.S. and M.Sc in Civil Engineering, and a Ph.D. in Oceanography, is a Professional Engineer in Mississippi, member of the American Society of Civil Engineers, member of ASBPA, and an Associate Editor for the ASCE Journal of Waterway, Port, Coastal, and Ocean Engineering. *She received ASBPA's M.P. O'Brien Award for outstanding contributions for the preservation and restoration of America's shorelines in 2023.*

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The future of coastal processes research: USCRP Decadal Visioning Workshop

By

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Manuscript submitted 1 May 2026, revised and accepted 15 May 2026.

Since its inception in 2015, the U.S. Coastal Research Program (USCRP) has enhanced the nation's coastal research capacity by coordinating federal initiatives, strengthening academic research programs, and promoting education in science, technology, engineering, and mathematics fields. The program also supports stakeholders in addressing their distinct challenges and improving the resilience of coastal communities. USCRP-funded research has tackled issues related to long-term coastal change, extreme events, and ecosystem and human health, all guided by the needs of those confronting challenges living and working along the coastline.

Over the past decade, the USCRP has promoted the transition from research to practical applications by encouraging early engagement with end-users in proposal guidelines and ensuring clear communication of research outcomes. This approach aims to facilitate the application of findings to real-world actions. USCRP amplifies the value and reach of coastal science by fostering partnerships, facilitating collaboration among multiple agencies, and strategically leveraging limited resources.

Coastal research needs are inherently interdisciplinary and often span across various agencies, frequently exceeding the capacity of any single organization. To address diverse science needs and perspectives, the USCRP regularly convenes the coastal science community (academics, federal agencies, and stakeholders, each with unique responsibilities for understanding and managing coastlines) to identify the most pressing coastal challenges shaping a collective research vision for the future. For example, in 2014, members of academia, industry, and federal agencies met to review the state of coastal science, discuss new and emerging directions and collaboratively develop a set of research priorities that would also provide significant societal impact (Elko *et al.* 2015).

The USCRP continued this model of convening the coastal community through thematic workshops on Dune Management Challenges (Elko *et al.* 2016), Coastal Storm Processes (Elko *et al.* 2019), and Human and Ecosystem Health (Elko *et al.* 2022), which were designed to support stakeholders and inform research directions. Over the past decade, these community-defined priorities steered research directions, including USCRP investments in over 90 research projects and two major collaborative initiatives: the large-scale community field experiment, DUring Nearshore Event eXperiment (DUNEX; Straub *et al.* 2023) and the 2025 Sediment Transport Collaborative Laboratory Experiment (SEDCOLAB).

Prioritizing management challenges and knowledge gaps

Given increasing environmental challenges affecting coastal areas, as well as significant advances in technology over the past decade, USCRP invited the coastal community to review the current status of science and management and establish research directions for the next decade. Technical experts, decision-makers, science funders, and coastal planners came together in 2024 in St. Petersburg, Florida, for the USCRP Decadal Visioning Workshop. The 116 attendees included academics (47%), federal representatives (38%), and stakeholders (15%).

The meeting was designed to share professional insights, explore the future direction of coastal research, identify key management challenges, and prioritize research addressing those challenges. The process of decadal visioning sessions, a tradition started in 1986 (Holman *et al.* 2015), ensures that USCRP remains responsive to developing needs and works collectively to advance coastal resilience and science for the benefit of communities nationwide.

To ensure that outcomes and final products were representative of the breadth and depth of the coastal science users and producers, USCRP, with the help of a professional facilitation team, led a multiphase approach to gathering input before, during, and after the meeting, which provided many opportunities for participation and increased the impact of workshop outcomes and recommendations. This approach included:

- Pre-workshop surveys and scoping sessions of USCRP members to build the agenda,
- In-person three-day workshop, with presentations, panel sessions, and breakout groups, to explore research questions to address community challenges, and
- Post-workshop survey to prioritize research needs.

The information gathered through this process was compiled by USCRP into a two-part, comprehensive final report to advance coastal science and build community resilience (Stockdon *et al.* 2026; Dusek *et al.* 2026). The two-part report will help guide USCRP investment in coastal research and future collaborative initiatives.

Laying the groundwork: Pre-workshop survey and scoping

To enable productive conversations between participants, gather input from those unable to attend the meeting, and strive for a national perspective, USCRP

Figure 1. Process diagram for designing the USCRP Decadal Visioning Workshop.

broadly distributed a set of pre-meeting questions to federal agencies, academics, and stakeholders (e.g., nongovernmental organization [NGOs], communities, state agencies). The surveys engaged participants to inform the workshop agenda by understanding their immediate (1-5 year) and long-term needs and priorities for coastal management, data and tools, research translation, and workforce development. Respondents were invited to virtual scoping sessions to offer additional context about their survey responses. The scoping sessions also allowed USCRP to seek feedback on draft agenda sessions and breakout session topics.

The stakeholder survey received 31 responses from coastal management, industry consultants, non-profit organizations, and state agencies, representing the majority of U.S. coastal regions: Northeast, Southeast, Great Lakes, Gulf Coast, West Coast, Hawaii, and Pacific Islands. Stakeholders identified resilience and coastal flooding as their immediate management challenges. A common concern among stakeholders is their lack of training in communications, despite the increasing demand to translate research findings for various audiences and formats. Stakeholders also identified limited staffing capacity for expertise in data analysis, geospatial analysis, and modeling.

The federal survey was completed by eight agencies from the USCRP Federal Team. Conversations with representatives from federal agencies were used to learn mission-specific coastal research needs, long-term priorities, and workforce development focuses. Responses from the National Oceanic and Atmospheric Administration, U.S. Geological Survey, U.S. Army Corps of Engineers, U.S. Department of Transportation, U.S. Naval Research Laboratory, National Aeronautics and Space Administration, Bureau of Ocean Energy Management, and the Federal Emergency Management Agency indicated that sediment transport and compound flooding were the top immediate coastal research needs. There was a strong demand for high-resolution observations, data visualization, and decision support tools, as well as design guidance to address long-term challenges. Additionally, federal partners identified essential technical skills required to enhance capacity in the coastal field and federal workforce.

The pre-workshop activities enabled organizers to identify challenges specific to a particular geography or role in coastal management. By including this diversity of perspectives, the meeting materials, discussions, and outcomes would be more representative of national concerns.

Collaborating for a united vision: A community workshop

An interdisciplinary steering committee organized an agenda of diverse presentations to establish a common starting ground and stimulate thinking, as well as breakout sessions to share perspectives and encourage conversation (Figure 1).

Presentations included a comprehensive review of previous coastal research visioning; progress priority themes -- extreme events, human and ecosystem health, and long-term coastal behavior; stakeholder perspectives; federal research priorities; current academic research; examples of co-produced solutions science and solutions; opportunities of applied research; and workforce development.

Six small breakout sessions facilitated in-depth discussions among professionals from a diverse mix of sectors and areas of expertise. The breakout discussions built upon each other throughout the workshop. First, they addressed community needs and challenges anticipated over the next ten years. Next, solutions to these challenges were discussed, followed by the tools and approaches necessary for implementing solutions. Finally, the groups discussed the research questions and data gaps that need to be addressed to meet these challenges effectively (Figure 1).

Breakout sessions focused on four priority topics that were determined in real-time during the workshop: Coastal Flooding, Adaptation, Ecosystem Changes and Habitat Distribution, and Water Quality. Sediment transport emerged as a science challenge that needed to be addressed in all topic areas. Each group's elected representative reported their find-

ings to the full audience following each breakout discussion.

The workshop left attendees hopeful, empowered, and committed to helping USCRP document the discussions and develop coastal research recommendations for the next decade.

Defining research priorities: Post-workshop survey and reporting

After reflecting and reviewing workshop notes and summaries, USCRP distributed a technical survey to the research community to refine priorities in coastal community challenges and cross-cutting themes. This survey aimed to prioritize basic and applied research topics for each challenge by ranking the topic's importance and urgency in being addressed. Respondents were routed to questions based on self-selecting their fields of expertise and asked to list any additional research questions.

Respondents indicated that Adaptation and Coastal Flooding are the most important issues to address, while Ecosystems, Sediment Transport, and Water Quality are seen as less critical, with a preference for focusing on Data, Models, and Methods over Collaboration and Social Science in coastal research applications.

USCRP organized report-writing teams to compile findings from workshop summaries and technical priorities. The result was a two-part, comprehensive final report detailing research priorities to advance coastal science and build community resilience (Stockdon *et al.* 2026; Dusek *et al.* 2026). USCRP envisions that academic institutions and federal agencies will leverage the work done by the program and integrate the findings and recommendations into their strategic research plans. USCRP aims to use these reports to inform program investments and to guide future collaborations.

SUMMARY

The visioning process involved over 200 coastal experts, including stakeholders, academics, and federal partners. The insights gained from the Decadal Visioning Workshop and continuous input from diverse coastal stakeholders reflect a collective commitment to addressing pressing issues and shaping the future of coastal management. As USCRP moves forward, the comprehensive findings and recommendations outlined in the two-part report will serve as a vital roadmap to guide investments, driving innovation and enhancing the resilience of coastal communities and ecosystems for generations to come.

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The future of coastal processes research, Part 1: A community-driven vision for the next decade of coastal science

By

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ABSTRACT

In June 2024, more than 100 professionals across coastal science and management disciplines — including academics, federal representatives, and community stakeholders—participated in the U.S. Coastal Research Program (USCRP) Decadal Visioning Workshop in St. Petersburg, Florida. This paper presents the primary management challenges identified by coastal communities, knowledge gaps and fundamental research to address these issues, and applied research essential to ensure that the science is useful and usable. A consensus emerged that improved understanding is needed on the following priority research topics: Coastal flooding, morphodynamics and sediment transport, and ecosystem change and health. Additionally, adaptation and applied coastal research, including observations, modeling, and decision support, were viewed as essential to ensuring that scientific information addresses user needs. We present key research questions for each topic area and offer a set of recommended actions, cutting across all topics, to make meaningful progress on advancing the science and building coastal resilience: (i) Embed social science into coastal research and community risk assessment; (ii) Enhance the translation and uptake of scientific knowledge; (iii) Collect more comprehensive and higher-resolution data; (iv) Maintain and share key open-source long-term national data sets and co-production platforms; (v) Develop coupled and holistic modeling frameworks; (vi) Strengthen promotion of integrated solutions; (vii) Apply artificial intelligence and machine learning technologies to data analysis and application; and (viii) Support funding mechanisms that advance interdisciplinary, holistic, community-driven solutions to coastal challenges.

KEYWORDS: Adaptation, applied research, coastal flooding, compound flooding, decision support, coastal ecosystems, interdisciplinary research, modeling, morphodynamics, observations, resilience, sea level rise, sediment transport, social science.

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This edition of *Shore & Beach* contains three complementary papers: "The future of coastal processes research: USCRP decadal visioning workshop," "The future of coastal processes research, Part 1: A community-driven vision for the next decade of coastal science," and "The future of coastal processes research, Part 2: State of the science." The workshop purpose, design, and general outcomes are presented in Elko and Stockdon (2026). This paper, Part 1, builds on the 2015 "Future of Nearshore Process Research" report (Elko *et al.* 2014), describing primary coastal management challenges, articulating key research to address these issues, and identifying applied research essential for meeting user needs. Part 2 (Dusek *et al.* 2026) provides a detailed description of the state of the science in alignment with the four key research areas outlined in Part 1.

Defining the coastal zone

Consistent with the 1972 Coastal Zone Management Act, the term "coastal zone" refers to the area where coastal waters and the adjacent shorelands interact and are strongly influenced by each other. This includes islands, transitional and intertidal areas, salt marshes, wetlands, and beaches. In the Great Lakes waters, the coastal zone extends to the international boundary between the United States and Canada and, in other areas, seaward to the outer limit of state ownership under the Submerged Lands Act (43 U.S.C. 1301 et seq.).

INTRODUCTION

The coastal zone of the United States is vital to the national economy and rapidly growing communities, supports critical ecosystems, and holds meaningful cultural and societal significance. While occupying less than 10% of the nation's land area, coastal counties support nearly 40% of the population (U.S. Census Bureau 2020) and underpin major infrastructure, transportation, security, and recreational systems. Coastal economies are sustained by key sectors such as maritime trade and tourism, with more than 73% of U.S. international goods (by weight) passing through coastal ports and an estimated 13.3 million U.S. jobs created (CMTS 2014). Beach tourism alone generates $520 billion annually (Houston 2024). Infrastructure for key U.S. military bases is located on or near the coast to ensure readiness and protect national security. In addition, coastal counties are home to a vast amount of the nation's energy infrastructure and major transportation hubs are concentrated by coastal metropolitan areas.

Coastal community challenges

The natural and societal systems integrated within these regions are dynamically evolving and increasingly vulnerable to changing environmental conditions. Sea level rise (SLR), chronic and acute shoreline erosion, intensifying storms, and changes in land use are driving compound risks and increasing impacts to communities, ecosystems, and resources. As evidence, from 2014 to 2024, 29 tropical cyclones caused over $820 billion in damage (2024 U.S. dollars) and more than 4,000 fatalities (NOAA NCEI 2024). As coastal regions continue to grow in value to the nation by providing significant economic trade, jobs, tourism, military security, and coastal hazard protection, so too does the need for strategies for adapting to future conditions, mitigating current and potential hazards, and preserving essential coastal functions.

The fundamental tension between the dynamic nature of coastal environments and the fixed nature of built infrastructure is a growing challenge. Coastal landscapes are naturally shaped by and evolve due to the interaction of physical and ecological processes; however, human modifications to coastal environments limit natural feedback mechanisms and compound the impact of disturbance events (May *et al.* 2023). Understanding and forecasting multidisciplinary coastal processes over time is crucial for developing proactive adaptation and management strategies that sustain healthy and productive coastal communities, economies, and ecosystems (NASEM 2025).

Coastal communities across the United States face interconnected challenges that threaten health and human safety, infrastructure, and the economy (Figure 1). Coastal flooding, driven by SLR, storm surge, waves, high tides, and heavy rainfall, is becoming more frequent and severe in many areas of the U.S., placing increasing pressure on vulnerable populations and aging infrastructure. Simultaneously, sediment transport and morphologic change — including shoreline erosion, barrier island migration, and altered estuary dynamics — can both influence and be influenced by extreme events, reshaping coastal landscapes and altering coastal resilience, including natural flood defenses.

These physical changes interact with ecosystem transformations, in some cases to detrimental effect. Habitat loss, nutrient loading, declining water quality, and shifts in salinity undermine the resilience and socio-economic benefits of wetlands, estuaries, and other critical ecosystems. To mitigate these conditions, coastal communities need information on holistic adaptation strategies that reduce hazard exposure and build long-term resilience. Strategies may include a mix of hardened and natural or nature-based solutions (NNBS), informed land use planning, and forward-looking policies that incorporate hazard projections, environmental dynamics, and community needs and values. Addressing these interconnected issues demands coordinated science and public engagement to ensure effective and sustainable decision-making (Kolesar *et al.* 2024).

Coastal scientific research to address societal needs

Over the past decade, the coastal research community has made significant progress in understanding extreme events (e.g., storms, flooding), applying new methodologies and technologies, and fostering interdisciplinary collaboration across natural systems, infrastructure, and communities (Dusek *et al.* 2026). Researchers have developed consensus tools for forecasting coastal flooding and harnessed the power of advanced observational technologies, such as drones, drifters, satellites, and remote- and shore-based sensing systems. Lower-cost instruments and citizen science initiatives have also expanded data collection capabilities and engaged stakeholders. Increased collaboration among interdisciplinary teams has advanced the state of the science and increased resilience for coastal landscapes. Yet critical knowledge gaps hinder our ability to more accurately predict coastal system response to complex storm forcing, long-term morphologic evolution, and ecosystem change — key processes shaping the coastal zone and impacting national interests and safety.

To identify and prioritize management challenges and scientific knowledge gaps for the upcoming decade, the U.S. Coastal Research Program (USCRP) coordinated efforts to engage the coastal community, including academics, federal representatives, and stakeholders, to assess user needs and review the current state of scientific knowledge (Elko *et al.* 2026). More than 100 professionals with diverse expertise and unique perspectives participated in the USCRP Decadal Visioning Workshop hosted in St. Petersburg, Florida, 11-13 June 2024. Through presentations, panel discussions, breakout sessions, and pre- and post-workshop surveys, attendees identified the primary management challenges faced by coastal communities and explored the scientific research necessary to address these issues.

A clear consensus emerged on the need to holistically increase coastal community resilience by focusing re-

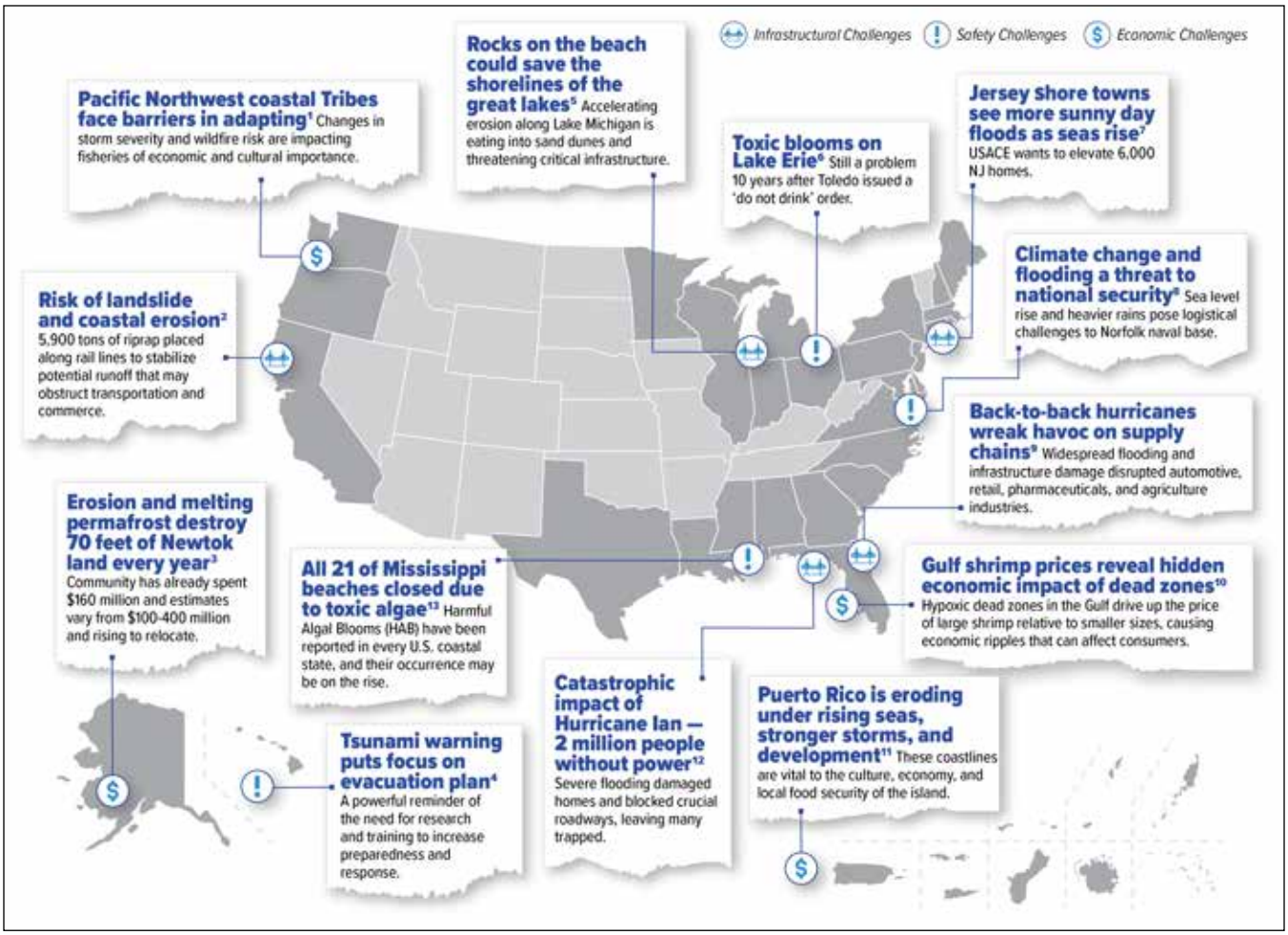


Figure 1. Examples of news article headlines of coastal challenges from across the United States and its territories including infrastructure damage, safety hazards, and economic losses, highlighting the urgent need for science-based strategies to build resilience in vulnerable coastal communities. Each headline is reproduced with attribution to its source: 1) *Coastside News* (2022); 2) *Los Angeles Times* (2025); 3) Associated Press (2024); 4) University of Hawai'i (2025); 5) Scienceline (2025); 6) Michigan Public (2024); 7) WHYY (2025); 8) PBS SoCal (2025); 9) ISM World (2024); 10) Lab Manager (2024); 11) Office of Representative Hernández, U.S. House of Representatives (2025); 12) CNBC (2022); 13) AL.com (2019). Complete headline citations are provided in the reference list.

sources and efforts on the following priority coastal science research topics: Coastal Flooding, Morphodynamics and Sediment Transport, and Ecosystem Change and Health. Additionally, several cross-cutting themes emerged across all topic areas related to the breadth of issues communities are facing. Adaptation and Applied Coastal Research, including Observations, Modeling, and Decision Support, were viewed as essential to ensuring that stakeholders have the science, tools, and guidance they need to address challenges along our coastlines.

Coastal ecosystems, communities, and infrastructure face multiple interacting hazards that can amplify one another. Continued development along coastlines increases the exposure of people, economies, and critical assets to these risks, while human activities such as pollution and wetland alteration diminish the natural capacity of coastal ecosystems to buffer impacts and sustain biodiversity. Coastal adaptation encompasses the actions taken to anticipate, respond to, and reduce the harms caused by these evolving hazards. Considering adaptation as a potential action also provides a unifying framework through which scientific understanding can be translated into practical solutions. Co-produced applied research that links fields such as oceanography, geomorphology, and ecology to engineering, social science, and policy, aligns observations, modeling, and knowledge production with the needs and values of coastal stakeholders. Communities, businesses, and governments determine when and how to adapt in ways that support long-term resilience and shared societal goals. Because individuals and groups often hold differing priorities and time horizons, decision support can aid adaptation by fostering collaboration, negotiation, and compromise. As social and environmental conditions continue to shift, coastal regions will increasingly rely on portfolios of flexible and evolving strategies — adaptation pathways — rather than any single, static solution to reduce future risk and foster resilient, thriving coastlines.

In the Coastal Scientific Research Challenges section, we discuss the three key coastal science research themes whose advancement over the next decade will provide foundational knowledge needed for understanding the complex processes shaping the coastal zone (Figure 2). The Meeting User Needs section provides details of how basic research can be translated into applied science coastal stakeholders can use to inform urgent and

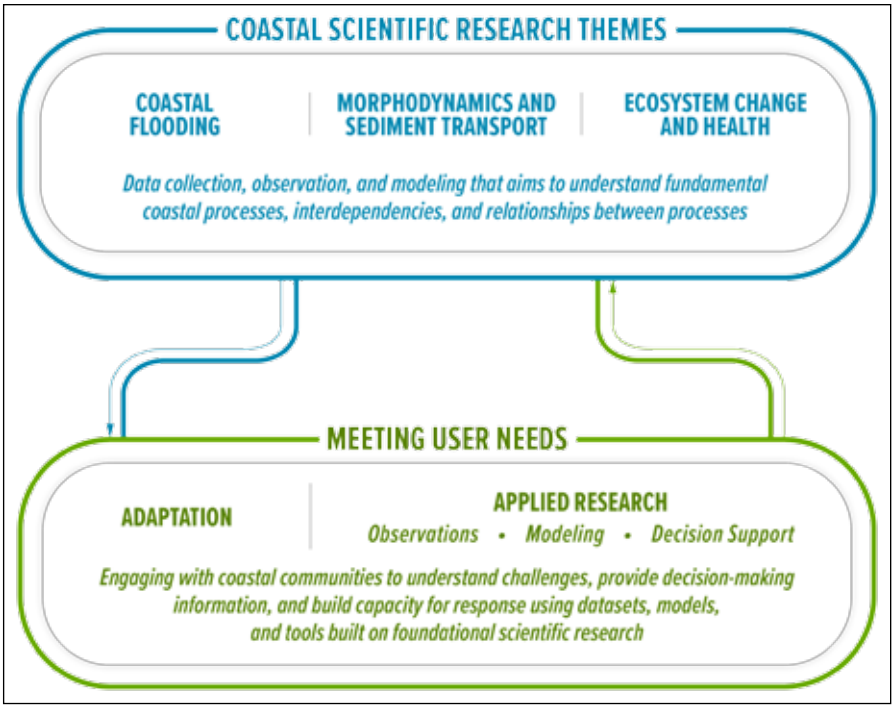


Figure 2. Priority topics for fundamental and applied research, as identified by the coastal science community, that aim to meet user needs addressing challenges along our nation's coasts.

consequential decisions and develop effective adaptation plans for reducing risk and building resilience (Figure 2). We close with a series of specific recommendations for making significant advances in these areas and meaningful progress on providing scientific information to help address national coastal challenges.

COASTAL SCIENTIFIC RESEARCH CHALLENGES

Coastal zones are dynamic, with changes driven by coupled physical, chemical, and biological processes operating across a wide range of spatial and temporal scales. Advancing fundamental research on coastal flooding, morphodynamics and sediment transport, and ecosystem change and health is critical for improving basic understanding of processes and impacts. Investing in coastal science will enhance the observational and predictive frameworks necessary to create innovative solutions, guide evidence-based adaptation strategies, and address management challenges in a changing coastal environment.

Coastal flooding

Coastal flooding represents one of the most pressing and complex hazards facing coastal communities and ecosystems. From 2015 to 2024, coastal flooding due to hurricanes, atmospheric rivers, and extra-tropical storms resulted in billions of dollars in damage (NCEI 2024). Future SLR and changes in storm frequency and intensity will continue to increase both the severity of impacts and the population exposed to flood events (Barnard *et al.* 2025). Although severe storm events draw much attention, recurrent or chronic flooding can be equally problematic. For example, the Intergovernmental Panel on Climate Change (IPCC) has called chronic flooding "the most urgent adaptation challenge" for coastal communities (Cooley *et al.* 2022). To manage flood risk now and into the future, decision-makers require detailed knowledge of where and why flooding occurs, as well as accurate predictions of flood extent, frequency, and severity. The processes driving coastal flooding are complex, operating across a range of time scales, from hundreds of years to hours, and across different environments, from natural to urban (Woodworth *et al.* 2019; Vitousek *et al.* 2017). Thus, understanding the physical mechanisms behind flooding events, their interactions, and their future occurrence and trajectories remains a central challenge for coastal science.

Defining the problem

Greater understanding of locally-specific coastal flooding depends on science to predict the extent, frequency, and severity of inundation. This includes interactions between coastal storms (surge and waves associated with hurricanes and extra-tropical storms), atmospheric rivers, sea level rise, precipitation events, and tides, and connections with fluvial systems, urban infrastructure, and groundwater.

Spatial and temporal variability in coastal flood processes have implications for how flooding is observed, modeled, and communicated (Figure 3). Processes like storm surge, waves, and rainfall can be generated by tropical and extra-tropical storms, are usually short-lived (lasting from hours to days), and confined to relatively local areas. Tides operate on predictable daily to twice-daily cycles, with changes occurring over weeks, months, seasons, and years. While tides across large regions may operate similarly, site-specific geography like the shape of the coastline or estuary can influence local variation in timing and range. Sea level anomalies represent the deviation of mean sea level from normal and vary over seasonal to annual time scales. They are often driven by large-scale climate or oceanic variability such as shifts in ocean currents or wind, and typically impact regional stretches of coastline. Processes such as SLR and vertical land motion typically operate globally and regionally over decades to centuries. Finally, local coastal morphology shapes how water flows and accumulates. Together, these processes shape flooding patterns at the coast. For example, storms such as hurricanes and nor'easters can generate significant short-term surges, which are amplified by SLR. SLR also increases baseline high tide levels, which has at least doubled chronic, high tide flooding at the coast over the last two decades in some locations (Sweet *et al.* 2022). Changes to land and morphology, such as subsidence, beach erosion, and wetland loss, can exacerbate flood impacts, while urban development, infrastructure, and poor drainage further heighten flood risk.

Recent advances in flood monitoring and modeling are providing data and forecasting necessary for communities to help understand flooding processes, prepare for future hazards, and reduce risk. Observations of coastal water level and overland flooding have advanced with a suite of in situ sensors, remote sensing

technologies, and crowdsourced data, enabling better real-time flood monitoring and impact assessment. In situ observations include federally sustained, national observing networks and, more recently, have expanded to community-led low-cost sensors (Silverman *et al.* 2022; Hernandez *et al.* 2025). Remote sensing spans space-based observations (Vignudelli *et al.* 2019; Schumann 2024) to those collected from aircraft, uncrewed aerial vehicles (Over *et al.* 2021), and stationary cameras (Dusek *et al.* 2019). Crowdsourcing of flood information is relatively nascent, but the collection of social media posts, images, and other web-based data has the potential to provide additional insights.

Flood prediction for forecasts, operations, hindcasts, and future scenarios are simulated through several numerical, data-driven (statistical or machine-learning), and hybrid modeling approaches. Numerical models can provide detailed, physics-based simulations of surge and wave dynamics and are typically run in two- or three-dimensional configurations. Recent improvements in application to flood modeling include the assimilation of measurements such as tide gauge observations (Rose *et al.* 2024). Reduced-physics and hybrid models improve the computational efficiency of flood modeling by either simplifying the governing equations representing the physical system or using surrogate techniques, which are simplified models that approximate the response of full numerical simulations. Model coupling has improved predictions by linking inland and coastal processes, facilitating the simulation of multiple flooding types, and predicting future flooding scenarios. See Part 2 of this paper in this issue, ("State of the science" (Dusek *et al.* 2026), for more discussion of recent advances.

Chronic high tide flooding

While advances have been made in flood observation and prediction, challenges remain, providing opportunities for expanding our knowledge. For example, flood modeling capabilities do not adequately capture the complexity of coastal flooding driven by the interplay of multiple factors such as storm surge, tides, waves, precipitation, groundwater, and drainage, leading to incomplete risk assessments. Additionally, there is difficulty in accurately representing small-scale features and feedback from evolving land use. For example, increased infrastructure such as roads and buildings can influence flood trajectories, timings, and magnitudes, and alter flooding patterns from what was historically observed. Further, challenges exist with adequately representing antecedent conditions, such as saturated ground, when modeling future coastal flooding. Current research priorities are aimed at better understanding drivers of coastal flooding, observing and quantifying chronic flood hazards, better accounting for changing coastal morphology and measuring and quantifying flood impacts.

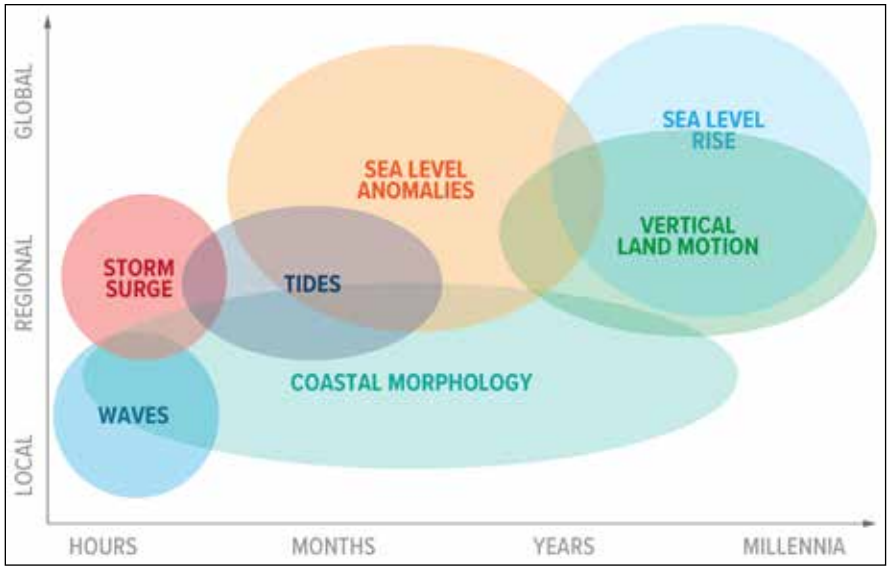


Figure 3. Schematic illustrating the different natural processes contributing to coastal flooding over different time periods (hours to millennia) and distances (local to global). (Based on Rodriguez *et al.* 2024.)

Understanding the drivers of coastal flood events

Coastal flooding often arises from the convergence of multiple natural drivers such as storm surge, waves, tides, rainfall, streamflow, and groundwater—termed "compound flooding" (Figure 4). Traditional flood models often fail to accurately simulate these interactions, leading to mischaracterizations of flood risk. Understanding coincident processes, such as waves and storm surge, and developing appropriate timeframes for capturing and examining joint behavior are key to accurately characterize future coastal flood risk (Green *et al.* 2025). Challenges include observing and modeling how multiple flood processes interact in different ways, especially at the subsurface level. For example, high tide flooding can be driven by compounding precipitation and high coastal water level interactions within drainage infrastructure (Thelen *et*

Chronic high tide flooding

Like many locations across the United States, Charleston, South Carolina, is experiencing the impacts of chronic, high tide flooding events—overwhelmed drainage systems and flooded roads (NOAA 2022). Many of the city's stormwater outfalls drain into tidally influenced bodies of water, where rising sea levels and high tides fill the system, reducing drainage capacity and causing flooding (City of Charleston 2024, 2019). The closer a rain event occurs to a high tide, the greater the flooding, as the excess water has nowhere to go. There have been 96 flood days* recorded at the Charleston tide gauge in the decade 2015-2024, compared to a total of 54 flood days over the previous 94 years of tide gauge observations (1921-2014) (NOAA 2025c).

*Flood days are calculated based on exceeding a NOAA-derived flood threshold for the Charleston, South Carolina, tide gauge that is approximately 1.87 ft above mean higher high water (MHHW).

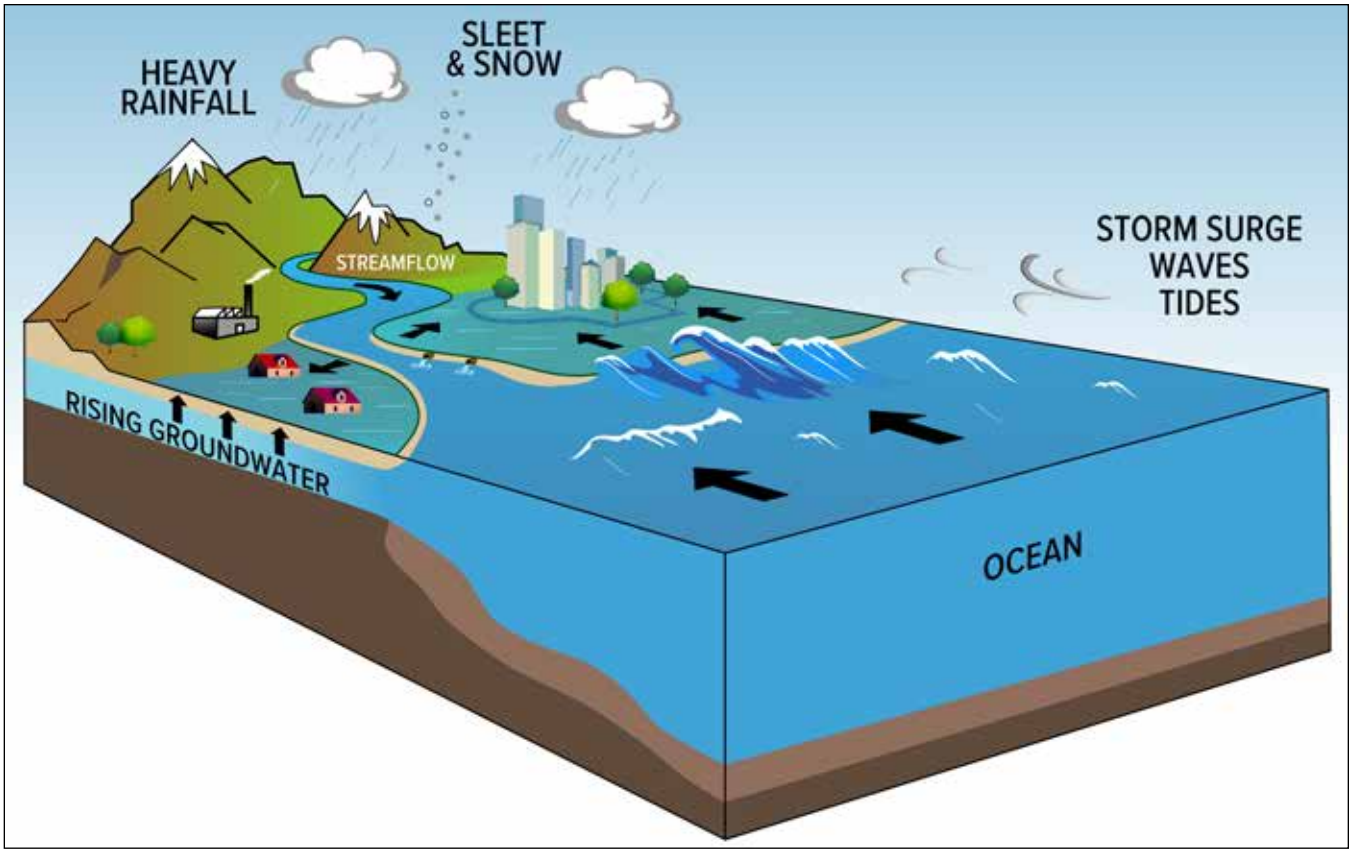


Figure 4. Schematic depicting the combined influence of coastal and inland hydrologic processes contributing to compound flooding. Key drivers include wind waves, tides, storm surge, high streamflow, precipitation, and elevated groundwater levels. Morphological features such as seafloor slope, land elevation, vegetation type, and substrate composition also play a significant role. The figure is conceptual and not to scale. (Modified from Green *et al.* 2025.)

al. 2024), which is especially important in highly populated, urban areas. This necessitates the use of pipe flow models accounting for storm water drainage and the inclusion of groundwater along low gradient coastlines. Due to the complexity, assessing the risk of compound events remains a challenge, even as data-driven and physical models improve.

Sea level anomalies (seasonal to annual deviations from mean sea level) can contribute significantly to coastal flooding by elevating coastal water levels, but because they are often a lower-magnitude process compared to storm surge, their importance and contribution can be overlooked. The linkage between sea level anomalies and climate variability has the potential to enable skillful prediction of anomalies on monthly to annual time scales (Shin and Newman 2021); however, the ability to predict anomalies with climate or statistical modeling approaches remains limited (Widlansky *et al.* 2017; Long *et al.* 2021; Frederikse *et al.* 2022). Limitations with both reanalysis and seasonal model predictions of sea level variability means that there are presently no skillful predictions of sea level anomalies along the U.S. east coast, even for a short lead time such as three months (Long *et al.* 2025). There are opportunities to improve skill for sea level anomaly prediction, especially by leveraging data-driven and artificial intelligence (AI) methodologies.

Observing and quantifying flood hazards from chronic events

To avoid increased losses, coastal communities should prepare not only for rare, acute flooding events but also the growing impacts of chronic, minor flooding driven by rising seas. For example, the occurrence of high tide flooding is accelerating with increasing SLR in locations along the U.S. coastline (Sweet *et al.* 2018). Though the extent and depth of inundation of high tide flooding is typically minor (Moftakhari *et al.* 2018), the cumulative cost of frequent events over time may exceed the cost of extreme events (Moftakhari *et al.* 2017b).

This growing challenge has led to the development of models to predict high tide flooding occurrence on seasonal (e.g., Dusek *et al.* 2022), annual (e.g., Sweet *et al.* 2020) and decadal (e.g., Thompson *et al.* 2021) time scales. However, due to logistical challenges, there are a limited number of observations of flooding during these chronic events. While the availability of remote-sensed data has increased flood-event observations, especially in data-sparse regions, the spatiotemporal coverage of satellite images does not provide high enough resolution for validating flood models at a variety of scales (Jafarzadegan *et al.* 2023), or may have too long of a revisit time to capture a short-lived event like that of a high-tide flood. Opportunities exist for the development of new types of sensors, such as pressure sensors and cameras in storm water drains to confirm flood occurrence (e.g., Gold *et al.* 2023; Hino *et al.* 2025), and methods, especially those leveraging AI, to observe the extent and depth of high-tide floods.

The impact of changing coastal morphology

Because coastal water levels respond to and can change morphology, knowledge of coastal elevation and shape, including dune elevations, beach slopes, and

nearshore bathymetry, is necessary for accurate predictions of flooding and its impacts (Sallenger 2000). Coastal elevation data are integral to empirical formulations of wave run-up on sandy beaches (e.g., Stockdon *et al.* 2006) and in other environments (Poate *et al.* 2016; Conlin *et al.* 2025). However, observations of morphology are often temporally sparse compared to the resolution of flood forcings, and most flood predictions are numerically modeled using static topography and bathymetry, not including real-time morphological change due to high water levels and waves. This is usually because regional topo-bathy surveys are infrequent, leading to outdated initial conditions in flood modeling. Additionally, storm events make it difficult to sample morphology in real time. However, new applications of technology are providing opportunities for better data collection. Collaborative field experiments — like the During Nearshore Event Experiment (DUNEX; Straub *et al.* 2023) or the Natural Hazards Engineering Research Infrastructure (NHERI) Natural Hazards Reconnaissance (RAPID) Facility — enable rapid deployment of scientists, equipment, and processing of data to prioritize extreme/acute events and capture critical information in both hydrodynamic and morphologic forcing before, during, and after an event occurs (Berman *et al.* 2020).

Rising sea levels are expected to exponentially increase wave overtopping of land-based features, such as dunes and seawalls (Almar *et al.* 2021). Thus, accurately characterizing wave overtopping is a fundamental challenge in coastal flooding applications (Gallien *et al.* 2014, 2018). Estimating overtopping volumes presents a number of challenges such as accurately representing nearshore wave transformation, beach topography, and the timing of the wave event with elevated coastal water levels.

Understanding flood impacts

Knowing how a flood actually impacts people, infrastructure, and places is a key component of flood forecasting, warning, and coastal adaptation. While impacts from flood events are often quantified using direct damages and economic losses, cascading impacts of flooding such as commute disruption (Jacobs *et al.* 2018; Kasmalkar *et al.* 2020; Hauer *et al.* 2023), isolation from emergency access (Logan *et al.* 2023), business losses (Hino *et al.* 2019), water-quality risks (Carr *et al.* 2024), long-term health impacts, and mortality risk (Mueller *et al.* 2024) are harder to quantify. Metrics related to community impacts may be more accessible and understandable to people when weighing risk as compared to physical variables like flood depth or extent. At the same time, it may be preferable to communicate flood risks using clear, accessible language and to frame these risks in both quantitative and qualitative terms (Luke *et al.* 2018). The complexity and importance of the social dimension in flood risk management is crucial for understanding risk perception and tolerance, community engagement. and policy development.

Key research questions for coastal flooding

1) How do landscape and morphology changes affect coastal flooding over short and long timescales?

Using static morphology and topography in models fails to account for dynamic changes in the landscape, which may introduce significant errors in flood prediction. Over both short and long timescales, factors like erosion, sedimentation, urbanization, or vegetation growth can alter the topography and influence how water flows and accumulates. Beach morphology is also a necessary input to wave run-up and overtopping models and often changes dynamically during a storm. The improved ability to predict morphodynamics and sediment transport (see next section) is fundamental to advancing these priorities. This involves:

- Sampling morphologic change in real time during flooding events to improve understanding of feedback between hydrodynamics and morphology.
- Integrating up-to-date and dynamic topography — from field observations to modeling — to enhance the accuracy of flood models and reveal how morphological changes influence flooding processes.
- Incorporating recent, real-time and modeled data on topography and coastal change, such as erosion, urban development, and vegetation shifts, into flood models to improve timeliness and predictive accuracy across short- and long-term timescales.

2) How do multiple processes contribute to and/or exacerbate flooding hazards?

Chronic and acute flooding are driven by multiple processes at the coast. Historically, ocean processes (waves, tides, storm surges) are treated separately from freshwater processes (streamflow, rainfall) or subsurface (groundwater or stormwater) processes. To develop a full understanding of coastal flooding, improve forecasts, and develop optimal adaptations, research is needed to:

- Identify the most important, or combination of, processes that influence flooding. For example, high-tide flooding can overtop flood barriers from both the ocean and inland water ways, as well as bubble up through drainage infrastructure, resulting from a combination of both short-term events and longer-term variability.
- Understand the feedback between surface flooding and subsurface processes (e.g., groundwater and stormwater networks) to improve predictions of high-tide flooding across timescales.
- Advance observation and modeling frameworks that capture the compounding effects of oceanic, freshwater, and subsurface processes to more accurately assess and manage flooding risks.
- Develop and deploy high-resolution (temporal and spatial), real-time observation systems to capture both chronic and extreme coastal flooding events.

3) How do both chronic and extreme coastal flooding impact people and communities, and how are risks most effectively communicated?

Flooding occurs across many coastal communities, and understanding its impacts is essential for effective flood forecasting, warning, mitigation, and coastal adaptation. While direct economic losses from flood events are often quantified, cascading losses are harder to measure yet are crucial for fully grasping community impact. By integrating social science with traditional flood risk management approaches, we can create more holistic and effective strategies to mitigate flood impacts. Key for addressing this question is:

- Improving documentation of the cascading human and environmental impacts of chronic and extreme flooding,
- Integrating indirect and cascading effects into flood modeling.

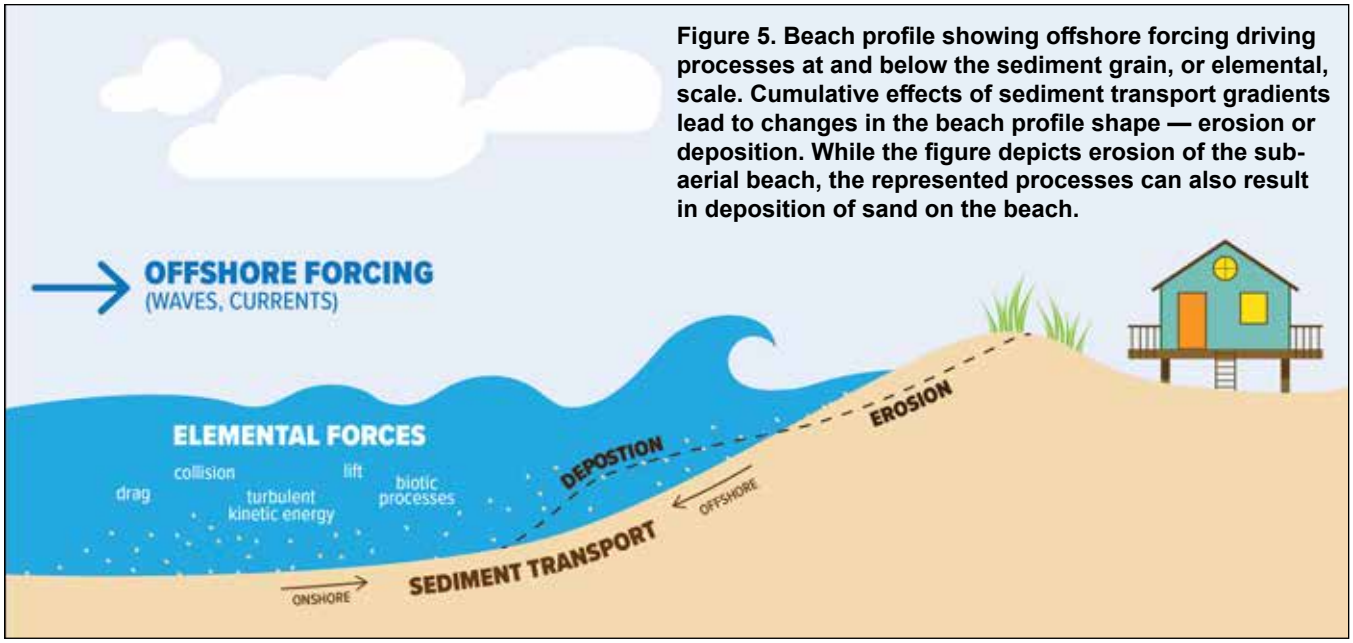


Figure 5. Beach profile showing offshore forcing driving processes at and below the sediment grain, or elemental, scale. Cumulative effects of sediment transport gradients lead to changes in the beach profile shape — erosion or deposition. While the figure depicts erosion of the subaerial beach, the represented processes can also result in deposition of sand on the beach.

● Exploring and expanding the role of narrative (e.g., storytelling), visual, and experiential communication strategies in enhancing public engagement with and response to flood risk.

Morphodynamics and sediment transport

Improved knowledge of sediment transport processes is critical for coastal populations impacted by beach erosion, accretion, coastal hazards, inlet migration, and coastal squeeze, where shorelines cannot retreat naturally due to development and infrastructure. With an understanding of short- and long-term coastal evolution, the strategic placement of sediment, alone or in along with nature-based, hybrid, and/or hard structures, has potential to reduce damages, improve safety, and decrease long-term costs. Consideration of sediment transport processes that spans a wide range of temporal and spatial scales, as well as the interaction between scales, would improve planning, designing, and maintaining these solutions. The study of coastal morphodynamics, or the interaction between morphology (shape and structure) and hydrodynamics (waves, currents, tides), is inherently complicated given the range of spatial and temporal scales, internal feedback, external constraints (e.g., pre-existing conditions and atmospheric and oceanic forcing), and interactions with geology, biology, ecology, and engineering. A quantitative understanding and predictive capability for these processes is crucial for forecasting coastal changes and maintaining or constructing natural or built protections against short-term hazards like coastal storms and long-term trends like SLR (NASEM 2025).

Defining the problem

Improved understanding and prediction of sediment transport processes and coastal response on short-, medium-, and long-term temporal and spatial scales is essential for addressing societal challenges related to coastal change, including beach erosion, barrier island migration, and inlet shifts. Improved ability to predict morphodynamics, including interactions with vegetation and nature-based, built, or hybrid coastal structures, will lead to better forecasts of potential impacts from hazards like hurricanes and SLR, as well as for development of adaptation plans to reduce risk and build resiliency.

Coastal morphodynamics are driven by small-scale, short-term sediment transport processes that accumulate over time, leading to larger-scale changes such as erosion and accretion (Figure 5). Small-scale processes operate over spatial scales from granular (mm) to wave orbital (cm-m) and occur on time scales ranging from fractions of a second to a few minutes. Medium-scale processes, spanning hourly to multi-year fluctuations, are important for understanding sediment budgets and coastal system evolution. Large-scale coastal change integrates smaller-scale dynamics and is influenced by weather and oceanic conditions over time scales of decades. Predicting sediment transport at these different scales is essential for building an understanding of local processes, developing engineering solutions, and managing coastal risks. A variety of models are used to simulate and forecast morphodynamic changes, although a lack of observations hinders forcing and validation and predictive capabilities are often poor. Additionally, there are challenges in predicting cohesive sediment transport in dynamic environments — particularly in estuaries — and the resulting ecological impacts (Allen *et al.* 2021).

Transport at the local scale

Sediment transport measurements on short temporal and spatial scales are fundamental to improving knowledge and predictive capability. The relative magnitudes and importance of bedload and suspended load across the nearshore is unknown, impacting predictive capability due to inaccurate sediment transport partitioning. Progress in quantifying sediment transport rates and modes is hampered by lack of instrumentation. No direct sediment transport sensor exists, due to the unavoidable interaction of the sensor with even simple fluid-flow fields. Instead, sediment transport rates are most commonly estimated using the product of water velocity and sediment concentration measurements. Velocity measurements can be routinely acquired using acoustic Doppler and other sensors. However, few commercial optical or

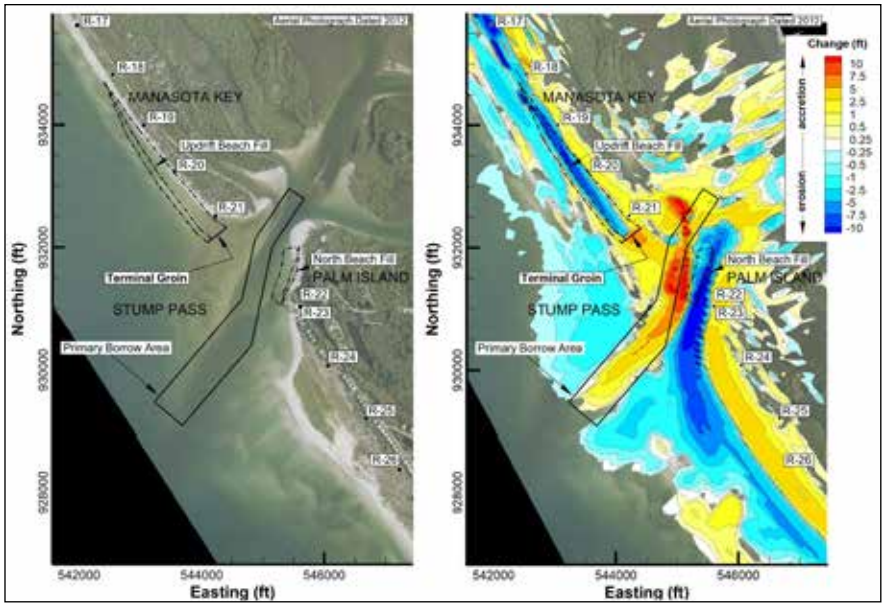
acoustic sensors for sediment concentration exist and are prone to error in bubbly environments, such as areas with intense wave breaking. More information on small-scale sediment transport, including references to recent advances, can be found in Part 2 of this paper (Dusek *et al.* 2026).

Transport at the solutions scale

Sediment transport measurements and modeling at medium- to longer-term scales lead to engineering solutions and future adaptation pathways. For example, sequential storm events and post-storm recovery of the beach and dune influence morphodynamics over many years (Dissanayake *et al.* 2015; Coco *et al.* 2014; Burvingt and Castelle 2023). Post-storm beach-dune recovery is primarily affected by wind, or aeolian, processes. As such, aeolian transport models (e.g., Duran and Moore 2013; van Westen *et al.* 2024; Cohn *et al.* 2019) are expanding the capabilities to predict ecological feedback and sediment connectivity. Strengthening the representation of these processes will improve simulations on timescales of years to decades (Elko *et al.* 2016; Sherwood *et al.* 2022). Key data and research needs are (1) expanding time series of morphodynamic observations beyond post-storm datasets to include seasonal and interannual beach-dune dynamics (Conlin *et al.* 2020) and evolution for model validation and (2) developing modeling techniques that incorporate uncertainty, including simulated processes and the feedback between them (Ruessink 2005; Wilson 2023) and errors in hydrodynamic forcing (Chataigner *et al.* 2022; d'Anna *et al.* 2021; Ibaceta *et al.* 2020; Kroon *et al.* 2020; Montaño *et al.* 2020; Simmons and Splinter 2022; Splinter and Coco 2021; Vitousek *et al.* 2021).

Spanning scales and expanding applicability

Simulating morphodynamic processes at relevant scales with appropriate levels of fidelity requires better quantification of the role of large-scale feedback mechanisms. New multi-scale, probabilistic models are needed to comprehensively assess coastal changes across a range of temporal and spatial scales (Ranasinghe 2020), evaluate impacts to infrastructure (Anarde *et al.* 2018), and develop coastal hazards adaptation needs. Other challenges include better understanding of processes in non-typical coastal environments, such as Arctic coastal regions where erosion is driven by changing sea ice conditions and melting permafrost, or places where other geotechnical, ecological, or hydrological processes influence large-scale coastal morphodynamics.



Sediment transport modeling to inform coastal protection design

The Stump Pass (Florida) area is heavily used for recreation. In 2018, it was determined that inlet and beaches at Manasota Key and Palm Island required stabilization and protection. Coastal consultants used numerical models to understand sediment transport processes shaping the beaches and inlet and to test alternatives engineering design. Ultimately, a terminal groin and beach nourishment were identified as the best approach for coastal protection. The aerial photo on the left shows the planned locations of the borrow pit, beach fill, and proposed groin. The image on the right shows predicted elevation changes over four years based on local sediment transport. Project conducted by Coastal Engineering Consultants, Bonita Springs, Florida.

Physical understanding of nearshore hydrodynamics is robust, and various numerical models enable accurate simulations of hydrodynamics at high spatial and temporal resolution. However, there is a challenge upscaling hydrodynamic modeling from turbulence to intra-wave processes to wave-averaged processes. Thus, it is currently not practical to use turbulence-resolving models (Tsai *et al.* 2024) to predict field-scale coastal morphodynamics. See Part 2 of this paper (Dusek *et al.* 2026) for a more detailed discussion of models and their limitations.

Additionally, there is a lack of agreement on what fundamental processes and relationships are needed for predicting sediment transport magnitudes. For example, more than 10 different formulas currently exist for estimating wave-driven sediment transport rates (Wengrove *et al.* 2019). Some formulas yield accurate predictions under a particular set of circumstances but will fail under other circumstances. No unifying theory or principles exist to determine which of these formulas is objectively correct or what fundamental processes are missing. If needed to improve predictions, it is critical that the theory integrate from the small-scale (Finn *et al.* 2016; Mathieu *et al.* 2025) up through large-scale processes. If a unified theory proves impractical, researchers could instead develop a modified predictive model framework for sediment transport using observational and/or high-fidelity simulation data to define the relationship between parameters. There may be direct parallels to the field of nearshore hydrodynamics (Galvin 1967) prior to the introduction of radiation stress theory

(i.e., momentum fluxes due to waves, Longuet-Higgins and Stewart 1964), which led to the subsequent rapid growth of theoretical and applied research in the 1970s to 1990s. In parallel, developing new parameterizations or surrogate modeling using artificial intelligence (AI) and machine learning (ML) for coastal processes including morphodynamics is gaining traction (e.g., Goldstein and Plant 2019; Chen *et al.* 2023).

Key research questions for morphodynamics and sediment transport

1) How important are grain-scale processes in altering larger scale sediment transport?

Uncertainties and inaccuracies in sediment dynamics modeling in coastal environments could result from ignoring the variability of geomechanical properties. Beaches composed of heterogeneous, or mixed-grain-sized, sediments experience various levels of bed shear stress and intergranular fluid processes. Strength and textural properties are often assumed constants; however, sediment-scale properties can deviate significantly from standard values (Stark *et al.* 2014, 2017) and hydraulic conductivity variations can significantly alter infiltration/exfiltration and swash flows (Horn 2006). New methods of measuring sediment transport, including in-situ and remote sensing, have led to improved data sets (Albatal *et al.* 2019; Stark *et al.* 2021; Brilli and Stark 2024); however, advanced approaches are still necessary to improve understanding of sediment transport, including the following:

- Include simultaneous measurements of geomechanics, sediment dynamics, morphodynamics, and hydrodynamic forcing.
- Integrate geomechanics into improved sediment transport simulations.
- Prioritize vertical, cross-shore, and alongshore measurements to capture fine-scale variability and improve understanding of morphology and bedforms despite logistical challenges.
- Develop advanced sensors, remote sensing, and increased spatial-temporal data collection within and beyond project boundaries.

2) Is a radically different framework required for sediment transport than for morphodynamics predictions?

Data-driven approaches may revolutionize sediment transport predictions by circumventing the challenge of resolving turbulence and intra-wave processes (Wei and Davison 2022; Schanta 2025) in larger scale models. Data-driven models will require vast amounts of training and validation data. Available remotely sensed data can provide detailed boundary conditions, land classification, and soil classification assisting in ML techniques. Additionally, the use of ML and AI-driven models is emerging in coastal sciences to classify land cover, predict shoreline change, or simulate estuarine morphology. (See Part 2 of this paper [Dusek *et al.* 2026] for additional detail.) The following would accelerate future model development and experimentation using data-driven approaches:

- Widely accepted practice of openly disseminating data from high-resolution models (for applications to surrogate modeling), laboratory experiments, and field observations (e.g. U.S. Army Corps of Engineers (USACE) Field Research Facility Data Portal; Ludka *et al.*, 2019).
- Standardized model training data (which observations and under what range of conditions) and expansion of existing databases.
- Improved dialogue between the numerical modeling and experimentalist communities to bridge the gap in understanding of complex sediment transport processes.

3) How can human interventions and ecological processes be used together to affect morphodynamics in a way that benefits both society and nature?

NNBS are increasingly used within environmental management, coastal engineering designs, and USACE civil works projects to address chronic erosion and SLR. For a complete decision-support framework for large-scale morphodynamics, inclusion of human behavior and intervention is needed (e.g., National Science Foundation Coastlines and People Initiative; Lazarus *et al.* 2016). Along developed shorelines, comprehensive models that incorporate structures with physical processes are needed for diverse environments (e.g., dunes, beaches, wetlands, buildings, roadways) to guide policy and project management (Elko *et al.* 2016; Daylander *et al.* 2016). Effective integration of human influence into predictive models requires transparent communication between researchers and stakeholders and accessible data across a range of stakeholder networks. Research and application essential for advancing this integration include:

- Collaborative decision-analytic frameworks and the inclusion of stakeholders and community members from project initiation to design planning.
- Improved ability to model the links between physical, biological, and geomechanical processes across scales to inform specific policy and management decisions.
- Standard codes and best practices for NNBS installation.
- Experiments to determine which are the most appropriate and effective NNBS for local community, morphology, and forcing conditions.

Ecosystem change and health

Coastal ecosystems, encompassing dunes, beaches, marshes, tidal flats, and nearshore waters, are dynamic interfaces that connect terrestrial and aquatic systems and support critical ecological and physical processes, such as sediment transport, tidal exchange, nutrient cycling, and habitat connectivity. These areas create a zone of resilience by providing essential benefits that sustain both people and nature: absorbing floodwaters, stabilizing shorelines, filtering pollutants, supporting fisheries and recreation, and protecting infrastructure. When this area is lost or constricted, so too are the services it provides, leaving communities more vulnerable to erosion, storms, and habitat decline.

Coastal squeeze is degrading wetlands, dunes, and other environments that once absorbed floodwaters, cycled nutrients, served as carbon sinks, provided habitat to a diverse range of species, and sustained fisheries and recreation. As ecosystems lose their capacity to adapt, the consequences extend beyond the environment to infrastructure, economies, and public safety. Addressing this decline requires not only protecting what remains but also scaling ecosystem restoration and natural infrastructure to match the scope of the challenge. When restored, coastal ecosystems recover remarkable functionality — dune vegetation rebuilds storm buffers, marshes filter water and sequester carbon, and oyster reefs, seagrass beds, and corals enhance biodiversity

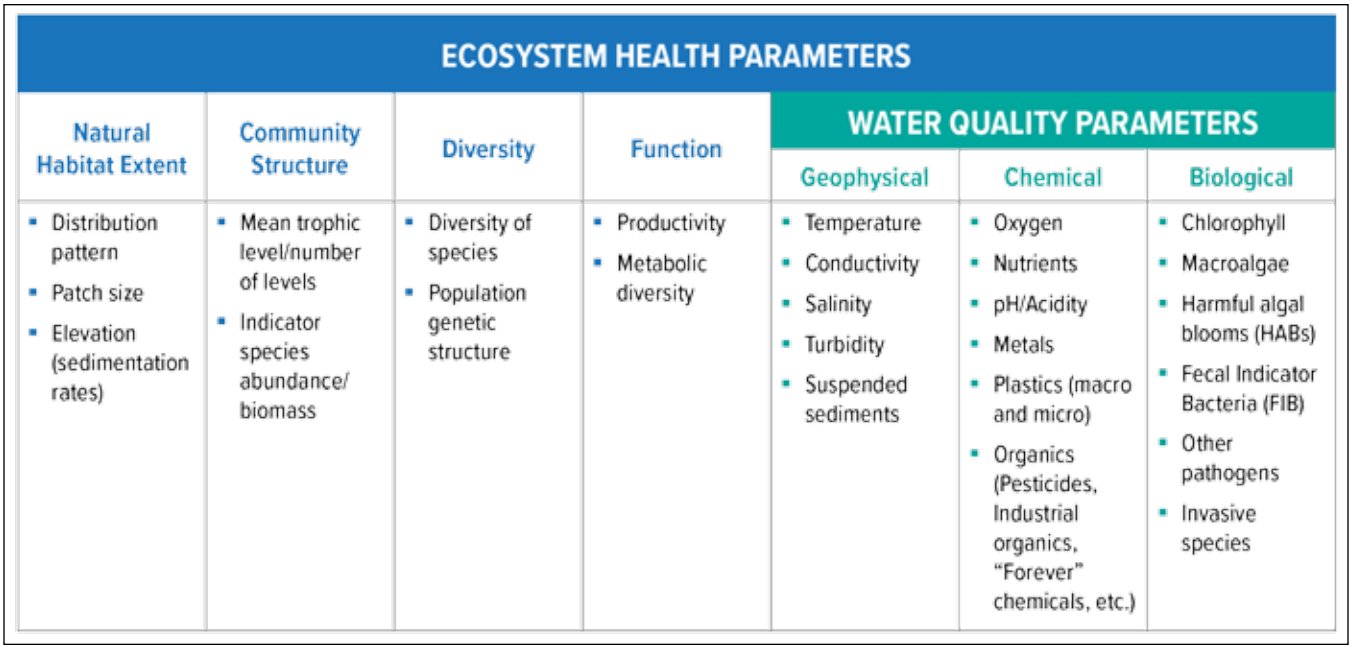


Figure 6. A nonexhaustive list of ecosystem health and water quality parameters (e.g., Boesch and Paul 2001; Neckles *et al.* 2012; Yu *et al.* 2022; Elko *et al.* 2022; Hannides *et al.* 2021).

and reduce wave energy (Perricone *et al.* 2023). These natural systems collectively provide the foundation for resilient coasts, supporting the environmental, economic, and social needs upon which communities depend. In recognition of these benefits, scientists, engineers, and decision-makers are increasingly co-developing NNBS that integrate ecological principles with engineering practices to enhance coastal resilience and restore the health of our nation's resilience zones.

Natural features such as coastal dunes and their vegetation exemplify these benefits, functioning as living infrastructure that stabilizes sediment, buffers storm surge, and sustains unique habitats. Vegetation traits such as root depth, rhizome structure, and biomass directly influence dune stability and erosion resistance, while dune health also depends on natural processes such as wrack deposition that promote sediment capture and nutrient cycling (Provost *et al.* 2022; White *et al.* 2024). Studies across U.S. coasts demonstrate that dunes with diverse native vegetation significantly reduce storm-related damages, highlighting their economic and ecological value (Sigren *et al.* 2018; Morton *et al.* 2025). However, over-stabilization of shorelines through armoring, and development-driven coastal squeeze, can diminish biodiversity and adaptive capacity (Lansu *et al.* 2025). Restoration that re-establishes native plants, natural sand transport, and organic inputs has proven effective in restoring both ecosystem function and protection even on urbanized coasts (Johnston *et al.* 2023; White *et al.* 2024). Federal agencies such as USACE and the National Oceanic and Atmospheric Administration (NOAA) have advanced these approaches through programs that integrate engineering and natural processes to build long-term coastal resilience.

Healthy coastal ecosystems are defined as resilient and able to maintain their productivity and organizational complexity in the face of change (Rapport *et al.* 1998). There are many key and contributing parameters governing ecosystem health (Figure 6). Single contributing parameters can be used to assess a specific aspect of health, such as using oxygen concentrations and hypoxia as measures of water quality. However, a holistic assessment of ecosystem health requires the integration of the values of multiple parameters into an aggregated status indicator. An example of such an approach, the U.S. National Estuarine Eutrophication Assessment state determination (Bricker *et al.* 2007), is shown in Figure 7.

Defining the problem

Healthy coastal ecosystems provide significant benefits for coastal communities. These systems naturally reduce impacts of coastal hazards, serve as vital economic drivers for the nation (fisheries, recreation, tourism, and real estate) and support human and environmental health. Threats to important ecosystem functions include eutrophication, hypoxia, acidification, harmful algal blooms (HABs), human pathogen contamination, habitat transformation, and species and diversity loss. Understanding how coastal ecosystems and water quality change under natural and anthropogenic forcing is key to sustaining essential services for the future.

Sustaining ecosystem health in the face of coastal changes requires both monitoring of current conditions and modeling to forecast future states. Advances in environmental monitoring have revolutionized how scientists observe and understand ecosystem health and water quality. Technological progress has enabled increasingly detailed, frequent, and wide-ranging measurements of environmental parameters. However, while sensor technology has improved data collection for physical and chemical parameters, biological and microbial monitoring still relies heavily on traditional methods and human labor (Graham *et al.* 2022). Issues such as biofouling, cost, and human interference hamper the broader use of advanced sensors (Johnson and Coletti 2002; Pellerin *et al.* 2016). Monitoring of pathogens,

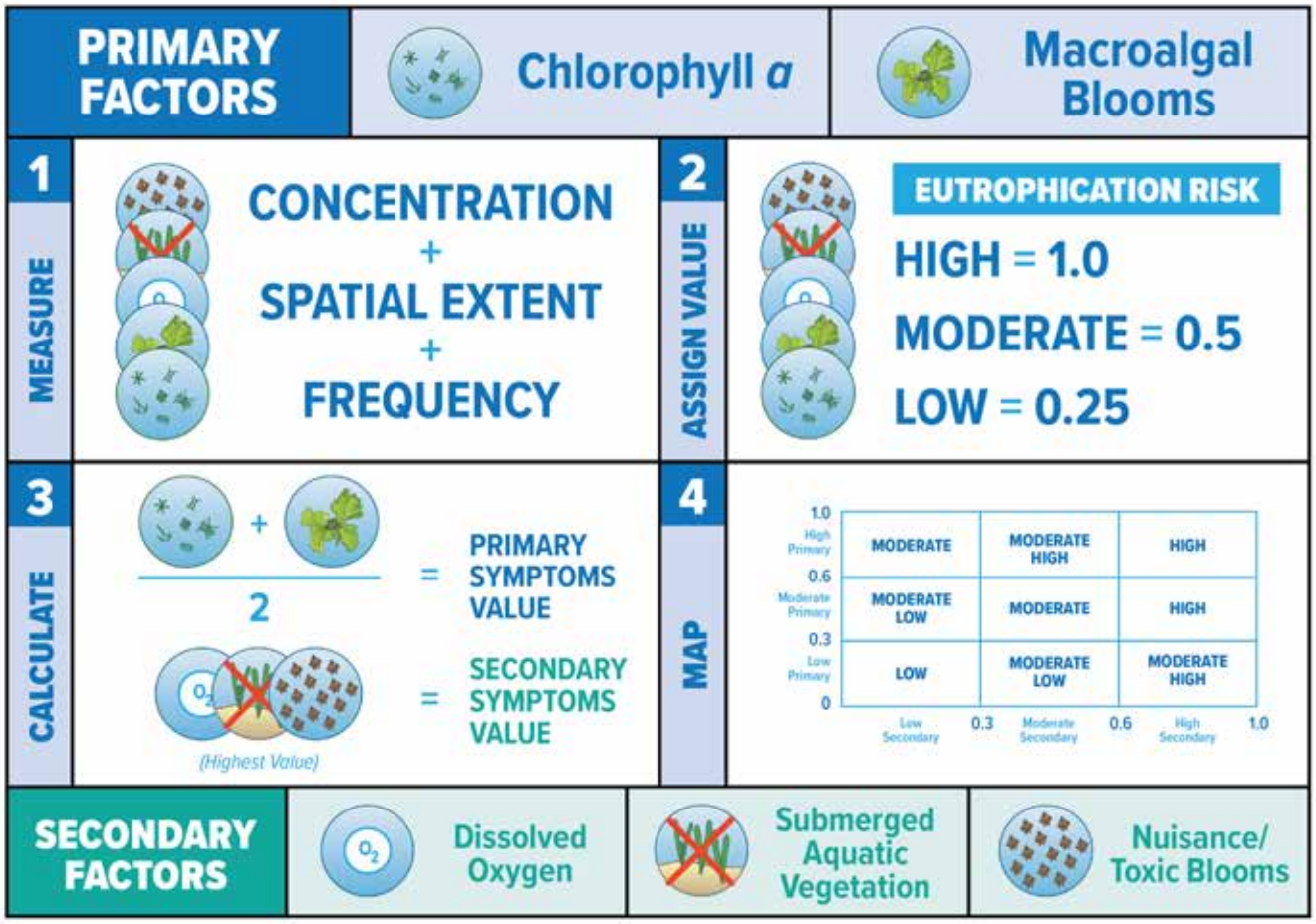


Figure 7. The process of estuarine eutrophication assessment (Bricker *et al.* 2007) through which measurements of numerous parameters are integrated to express an overall eutrophication risk/status.

HABs, and habitat change is extensive but often patchy (see reviews in Elko *et al.* 2022; Hannides *et al.* 2021), with emerging tools such as environmental DNA (eDNA) and remote sensing offering promising improvements (Ventura *et al.* 2023; Goodwin *et al.* 2024). Sediment and groundwater monitoring lag behind, despite their importance in carrying and storing pollutants (Halliday and Gast 2011; Herren *et al.* 2021) and in understanding saltwater intrusion and rising groundwater tables.

Ecosystem modeling efforts range from data integration for multi-parameter ecosystem health and water quality assessments (e.g., the Water Quality Index, Uddin *et al.* 2021) to predictive nowcasting/forecasting models (e.g., for fecal indicator bacteria and HABs [Searcy *et al.* 2006; Francy *et al.* 2019]) that aim to identify risks to the health of ecosystems and humans. Predictive models are already tied to decision-making procedures that dovetail with public outreach and citizen input initiatives, such as public health warning-and-response systems using web portals that project nowcasting outcomes and risks or closures to the public (EPA 2024; University of South Carolina *et al.* 2025). Comprehensive decision-making at the ecosystem-wide or regional level relies on holistic schemes, like the Ecosystem-Based Management approach (NOAA 2025a; Ray 2023; NOAA Fisheries 2024), that incorporate not only synergistic effects of various parameters/processes but also human activities and socio-economic factors.

For increased understanding of ecosystem health and water quality, it is essential to focus on the following topics: (1) system-level impacts and dynamics rather than individual components of a system; (2) improved accuracy of forecasting and modeling tools; and (3) development of appropriate decision-support tools and inputs for policy development and management.

Ecosystem health and water quality are governed by a range of processes: hydrodynamic, biological, chemical, geological, ecological, and anthropogenic, as well as the interplay between these processes. Integrating numerous, often discipline-specific streams of knowledge to evaluate system-level dynamics is a key need for understanding ecosystem health and water quality. These approaches are needed to determine priorities for data gathering and modeling (O'Brien *et al.* 2016), to evaluate multi-stressor impacts on ecosystems and water quality, including rapid response to emergent threats (Gunderson *et al.* 2016), and to identify metrics of coastal ecosystem health and resilience (Capotondi *et al.* 2019; O'Brien *et al.* 2016).

Finally, as for all the research themes presented, integrated approaches and forecasting would ideally be usable for policy development and management. Decision-support tools are used to put research and monitoring outcomes into practice (see Applied Research section). For example, defining the role and prioritization of NNBS is an ongoing challenge. The utility of specific NNBS and their long-term performance need to be both rigorously studied and communicated to policymakers and stakeholders (Bridges

et al. 2022). Development of standardized methods, model parameterizations, ecosystem health indicators, and best practices and performance metrics will enable widespread application of forecasting and response tools that can be applied to local and regional issues (e.g., EPA 2025a).

Key research questions for ecosystem change and health

1) How do we define and evaluate ecosystem health?

A holistic ecosystem health evaluation encompasses a broad range of dimensions and considerations. Critical observations of processes span spatial scales, from individual plants to entire watersheds, and temporal scales, from wave orbital and tidal periods to season and annual cycles. Connection between and integration across the different scales is needed to address multiscale problems (Dickey and Bidigare 2005). Specifically:

- Ecosystem characteristics that are strongly interdependent across species, habitats, and trophic levels, including plankton/microbiota, algae, plants, invertebrates, and vertebrates, should be evaluated, quantified, and ultimately predicted (Ventura *et al.* 2023; Capotondi *et al.* 2019).

- Human societies, their activities, and their impacts on coastal ecosystem function and change are often inextricable from the above and, thus, could be integrated into this evaluation to improve accuracy (NOAA 2025a).

- Given the variability of ecological indicators for a functioning ecosystem across regions, location-specific research is needed to specify evaluation approaches, models, and management strategies.

2) To what degree have connections across major fundamental processes and disciplines been identified, parameterized, and modeled?

Conceptualization of the connections between fundamental processes has improved on some topics, such as eutrophication, hypoxia, acidification, and HABs (Hall *et al.* 2024), but it remains under development in others, such as the effects of vegetation and oyster reefs on sedimentation/erosion (e.g., Conde-Frias *et al.* 2023), long-term sustainability of NNBS (Palinkas *et al.* 2022), and marine disease transmission (Shore and Caldwell 2019; Sullivan *et al.* 2018). Approaches to identify or utilize cross-discipline connections include:

- Co-located observations and measurements of multidisciplinary parameters and processes.

- Real-time ecological forecasting tools that integrate ML, data assimilation, and digital twins with uncertainty quantification.

- Multi-scale modeling of NNBS, from the individual organism to the population/community and landscape scale, to incorporate both hydrodynamic effect and environmental factors, like larval transport and environmental stressors (Elko *et al.* 2022).

- Multidisciplinary collaboration between marine ecologists, coastal scientists, and climatologists to improve predictions of biological responses coupled to physical drivers.

- Clearly defined best practices for ecosystem restoration (e.g., seed-based vs. transplant-based restoration of seagrass; Orth *et al.* 2020, Gräfnings *et al.* 2023) that incorporate guidance across major disciplines.

3) How can data collection and modeling best inform guidance and reinforce and build decision-support tools?

The development of widely adopted guidelines and best practices for modeling and data collection will help improve feedback between the two. This includes:

- Standardization of methods and intercomparison exercises within monitoring networks that allow for continuous assessment and improvement (e.g., EPA 2025a).

- Development of universal indices of ecosystem health or other ways of synthesizing novel data streams (Minello *et al.* 2021; Ridge and Johnston 2020; Ramírez *et al.* 2023).

- Development of more accurate and accessible decision-support tools that can be used by policymakers and communities, which will be aided by method standardization where possible and appropriate.

4) How can we monitor, measure, and manage ecosystem health to sustain resilience across regions and time?

The holistic evaluation outlined in Question 1 is supported by effective monitoring. Management of ecosystem health will benefit from the development of adaptive frameworks that translate complex ecological processes into actionable, decision-relevant information. Research is needed to:

- Develop adaptive monitoring systems that evolve with changing environmental conditions and new scientific

A nearshore Gulf of Maine water sample full of *Tripos muelleri* collected in May 2023. Photo courtesy Joe Vallino, Marine Biological Laboratory.

Confluence of environmental issues

In the summer of 2023, an unusually large bloom of brown algae, the phytoplankton *Tripos muelleri*, developed in the Gulf of Maine, stretching from Massachusetts to Maine (Ray 2023; NOAA Fisheries 2024). Researchers at the University of New Hampshire monitored the eutrophic bloom and found that it coincided with the lowest carbon dioxide levels and highest pH levels in surface water in the 20 years that researchers have been monitoring the gulf, contrary to acidification trends elsewhere (Stewart *et al.* 2025). While the phytoplankton itself was not toxic to humans or animals (thus technically not a harmful algal bloom), the murky bloom did significantly block light to submerged vegetation, clog marine filters, and threaten the stock of lobster and other shellfish through oxygen drawdown. Researchers struggled to understand the cause of the bloom and how to predict future blooms, noting that this is an especially urgent issue as the Gulf of Maine is among the fastest warming regions in the world (Stewart *et al.* 2025).

understanding, linking short-term indicators of ecosystem condition to long-term trends in resilience and recovery (Thrush *et al.* 2021).

- Establish universal, measurable indicators and dynamic thresholds of coastal ecosystem health across physical, biological, and chemical domains (e.g., vegetation cover, sediment stability, nutrient cycling, biodiversity, and habitat connectivity), that can distinguish between natural variability, gradual change, and early warning signs of degradation (Rapport *et al.* 1998; Bricker *et al.* 2007).

- Determine the appropriate temporal and spatial scales for observation and management, ensuring that monitoring captures both fine-scale dynamics and regional-to-national trends while aligning with the multiscale evaluation approaches described in Question 1.

- Integrate monitoring outcomes into adaptive management and policy frameworks, establishing mechanisms that enable managers to act before ecological thresholds are crossed and clarifying institutional roles and responsibilities for sustained long-term observation (NOAA 2025a; EPA 2025b).

- Leverage data synthesis, modeling, and visualization tools to connect site-based monitoring with broader ecosystem health assessments, supporting cross-regional comparisons and continuous learning across diverse geomorphic and ecological contexts.

MEETING USER NEEDS

Addressing society's most pressing coastal challenges requires an interdisciplinary approach with experts from many sectors working together with those in the communities who are facing threats of coastal hazards, resource loss, and habitat shifts (NASEM 2025). Fundamental physical science, as previously discussed, provides information about system processes, interdependencies, and feedback. Applied coastal research, when science is used to solve specific problems, is where investment in fundamental science begins to pay off for end users. Here, scientific understanding of coastal systems is translated into information, methods, and tools for those living and working along coastlines. Applied coastal research, including observations, modeling, and decision-support tools (DST), serves many types of end users such as federal and state government agencies, non-governmental organizations (NGOs), consultants, emergency managers, and coastal community members.

Social science is essential for helping span boundaries between biophysical research and stakeholder needs. This field of practice can bridge science and practical application through communication across disciplines and organizations and the consideration of their different incentives, values, and informational needs (Goodrich *et al.* 2020). Over the last decade, there has been a national focus on supporting the flow of research to operations or applications, encouraging early engagement with end users, and clear communication of research outcomes to ensure application to real-world actions.

Management for coastal adaptation provides a framework through which scientific understanding can be translated into practical solutions for a wide range of users. Adaptation integrates the complex issues of environmental change (e.g., flooding and erosion), ecosystem health, and socioeconomic development under a common goal: building resilience in coastal communities. While there are still many technical and social challenges remaining, from event scale to long-term resilience, this approach fosters collaboration and compromise across different sectors and disciplines.

Here we discuss cross-cutting themes that emerged in the USCRP Decadal Visioning Workshop as essential to stakeholders. Coastal adaptation and applied research, including observations, modeling, and DST, were identified as top priorities in providing the public with the information needed to make informed decisions and effectively address coastal hazards (Dusek *et al.* 2026).

Adaptation to coastal hazards

Coastal adaptation describes actions taken to prepare for, respond to, and reduce the harms caused by changing and evolving coastal hazards. Across the United States, the rate and scale of coastal adaptation, although growing, is still generally insufficient to address both current and future risks. Therefore, more sustained collaborations between researchers and practitioners are needed to develop innovative adaptation strategies, overcome barriers to adaptation implementation, and assess the performance of adaptation portfolios over time.

Adaptations may take many forms and can affect all aspects of a coastal socioeconomic system, including people, livelihoods, ecosystems and species, environmental services, infrastructure, and economic, social, and cultural assets (IPCC 2022). Adaptation strategies are generally categorized as resistance, accommodation, avoidance, or relocation (Figure 8). Adaptation efforts have traditionally focused on individual projects designed to address specific environmental hazards (e.g., extensive beach nourishment projects following Hurricane Sandy). However, multiple hazards can compound at the same time, as when a hurricane hits a region already experiencing severe coastal erosion.

Hazards can also accumulate over time. For example, long-term coastal erosion slowly narrows beaches, reducing resiliency and threatening infrastructure. Natural hazards like flooding and erosion also interact with social, economic, and technical drivers to increase risk, as when an industrial accident pollutes wetlands and reduces their ability to absorb rainfall, or to decrease risk, as when a new building code requires higher home elevations or floodproofing measures to protect residents (IPCC 2022; Zscheischler *et al.* 2018; Simpson *et al.* 2023). As more communities experience these types of compounding events, coastal decision-makers increasingly seek adaptation portfolios—collections of strategies rather than isolated actions—that address multiple hazards and that consider how natural and human systems interact (Kopp *et al.* 2019; Sandifer *et al.* 2021; Peek *et al.* 2020; Haasnoot *et al.* 2013).

The United States currently lacks sufficient coastal adaptation due to a combination of factors (Wasley *et al.* 2023). In the U.S., some coastal communities continue to build and expand infrastructure in hazard-prone areas without advance planning for risk mitigation (Agopian *et al.* 2024; Wing *et al.* 2018). A lack of standardized methods to assess adaptation actions contributes to uneven implementation (Berrang-Ford *et al.* 2021; Cabana *et al.* 2023) and raises the potential for ineffective projects or even maladaptation—adaptation actions that inadvertently cause harm, such as a seawall that cuts off critical sediment supply (Correll-Brown *et al.* 2022). The complexity presents a challenge and opportunity to creatively explore innovative

Figure 8. Examples of coastal adaptation strategies — resist, accommodate, avoid, or relocate (Doberstein *et al.* 2018) — and representative infrastructure and management sites. Images are reproduced with permission from (upper left) U.S. National Park Service (2019), Seawalls, Bulkheads, and Revetments; (upper right) NOAA National Ocean Service (2021); (lower left) City of Newport Community Development Department (2016); (lower right) U.S. National Park Service (n.d.), Cape Hatteras Light Station. Complete citations appear in the reference list.

methods of science-practice collaboration and communication.

Increasing the practice of adaptation

While many communities are aware of coastal challenges that they face, adaptation in practice is still limited (Magnan *et al.* 2023; Simpson *et al.* 2023). There are a range of opportunities for improvement; all need additional research and development, including:

- **Capacity building:** Coastal resiliency requires planning and action across sectors by decision-makers with varied backgrounds and expertise. Many communities and organizations have limited capacity to adapt due to financial, physical, psychological, informational or knowledge constraints (Klein *et al.* 2014). For example, a small town with limited employees and a smaller tax base may not have the capacity or resources for developing and implementing a comprehensive adaptation strategy. Building working partnerships between researchers and community partners, and across disciplines, agencies, and professions will better support productive collaborative research and application (e.g., Schmidt *et al.* 2025).

- **Science communication and community uptake of existing resources:** Tools exist to help communities develop long-term plans and adaptation portfolios, such as scenario planning, future visioning, and dynamic adaptation policy pathways, but they are not yet widely used (Haasnoot *et al.* 2013; see box). Scientific advances and methods, such as improved forecasts of future hazards and their effects on social and physical systems or coupled natural human systems models that help assess the likely effects of adaptation actions, are also available but not yet widely implemented. Information and tools are more readily adopted when they are accessible, relevant, trusted, understandable, and presented in a usable format (Jagannathan *et al.* 2020; Bamzai-Dodson *et al.* 2023; Goolsby *et al.* 2023). In the coming decade, the coastal scientific community can significantly advance the extent to which tools, data, and knowledge are delivered in a useful and usable manner. More transdisciplinary research approaches could be especially useful as these teams challenge traditional norms and invite creativity and collaboration (Ross and Mitchell 2018). Co-developed research with communities and partners does not stop at the end of a funding cycle, stressing the importance of research institutions, boundary organizations, and funders developing plans for sustaining continuity of relationships.

- **Guidance documents and tools for adaptation actions:** Developing practical and accessible tools and guidance documents in collaboration with end users, centered around community needs, will build capacity and increase adaptation practice by ensuring the tools are in fact useful and usable (Eisenack *et al.* 2014; Bamzai-Dodson *et al.* 2021). For engineers, these could be guidelines for the design of hybrid and nature-based strategies for coastal protection. For coastal planners, these could include decision frameworks that enable planning for coastal change and for the impact of cascading hazards. For community members, clear information about how coastal hazards are likely to affect their properties and livelihoods would enable more risk-informed decisions. Access to information and tools is important to enable **all** communities and residents to make informed decisions (e.g., White *et al.* 2010).

A systems approach to adaptation

A key effort for coastal resilience in the coming decade involves shifting from isolated, project-based adaptation efforts, including studies and assessments, toward a systems approach of integrated, long-term adaptation portfolios and pathways (Figure 9; Hossain *et al.* 2024). Traditional approaches that emphasize isolated infrastructure projects or one-time policy interventions often fail to account for: (i) the ways that multiple hazards interact; (ii) the way hazards, infrastructure, and communities change over time; and (iii) the ways that actions add up over time and across space. A single coastal homeowner may build a seawall, for example, without considering how the adjacent coast will be affected or the impacts if all their neighbors also build seawalls.

A systems approach to adaptation will require additional research to understand how adaptation actions interact with one another, how local efforts accumulate over space or time, and how different local communities interact (Hossain *et al.* 2024). These efforts will require new types of data — such as time-series evaluations of adaptation actions, assessments of cumulative impacts, and long-term monitoring systems tied to decision-relevant thresholds. A systems approach to adaptation may also require research into emerging innovations and transformative strategies, the drivers for and barriers to transformative change, and shifts in both the framing and methods of adaptation research.

Developing long-term flexible portfolios of adaptation strategies can be demanding. Using established frameworks, such as the Dynamic Adaptation Policy Pathways (DAPP; Haasnoot *et al.* 2013; see Part 2 of this paper [Dusek *et al.* 2026] for additional details) can help communities address this challenge. These frameworks could be improved by adaptation assessment research that helps communities consider the suitability and sustainability of adaptation strategies in their context. Adaptation pathway models currently include a limited set of strategies and could increase their emphasis on supporting community innovation to address coastal hazards creatively.

Adaptation decision-making processes, and research to inform and evaluate adaptation decisions and actions, are more likely to avoid inadvertent harms (maladaptation) and to produce multiple benefits when they involve a wide range of stakeholders, include multiple knowledge sources (e.g. scientific, local, Indigenous), and consider numerous social dimensions (Collini *et al.* 2022). Exploring how diverse knowledge systems and sources can be brought into meaningful dialogue, and how institutions can build the trust, capacity, and mechanisms required to support inclusive, multi-scalar, and adaptive planning processes (Ross *et al.* 2015; Khalil *et al.* 2016) are examples of research activities needed to improve adaptation decision-making. Involving a wider set of goals, adaptation options, and knowledge sources may also require rethinking how "data" is defined and used in decision-making contexts (Kolesar *et al.* 2024).

Adaptation pathways

Adaptation pathways are practices designed to help communities, businesses, governments, and other organizations plan out sequences of future actions that will be taken to address potential hazards and to respond to uncertainty and unforeseen events (Haasnoot *et al.* 2024). Numerous types of pathways analyses exist and are used in a wide range of strategic planning contexts. What makes adaptive pathways unique is the process of considering future uncertainties and planning for future flexibility to develop strategies that can respond to changing conditions (Werners *et al.* 2021). For example, a community might identify a pathway that involves building dunes for short-term coastal flood protection, while also adopting a building elevation requirement so that by the time the coast has eroded making the dunes unstable, the homes on the coast are elevated and will face less damage from floods

Key research questions for adaptation to coastal hazards

1) What factors limit local capacity to engage in coastal adaptation, and how can those barriers be reduced?

Research on capacity and barriers exists but has not been frequently translated into improved capacity (or is implemented through ad hoc processes) (Lipiec *et al.* 2018; Williams *et al.* 2020). Barriers can be reduced with:

- Fine-scale data on the financial, institutional, and social capacity of local governments and communities to implement adaptation.
- Synthesis of local case studies to inform generalizable patterns and scalable best practices (Dupuis and Biesbroek 2013).
- Consistent data collection methods to facilitate cross-case analyses.
- Training for physical scientists and engineers in the use of adaptation pathways and creation of practices to integrate more disciplines into adaptation pathways analyses.

2) What mechanisms best support the uptake and use of scientific information in local adaptation decision-making?

There is an enduring gap between adaptation research and implementation (UNEP 2024). One step to close this gap requires research on science communication practices and improved research-practice partnerships. Research to identify and co-develop effective visualization tools, platforms, and data content and formats is needed to shape both science communication and adaptation practice. Additionally, research is needed to identify the methods and information that support innovation, creation, and piloting of new adaptation options. The coastal scientific community can also address these gaps by developing standard practices and training in science communication, partnerships, and collaborative research. Essential for supporting the use of scientific information for decision-making are:

- Shared knowledge and best practices of science, risk, and decision analysis communication and information services;
- Training in co-development and partnership to produce actionable data (Goolsby *et al.* 2023);
- Interdisciplinary collaborations (e.g., with communications researchers) on effective data visualizations and communication strategies;
- Dissemination of information at user-relevant scales (e.g., parcel-by-parcel for landowners) through existing and widely used platforms;

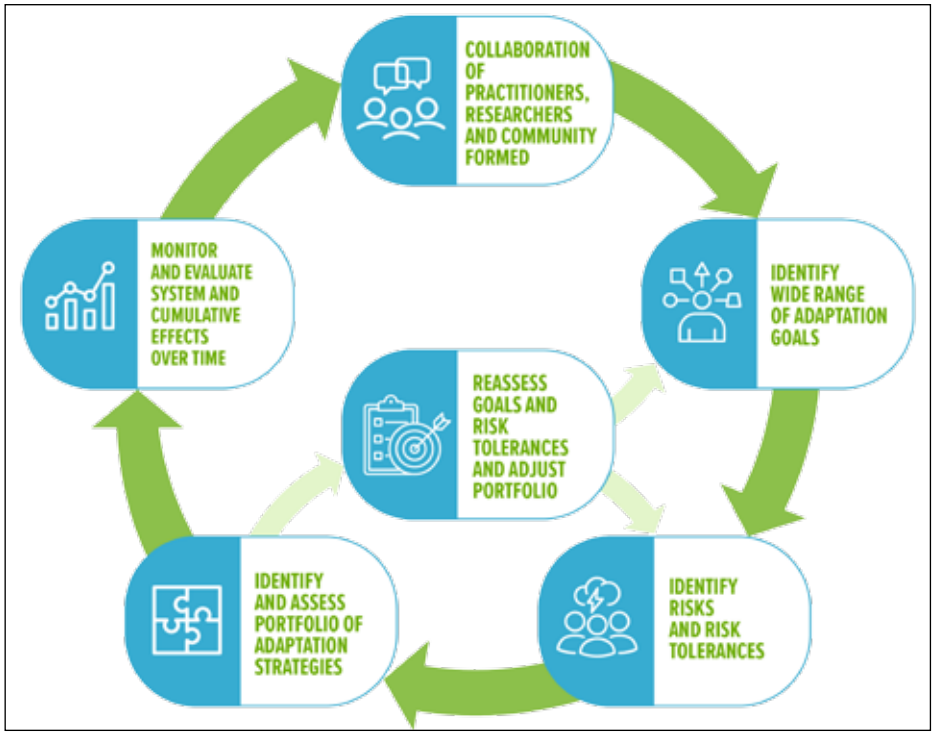


Figure 9. A systems approach to adaptation starts (top center, moving clockwise) with collaborations between researchers, practitioners, and a wide range of community members. Input from a variety of people helps to identify a spectrum of goals, knowledge sources, and risk tolerances. Using those goals, risks, and thresholds, the collaborative identifies and assesses a collection of adaptation options and strategies. Once an initial portfolio is identified, the group re-assesses their goals, capabilities, and risk tolerances and re-evaluates whether the portfolio advances their goals. After an adaptation portfolio is implemented, monitoring and evaluation is used to assess performance over time and to inform future efforts as the cycle continues.

- Innovations to inspire future visioning, such as through art, games, and scenario building (Nalau and Cobb 2022); and
- Exploration of adaptation options that may not exist yet or are not yet fully explored (e.g., the use of AI to assist with dynamic pathway approaches; the advantages and limitations of nature-based strategies).

3) How can the cumulative impacts of adaptation outcomes be evaluated to determine whether they are successful, sufficient, or maladaptive across time and space?

Monitoring frameworks that consider geographic and temporal scales and include analysis tools will better assess both intended and unintended benefits and harms. Research on the lifecycle of adaptation actions will assist with long-term planning, and research on how isolated adaptations interact (cumulative effects) will assist spatial planning. A key research challenge for the coming decade is to develop shared methods that enable cross-case comparisons to advance our understanding of how context shapes adaptation (e.g., whether seagrasses provide similar flood mitigation benefits in Maine, Texas, and California; Forrester *et al.* 2024). This will require:

- Standardized methods for assessing sufficiency, effectiveness, or maladaptiveness of adaptation actions, particularly when performance is mixed across outcomes;
- Longitudinal (time-series) data on the performance of adaptation projects.
- Cumulative datasets and monitoring and analysis both for coastal hazards and the impact of adaptation actions (Moftakhari *et al.* 2017a; Swanson and Bohlman 2021).

4) What cooperative structures and data systems are needed to enable long-term, coordinated adaptation portfolios and flexible pathways?

Limited capacity and coordination constrain adaptation in practice. Research is needed on effective coordination methods to support adaptation across jurisdictions (e.g., two towns collaborating) and across governance levels (e.g., town and state working together). Additional research is also needed to (1) identify the constraints of implementing adaptation in practice and (2) to compare the value and trade-offs of large-scale, long-term adaptation planning compared to local, short-term adaptation plans. Data to support this research could include:

- Long-term, longitudinal monitoring of adaptation performance and evolving hazards/risk to identify decision-relevant thresholds within pathways and when new strategies are required.
- Comparable datasets, monitoring, and analysis of cumulative impacts of adaptation strategies across regions.

5) How can coastal adaptation integrate diverse knowledge types (e.g., traditional, Indigenous, local) and diverse decision-making processes?

Adaptation planning and execution inherently involves knowledge and value systems (e.g., judgements about what is considered data (Kolesar *et al.* 2024) or how far into the future to consider the harms and benefits). Methods that support a variety of timelines, goals, and data sources (e.g., participatory mapping, lived experiences) are being developed and will need to expand and continue in the coming decade (Ross *et al.* 2015; Khalil *et al.* 2016). Increased collaboration between social and physical scientists would assist this effort. Needs for integrating diverse knowledge types include:

- Adequate and ethical methods for documenting, integrating, and protecting Indigenous, local, and traditional knowledge across sectors.
- Data storage and metadata formats that allow for accurate attribution for local knowledge, respecting data sovereignty.
- Critical examination of how adaptation decision-making processes bias results (e.g., how simulation models often value properties, residents, households,

and economies over benefits to culture, ecosystems, and resources (Fox *et al.* 2023).

- Improved integration of social indicators (e.g. demographics, socioeconomics, community infrastructure) into coastal hazard and adaptation datasets.

Applied research

Observations

The importance of well-developed monitoring networks and abundant data streams in addressing societal needs is recognized by those in both the research and practitioner communities (Elko and Stockdon 2026). Widely available, high-quality coastal datasets are essential for addressing both the posed scientific research questions (Coastal Scientific Research Challenges section) and for providing near-real time information to coastal communities for decision-making. Greater support for accessing open, standardized repositories of data and interpreting large datasets will increase the application of data to address challenges along the coastlines as well as facilitate the development and application of AI and ML models for extracting value from data.

Data sets spanning temporal and spatial scales can be used to solve practical problems in coastal systems. Given increasing access to new data sources, improved sensor technology, low-cost sensors, increased collaboration, citizen science, and data sharing coastal researchers may combine data across disciplines, including the social sciences, to address real-world problem. Social science information on infrastructure, population, and economic values combined with data on natural and anthropogenic changes in coastal environments can provide valuable insights into risk and tradeoffs between management decisions.

Collecting and applying new data sources, and sharing those data with communities for application, makes it increasingly important to understand and communicate the data uncertainties (Barnhart *et al.* 2018). Newly available low-cost or high-volume data may come with greater uncertainty, thus increasing the need for clearly communicating those values for both the data and tools used for interpretation (Williams 2019). The development of approaches to quantify the uncertainty in observations is paramount, especially as disparate observations are fused together, data are incorporated into models and forecasts in real time, and data-driven models are used to inform DST (Simmons *et al.* 2017). Quantifying uncertainty will become even more important when considering the training of ML and AI models with high-quality data and understanding the limitations and applications of results.

At present, and for the first time in the history of coastal science, researchers can rapidly capture large volumes of data, which has led to the development of new processing methods (Vitousek *et al.* 2023; Calkoen *et al.* 2025; Cavanaugh *et al.* 2025). With the onset of ML and cloud computing, there are opportunities to learn even more from data that have already been collected. Hyperlocal, high-frequency, high-resolution data have the potential for significant advancement in understanding by helping transition single-process case studies to holistic understanding and application. The integration of these data sets into our coastal management and engineering actions may enable leap-ahead capabilities for predictive coastal hazards. The next decade of coastal research will be data-driven and powered by intelligent ML models providing actionable decision-support tools in coastal communities.

Modeling

Models that explain coastal processes and the relationship between forces — natural and human — are a fundamental bridge between scientific information and decision-making. Model types are varied and include conceptual, analytical, empirical, ML, process-based and physics-based numerical. Hybrid approaches, which bring multiple types of modeling together, have significant potential to address the multi-scale, complex challenges of coastal science and engineering. Models provide the framework for empirical observations to be utilized beyond a specific point in time or space and provide answers to real-word coastal issues.

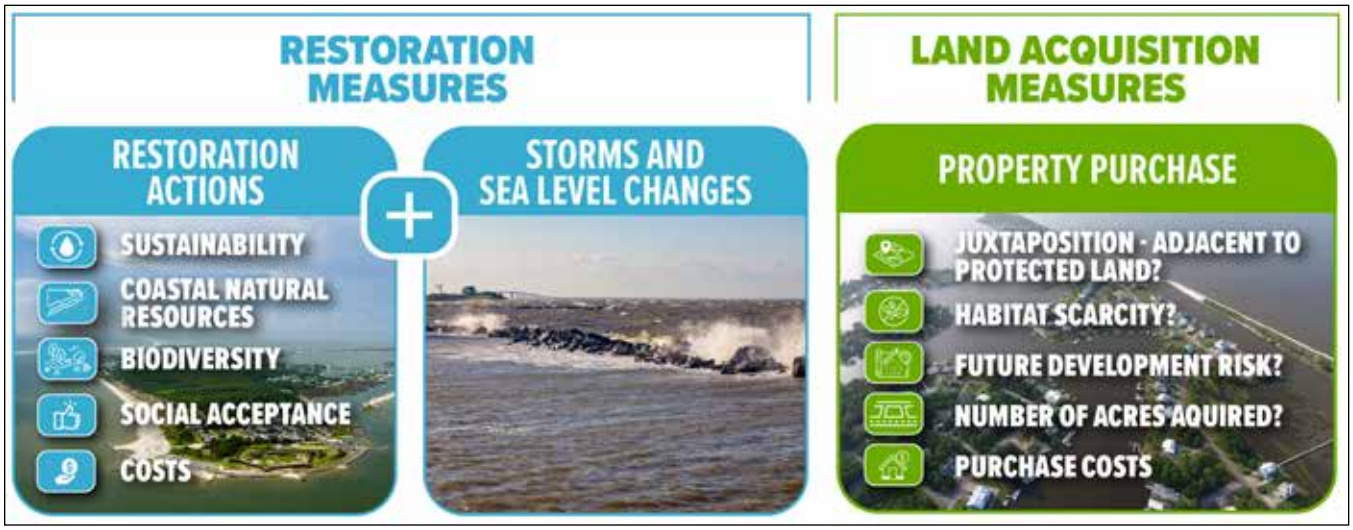
The role and importance of models is evident across the three coastal science research challenges reviewed in this paper (see the Coastal Scientific Research Challenges section). Common themes within the research questions include development of ML models, operational forecasting systems, and clear communication of model results with end users of the information. At the USCRP Decadal Visioning Workshop, stakeholders described needing models that address coastal challenges in two ways: (i) supporting real-time predictions of nearshore coastal processes for application to emergency management and risk assessment; and (ii) supporting longer-term management decisions, such as coastal adaptation planning and resource management (Elko *et al.* 2026). In both cases, quantification of model uncertainty, as well as understanding stakeholder tolerance for uncertainty, plays a role in model usefulness.

Since the previous USCRP decadal report (Elko *et al.* 2014), the development of ML and AI methods has added to the range of modeling approaches available to coastal scientists. These advanced tools create new possibilities for model development, building on increased availability of large amounts of data for model training. ML is also changing the way scientists operate, including experiment design, data processing, code development, and data interpretation. While these new methods and tools can be powerful, the application of the results still requires review from researchers and will not completely replace physics-based models. However, there is strong potential to enhance and improve efficiency, allowing for greater application and wider use. Employing ML methods comes with several challenges, including developing high-quality datasets for model training, translating ML models, availability of computing resources and data storage, and training of nearshore scientists with ML skills. In the next decade, ML is likely to continue to be a high-value, burgeoning research direction, with further development of methodologies such as physics-informed ML approaches (Wang *et al.* 2022).

Operational, real-time forecasts for coastal environments, highlighted as a goal in the previous decadal report, have seen rapid development over the past decade (Turner *et al.* 2024). However, technical challenges continue to limit operational forecasts. These include computational and run-time constraints, poor spatial and temporal coverage of observations and data assimilation, model validation, poor model efficiency, cybersecurity needs, and inadequate service delivery to stakeholders. Perhaps the most significant technical challenges in data assimilation and data-driven modeling are obtaining the appropriate observations for real-time

Decision support for barrier island restoration

For decades Dauphin Island, AL, has experienced severe erosion and flooding, leaving the island communities vulnerable to the effects of storms and rising sea levels. Further degradation of the island could result in exposure of the mainland coast to additional hazards. A multidisciplinary and cross-organization team explored the effects of possible island restoration strategies and the effects that threats and stressors (including uncertainties) have on island structure and resources. Physical processes related to restoration strategies were tested using numerical models to understand coastal morphologic change, water quality, habitat, and coastal engineering structures. Costs for restoration options were also evaluated. Following a structured decision-making approach, the team was able to use probability-based decision tools to evaluate efficacy of the possible restoration measures to address complex stakeholder objectives (U.S. Army Corps of Engineers and U.S. Geological Survey 2020).



Possible restoration and land acquisition measures considered in the structured decision- making approach employed at Dauphin Island, Alabama. A probabilistic model was developed to evaluate potential activities related to stakeholder objectives (Modified from U.S. Army Corps of Engineers 2020).

modeling and conducting quality-control on observations in real-time.

Creating and providing operational forecasts also requires addressing non-technical challenges. One example is the difficulty in supporting and sustaining the transition of forecasts from research to operations and then subsequent, necessary iterations between research and operations, especially in a timely and efficient manner where technical advances might happen faster than can be incorporated into operational systems. Support can come from research groups working in partnership across organizations. For example, the NOAA Unified Forecast System, a coupled, comprehensive earth modeling system, is an example of a community-supported approach designed to address a range of uses from research to operations, including engagement and communication with end users. Publishing and developing open-source code is crucial in data analysis and community modeling, where research and development done by academics and government researchers can be incorporated into operational models (Goldstein *et al.* 2019; Gordon *et al.* 2023; Jafarzadegan *et al.* 2023).

Finally, communicating results to end users and delivering practical data, tools, and services is a major non-technical challenge for operational modeling (NOAA 2020). Communication that begins early in the development of applied and operational models will influence project design and increase the likelihood of end-user applicability. This includes explaining forecast methodology and production to convey uncertainties in forecasts and instill trust in products. Additionally, applied researchers and operational model developers can engage with science communicators early to support flow of information from forecasts to end users.

We anticipate the next decade will see rapid advances in the forecasting skill of coastal evolution and hazards, driven largely by improved access to higher-quality model input and data-assimilation of historical and real-time data into forecasting models. Much like the weather forecasting community, which saw an increase in prediction skill with the launch of satellite technology in the 1960s, development of shared observational network resources and increases in access to computational power, the coastal research community expects to see a large surge in understanding and application associated with recent technological and processing advances.

Decision support

The translation of research into actionable insights and adaptation solutions for coastal communities is central to providing information for decision- and policy-making to communities, protecting national security assets, and sustaining vital economies. To effectively address these issues, DST are ideally based on scientific knowledge and an understanding of the end-user audience, consider ease of use, and meet the time requirements (Refulio-Coronado *et al.* 2021).

DST are developed to enable communication about coupled human-natural systems across the research-to-application boundary (Barzehkar *et al.* 2021). These types of tools require input

from those working at the intersection of science and information for decision-making (see Decision Support box). Tools that consider the integration of ecosystems and socio-economic systems, along with trade-offs and feedback loops, can inform management strategies through a more practical lens that considers critical aspects such as political will, economic costs, cultural values, and anthropogenic impacts, in addition to more traditional physical coastal processes (Refulio-Coronado *et al.* 2021).

While many coastal DSTs have been developed over the last decade (see Dusek *et al.* 2026), there is currently no centralized, open-access platform that catalogs mitigation and adaptation techniques along with measured outcomes. A major barrier to widespread adoption is the absence of standardized metrics for assessing model and tool performance across time and space (see Coastal Scientific Research Challenges section 2). It is important for communities to understand not just what strategies are available, but how well they work, where they work best, and under what conditions. Developing such a resource depends on significant investments in monitoring and data infrastructure. Consistent, high-resolution collection of topographic, bathymetric, and vegetative data — paired with hydrodynamic inputs such as wave height, wind, and precipitation and SLR projections — can support evaluations of the effectiveness of mitigation strategies. Tools such as NOAA's Green Infrastructure Effectiveness Database (NOAA 2025b) are an important starting point; additional datasets and broader integration into DST platforms can advance this approach.

Looking forward, we anticipate that the next decade of DST development will play a transformative role in removing barriers between science and community-centered adaptation. These action-oriented tools will extend beyond physical landscape responses to include ecosystem function, socio-economic conditions, engineering capacity, funding mechanisms, policy decisions, and user behavior. For full end-user adoption, mitigation performance metrics and return-on-investments information are often needed to communicate the efficiency of their work. Additionally, there is a need for searchable, continuously updated, open-source catalogs of mitigation and adaptation techniques alongside their measured efficacy. Developing and standardizing metrics for mitigation performance, such as life-cycle effectiveness under varying flooding scenarios, is key for widespread adoption by both the scientific and management communities and will require support for long-term monitoring. By grounding these tools in real-world data, community engagement, and adaptive learning, the coastal science community can enable a decision-making framework where the coastal system is modeled, measured, and sustained.

Key research questions for applied research

1) What methods and data are needed to improve the accuracy and forecast horizon of models used to predict coastal hazards at timescales of hours to decades?

Stakeholders use models to support both real-time and longer-term prediction of coastal hazards. To provide and improve these capabilities involves:

- Including new methods and parameterizations, two-way coupling between models, and new data and processing methods, such as AI/ML tools.

- Conducting research dedicated to understanding the timing, duration, and magnitude of coastal hazards to improve information for decision-making.

2) How does physical science research incorporate social science methodologies and anthropogenic factors?

Humans, their culture, and their behavior are a key factor in the three coastal science research priorities (see Coastal Scientific Research Challenges section). Considering anthropogenic effects, uses, and needs within coastal research can increase the accuracy of coastal processes research and accessibility of product outputs. Addressing this question requires:

- Integrating social data, such as population, infrastructure, economic, and cultural values into coastal processes; developing research questions to increase understanding of risk, error, and the actionability of research results; and enabling transition of model results into decision making.

- Research how social dimensions can better incorporate into existing models.

3) What information and tools do stakeholders in coastal communities need to make decisions or help others do so?

Research is needed on the roles and functions of stakeholders in transitioning science to decision-making to understand the data and data delivery gaps. Specific research topics to address this may include:

- An understanding of how to convey the best use of existing tools, through interpretive products or explanatory guides.

- How best to incorporate concerns of decision-makers and uncertainties into the delivery of scientific information.

CONCLUSION

Coastal zones provide extensive economic, environmental, social, and national security benefits, including natural buffers against coastal storms, highly productive ecosystems and fisheries, commercially valuable ports, and strategically important military bases. These are the most densely populated areas in the nation and drive industries like shipping, fishing, tourism, recreation, and energy production. Home to many of our oldest communities as well as treasured cultural resources, coastal cities and towns often have deep histories and a strong sense of place and heritage for many.

However, coastal areas are increasingly exposed to compounding stressors, as discussed in the priority research themes — coastal flooding; morphodynamics and sediment transport; and ecosystem change and health. Scientific research, especially that focused on the key research questions presented here, is needed to fully understand and accurately predict the response of coastal systems to both natural and human drivers and to provide actionable information to address user needs. Meeting the complex demands of adaptation, hazard resilience, and sustainability will require the continued transformation in coastal science toward integrative, systems-based research that synthesizes physical, ecological, and social processes. Achieving this vision necessitates a sustained commitment to innovation, cross-sector collaboration, and enhanced pathways for translating scientific knowledge into actionable, stakeholder-informed strategies.

To make meaningful progress on restoring, protecting, and managing coastal areas, we offer key actions targeted at accelerating scientific progress to address these issues. They represent priorities and strategies for addressing critical gaps in

knowledge, integrating research across disciplines, making science meaningful and accessible to decision-makers, leveraging emerging technologies, and enhancing available data, modeling, and decision-support approaches within and across themes. These actions can guide various organizations — academic, federal, state, municipal, private—when deciding on priorities to collectively meet the needs of coastal communities in the coming decade.

- ***Effectively embed social science into coastal research and community risk assessment*** by designing interdisciplinary studies that include social science questions and methods. Evaluate decision-making, risk perception, and communication strategies to better understand societal responses to hazards.

- ***Enhance the translation and uptake of scientific knowledge*** into decision-making by co-developing actionable, context-specific data, models, and tools (e.g., guidance documents) with end users. Improve communication strategies, visualization platforms, and delivery at user-relevant scales. Involve users in the design of communication strategies, platforms, and tools.

- ***Collect more comprehensive and higher-resolution data*** across spatial and temporal scales using new sensors and lower-cost technologies.

- ***Maintain* shared, *open-source long-term, national data sets and co-production platforms*** to enhance transparency and innovation across sectors. Promote use, investment, and improvement over time to integrate diverse epistemologies, communicate risks and tradeoffs, and visualize potential outcomes.

- ***Develop coupled and holistic modeling frameworks*** that integrate multiple interacting systems — physical, ecological, and human — such as compound flood processes, geomorphic and ecological responses, and decision-making under uncertainty.

- ***Strengthen approaches to promote integrated solutions*** by creating opportunities for interdisciplinary research, maintaining long-term partnerships that focus on co-produced knowledge and shared outcomes, and developing a coordinated nation-scale road map for coastal research.

- ***Apply AI and ML approaches*** to integrate and analyze large, heterogeneous data sets, fill gaps caused by limited field observations, and improve model accuracy and computational efficiency — particularly for operational flood predictions.

- ***Advance multidisciplinary, systems research*** and enhance community and stakeholder involvement for innovative coastal resilience solutions, including nature-based approaches.

Realizing the ambitious vision for coastal resilience and adaptation outlined here requires a co-developed, multidisciplinary, and stakeholder-driven approach. Also essential are a sustained commitment to long-term datasets, embracing innovation and cross-sector collaboration, and enhancing pathways for translating scientific knowledge into action. The research recommendations outlined here emphasize that no single discipline or group can meet the scale and complexity of today's coastal challenges. Advancing adaptation, improving forecasts, protecting ecosystems, and sustaining communities require a commitment to shared data, innovative technologies, and intentional, interdisciplinary collaboration among researchers, decision-makers, and local stakeholders. We can bridge critical knowledge gaps by embedding social sciences into physical and ecological research, modernizing funding structures, standardizing metrics and indicators, and embracing cutting-edge tools such as AI-driven modeling and holistic forecasting frameworks. These collective efforts, based on a strong foundation of research, will drive innovation, provide actionable information, and build capacity for science-based implementation, ultimately empowering coastal communities to adapt to changes along coastlines through flexible, long-term resilience strategies.

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The future of coastal processes research, Part 2: State of the science

By

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ABSTRACT

In June 2024, more than 100 professionals across coastal science and management disciplines — including academics, federal representatives, and community stakeholders — participated in the U.S. Coastal Research Program (USCRP) Decadal Visioning Workshop in St. Petersburg, Florida. The first part of this paper shared primary management challenges identified by coastal communities, knowledge gaps and fundamental research to address these issues, and applied research essential to ensure that science is useful and usable. This paper provides a deeper exploration of the state of the science for the priority research topics outlined in Part 1: coastal flooding, morphodynamics and sediment transport, and ecosystem change and health. We further examine how advances in fundamental coastal science are translated into operational tools, predictive capabilities, and decision-support applications relevant to coastal stakeholders. Through a synthesis of progress in observation, prediction, modeling, and multidisciplinary collaboration, this paper provides a scientific foundation to guide the next generation of coastal research in alignment with the needs of the coastal communities it serves.

KEYWORDS: Adaptation, applied research, coastal flooding, compound flooding, decision support, coastal ecosystems, interdisciplinary research, modeling, morphodynamics, observations, resilience, sea level rise, sediment transport, social science.

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This edition of *Shore & Beach* contains three complementary papers: "The future of coastal processes research: USCRP decadal visioning workshop," "The future of coastal processes research, Part 1: A community-driven vision for the next decade of coastal science," and "The future of coastal processes research, Part 2: State of the science." The workshop purpose, design, and general outcomes are presented in Elko and Stockdon (2026). Part 1 builds on the 2015 Future of Nearshore Process Research report, describing primary coastal management challenges, articulating key research to address these issues, and identifying applied research essential for meeting user needs. This paper, Part 2, provides a detailed description of the state of the science in alignment with the key research areas outlined in Part 1 (Stockdon *et al.* 2026).

INTRODUCTION

Coastal research is positioned at the interface of ocean, land, and society, and provides the foundation for understanding risk and guiding communities' adaptation to coastal hazards. Over the past decade, the coastal research community has made major progress in understanding the physical, ecological, and human systems that interact along our coastlines. Researchers are advancing the understanding of the fundamental dynamics of nearshore and coastal processes, developing new observational tools and models, and applying this knowledge to support decision-making and adaptation.

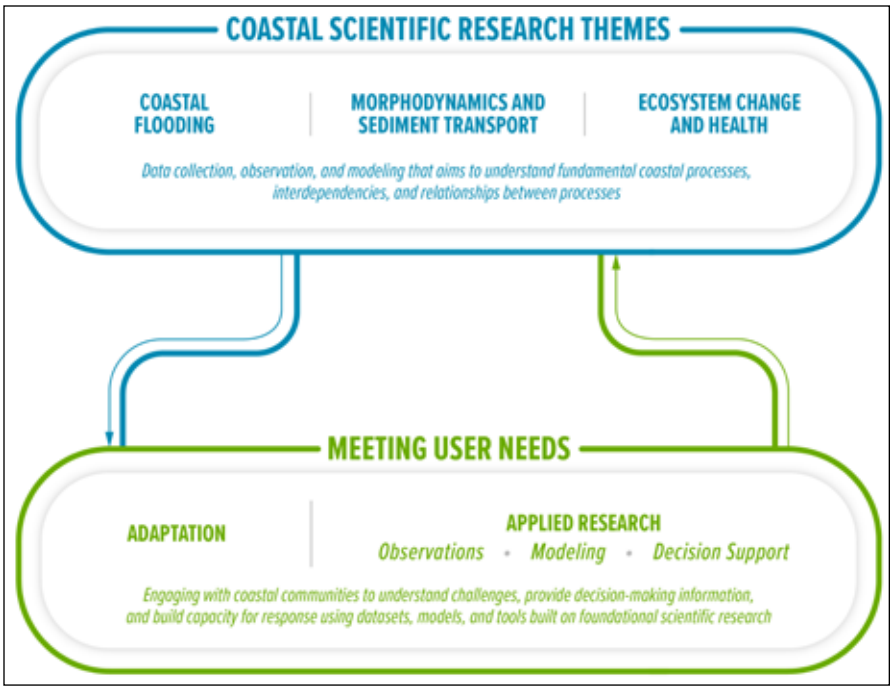

Figure 1. The organization of coastal scientific research themes and how those research themes help meet user needs. This structure is followed in both Part 1 and Part 2 of this paper.

This paper provides a synthesis of the current state of coastal processes research across three key research themes and two applications. It highlights what is well established, identifies gaps in data and knowledge, and describes emerging methodologies that hold promise for the next decade. Though extensive, the overview provided here is not exhaustive. We chose to highlight key research examples that demonstrate the breadth of advancement over the past decade. The topical space is guided by the preceding "The future of coastal processes research, Part 1: A community-driven vision for the next decade of coastal science" (Stockdon *et al.* 2026), and the information collected during data collection, discussion and surveys leading up to and during the United States Coastal Research Program (USCRP) Decadal Visioning Workshop hosted in St. Petersburg, Florida, 11-13 June 2024. This paper is organized around the same scientific research and cross-cutting themes (Figure 1) as in Part 1:

- **Coastal flooding:** Compound and high tide flooding, the roles of changing sea levels and morphology, and the state of coastal flood modeling and observations;
- **Morphodynamics and sediment transport:** Small, medium, and large-scale sediment transport and morphodynamic processes, modeling transport, and morphologic change;
- **Ecosystem change and health:** Monitoring and modeling ecosystem change and water quality;
- **Adaptation to coastal hazards:** Adaptation to coastal hazards; and
- **Applied research:** The application of observations, models, and decision support.

Taken together, these themes capture the scientific foundations and applied dimensions of coastal research. The interconnectivity between themes is also notable, as coastal challenges span physical, ecological and human dimensions (Figure 2). By establishing a common understanding of the state of the science, this paper helps researchers build on existing knowledge, adopt the latest techniques, and foster intentional interdisciplinary collaboration. It also provides organizations with guidance on emerging priorities and development opportunities that can accelerate progress toward more resilient coasts.

COASTAL FLOODING

Coastal flooding is driven by a range of complex, interacting processes that operate across multiple time scales, from hours to centuries, and across diverse environments, from urban coastlines to sandy beaches. Key challenges in understanding and predicting flooding events include the growing impact of sea level rise (SLR; Sweet *et al.* 2022), the increasing frequency of high-tide flooding (Thompson *et al.* 2021), and the occurrence of compound events where multiple drivers (e.g., storm surge, rainfall, and tides) coincide (Wahl *et al.* 2015). Coastal morphology also plays a critical role in modulating flood impacts, yet the relationship remains difficult to capture fully. Significant advancements in coastal flood observation and modeling have been made, which improves the understanding and prediction of coastal flooding events.

Compound flooding

Coastal flooding events are often caused by interactions across multiple, compounding factors such as sea level variability, storm surge, waves, rainfall, tides, streamflow, groundwater, and morphological change. The combination of two or more co-occurring or consecutive flooding drivers with the potential to have greater impact together than individually is often termed a "compound event" or "compound flood" (Zscheischler *et al.* 2020; Wahl *et al.* 2015; Moftakhari *et al.* 2017; Green *et al.* 2025). Coastal flood depth and extent models traditionally use only ocean forcing; however, these have the potential to mischaracterize water levels where multiple processes, such as precipitation, river discharge, and groundwater processes contribute to flooding (Bilskie and Hagen 2018; Serafin *et al.* 2019; Moftakhari *et al.* 2019).

The characteristics of extreme weather events frequently give rise to compound flooding events. For example, tropical cyclones bringing rain, waves, and storm surge drive most extreme compound flood events (Maduwantha *et al.* 2024), as demonstrated during Hurricanes Hermine (Gori *et al.* 2020), Harvey (Valle-Levinson *et al.* 2020), and Irma (Juárez *et al.* 2022), while extratropical storms, such as nor'easters, contribute more frequently to moderate compound flooding (Maduwantha *et al.* 2024). The evaluation of the spatiotemporal dependence between inland and coastal processes has highlighted compound flood hotspots predominantly occurring along the mid-Atlantic Ocean and southeastern U.S. coastlines due to both tropical and extratropical storm systems (Wahl *et al.* 2015; Ridder *et al.* 2020; Nasr *et al.* 2021). These storms can generate powerful storm surges that cause temporary but severe flooding. Storm characteristics — including size, intensity,

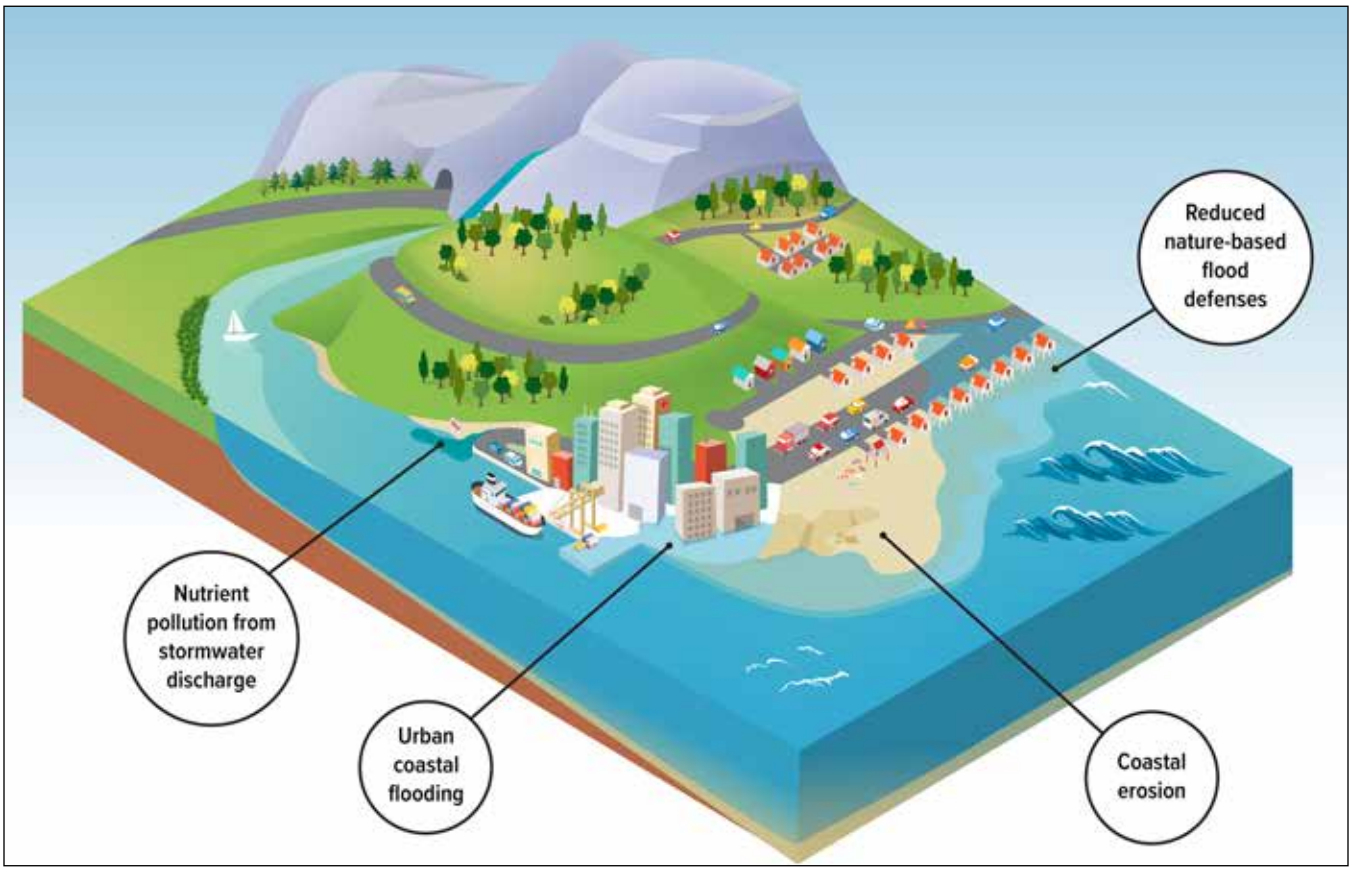

Figure 2. An illustration of the interconnections of the coastal system and how the core research themes explored here require broad interdisciplinary collaboration to address. Increasing sea level coupled with waves leads to greater coastal flooding and coastal erosion. Degraded nature-based flood defenses and a lack of urban adaptation lead to flooded city streets. Storm water discharge and runoff increases nutrient pollution and reduces water quality.

speed, track, and duration — influence the spatial distribution and magnitude of coupled rainfall, surge, and waves. During energetic storm conditions, wave setup and run-up can contribute significantly to total water levels, especially on open coastlines and steep beaches, leading to dune overtopping and coastal inundation (Stockdon *et al.* 2007). Waves and rainfall can also combine, driving variations in groundwater-induced flooding (Housego *et al.* 2021), and antecedent groundwater conditions can have a direct influence on how far wave runup travels (Delisle *et al.* 2025).

High tide flooding

Chronic high tide flooding (HTF) has more than doubled in frequency over the past two decades due to SLR (Sweet *et al.* 2022) and is projected to become a near-daily occurrence in many U.S. coastal cities by mid-century (Thompson *et al.* 2021), causing disruptions across multiple sectors of the economy (Hino *et al.* 2019; Hummel 2018).

HTF — sometimes called "nuisance," "sunny day" or "minor" flooding — refers to the overflow or excess accumulation of ocean water at high tide on typically dry land. While HTF may not result in immediate catastrophic damage, it is increasingly disruptive to coastal communities, leading to routine inundation of low-lying land, infrastructure, and transportation networks. The processes that contribute to HTF (Li *et al.* 2022) include long-term relative SLR (Moftakhari *et al.* 2015; Dahl *et al.* 2017; Sweet *et al.* 2018), storm surge and tidal characteristics (Hague *et al.* 2023; Hague and Talke 2024), changes in tidal amplitudes (Li *et al.* 2021; De Leo *et al.* 2022), river discharge (McKeon and Piecuch 2025), atmospheric circulation (Sheridan *et al.* 2017), and large-scale oceanographic forcings (Ezer 2020). Chronic flood events may also depend on the combination of tide and land-based factors such as rainfall and impaired stormwater networks (Thelen *et al.* 2024; Wahl *et al.* 2015).

The role of sea level change

SLR is a primary long-term driver of coastal flooding. Globally, SLR on centennial to decadal scales has increased by about 17 cm from 1920-2020 (Sweet *et al.* 2022), with U.S. relative sea levels rising on average by about 28 cm over the same period (Frederiske *et al.* 2020), in part due to land subsidence. Future projections show sea levels along the contiguous U.S. (CONUS) coastline could rise by 30 cm-50 cm by 2050 (relative to sea level in 2000), 60 cm-2.2 m by 2100, and 80 cm-3.9 m by 2150 (Sweet *et al.* 2022). The amount of SLR varies spatially and is determined by vertical land motion and ocean dynamics. SLR elevates baseline water levels that will amplify extreme compound events, especially along the low-lying southeast Atlantic coast (Ghanbari *et al.* 2021; Gori *et al.* 2022), and lead to an increasing threat of groundwater hazards (Befus *et al.* 2020; Barnard *et al.* 2025), and more frequent high tide flooding (Sweet *et al.* 2022).

The variability of coastal sea levels also fluctuates on shorter timescales, ranging from sub-seasonal to seasonal and inter-annual scales. These are often characterized by sea level anomalies, which are deviations from climatological average conditions and are typically linked to seasonal climate variability (Han *et al.* 2019;

Long *et al.* 2020; Wang *et al.* 2023). These localized variations in sea level across shorter timescales affect flooding and are influenced by large-scale climate patterns such as the El Nino Southern Oscillation (Hamlington *et al.* 2015; Muis *et al.* 2018; Goodman *et al.* 2018) and the North Atlantic Oscillation (Valle-Levinson *et al.* 2017; Zhang *et al.* 2024).

The role of morphological change

Extreme flood levels cause morphological changes, such as beach and dune erosion, barrier island overtopping or breaching, and wetland loss. At the same time, morphological change can induce and exacerbate flooding and alter flood pathways (e.g., Gharagozlou *et al.* 2021; Hegermiller *et al.* 2022). For example, storms can alter beach slopes, which are important parameters in empirical wave run-up models, leading to increased flood model errors as morphology evolves and then deviates from what was modeled (Kim *et al.* 2023). Land-use changes, such as developing infrastructure or ecosystem migration, have direct impacts on where and when floods occur (Pendleton *et al.* 2023). Increased urbanization and impervious land development exacerbate impacts, for example, when drainage is impeded due to a lack of natural drainage and inadequate or disconnected, aging stormwater infrastructure (Gold *et al.* 2022; Tran *et al.* 2024). Changing modeled land elevations to represent beach and dune erosion improves flooding estimates (Gharagozlou *et al.* 2020), and including changes to nearshore topography or urbanization can amplify surge-driven flood levels (Bilskie *et al.* 2014).

Coastal flooding models

The three major flood modeling techniques are data-driven (statistical or machine-learning), numerical (physics-based simulation), and hybrid (integrating both data-driven and numerical). Each modeling technique can be used to model individual processes (e.g., waves or storm surge) or compounding processes (e.g., storm surge and streamflow).

Data-driven models make predictions based on data, observed or modeled, and are typically either statistical or machine learning (ML) models. Data-driven models do not include numerical or physics-based models as a component of the predictions; however, they may be trained partially or entirely from numerical model output (often called surrogate models or emulators). Data-driven methods have long been used to predict the likelihood of extreme events, using extreme value theory to quantify return periods of sea levels, storm surges, or waves rarer than those observed in the observational record (e.g., Wahl *et al.* 2017; Vitousek *et al.* 2017; Serafin and Ruggiero 2014). Data-driven approaches are also common for subseasonal-to-seasonal predictions, such as ML and statistical methods for coastal sea level anomalies (Lee *et al.* 2023; Long *et al.* 2025), or for seasonal HTF at tide gauges (Dusek *et al.* 2022; Holmes *et al.* 2025). The advancement of ML methods has also enabled the development of viable weather-scale (hours to days) models, such as for urban flooding (Zahura *et al.* 2020) and for regional (Chen *et al.* 2021), and global wave modeling (Bodnar *et al.* 2025). In addition, ML methods have been used to enhance the spatial coverage of parameters important for predicting future flooding, such as defining spatially continuous coastal flood thresholds (Mahmoudi *et al.* 2024). Multivariate data-driven/statistical approaches have been heavily utilized in the past decade for advancing joint flood-risk estimation (Wahl *et al.* 2015; Moftakhari *et al.* 2017).

Numerical hydrodynamic models applied to weather-scale predictions typically focus on storm surge and wave contributions. Popular storm surge models such as the ADvanced CIRCulation model (ADCIRC) (Luettich and Westerink 2004), Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) (Zhang *et al.* 2016), Regional Ocean Modeling System (ROMS) (Warner *et al.* 2013) and the Delft3D D-Flow Flexible Mesh (DFLOW-FM) (Deltares 2025) have a variety of numerical schemes, discretization of time and space, and can typically be run in two-dimensional (2D) or three-dimensional (3D) configurations. When run operationally, numerical models can produce hourly predictions spanning 2-7 days at spatial resolutions down to O(10)m (Weston *et al.* 2023). Recent coastal flood modeling improvements assimilate tide gauge observations to better account for subtidal water level variability (Asher *et al.* 2019). The development of a high-resolution, U.S.-scale, 40-year re-analysis helps to better understand variations in coastal water levels (Rose *et al.* 2024; Keeney *et al.* 2025). Spectral wave models such as Wavewatch III (Tolman 2009) and Simulating WAves Nearshore (SWAN) (Booij *et al.* 1997) are run operationally at large spatial scales and may be coupled with surge models to make hourly predictions a week or more into the future. These models power tools such as the National Oceanic and Atmospheric Administration's (NOAA) Nearshore Wave Prediction System (van der Westhuysen *et al.* 2011). Phase-resolving wave models such as FUlly Nonlinear Wave (FUNWAVE) (Shi *et al.* 2012), XBeach (Roelvink *et al.* 2009; McCall *et al.* 2014), Non-Hydrostatic Wave (NHWAVE) (Ma *et al.* 2012; Derakhti *et al.* 2016), and Simulating WAves till SHore (SWASH) (Zijlema *et al.* 2011), enable deterministic modeling of individual waves and are often used for high-resolution modeling of wave run-up and overtopping (Gallien 2016). In addition to weather-scale operational flood predictions, systems that combine several models, such as the Coastal Storm Modeling System (CoSMoS) (Barnard *et al.* 2014), enable hindcast studies and assessments of flooding under future climate scenarios.

While each model can operate independently, they can also be integrated in a coupled framework where information is exchanged between models to better capture the complex interactions across domains and environments. For example, model coupling is often essential for the numerical modeling of coastal erosion and compound flooding. Models developed for different types of flooding can be linked in simple (one-way) or complex (fully) ways, each with its own advantages and drawbacks (Santiago-Collazo *et al.* 2019; Jane *et al.* 2025). One example is the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System (COAWST), which enables fully coupled, two-way interactions between ocean, atmosphere, waves, and sediment processes through the integration of ocean (ROMS), atmosphere (WRF), waves (SWAN), and sediment transport models (Warner *et al.* 2010). This enables realistic, high-resolution simulations of coastal dynamics where interactions between wind, waves, currents, and sediment are critical. Modeling compound flooding is another example where model coupling is frequently utilized to represent interactions across different physical processes and domains (e.g., coastal and terrestrial flooding). However, the computational

demands of fully coupled compound flood models can be prohibitive, prompting the development of reduced-physics approaches that retain essential dynamics while improving efficiency (e.g., Leijnse *et al.* 2021; Santiago-Collazo *et al.* 2024). .Comprehensive reviews of compound flood modeling procedures and advancements are provided by Jafarzadegan *et al.* (2023), Jane *et al.* (2025), and Green *et al.* (2025).

Hybrid models merge data-driven approaches with numerical modeling to reduce computational costs, often by leveraging surrogate models, which approximate the response of a full numerical simulation. Hybrid models have been found especially useful for flood forecasting and prediction (e.g., Muñoz *et al.* 2022; Plumlee *et al.* 2021) and estimation of storm surge hazards (Lee *et al.* 2023; Kim *et al.* 2015; Jung *et al.* 2025). They are also commonly used to model compound flooding, such as assessing annual exceedance probabilities for the interaction of waves, tides, and storm surges (e.g., Anderson *et al.* 2021), and fluvial and coastal processes in coastal watersheds (Bass and Bedient 2018), estuaries (Parker *et al.* 2019; Wang Z. *et al.* 2024), and along rivers (e.g., Serafin *et al.* 2019; Moftakhari *et al.* 2019; Jane *et al.* 2022; Bermúdez *et al.* 2019). The reduction in computational cost also makes them useful for modeling coastal change related to extreme storm events (Santos *et al.* 2019). Hybrid models have also been implemented operationally, such as the U.S. Geological Survey (USGS) Total Water Level and Coastal Change model, which makes hourly predictions of wave run-up, inundation, and coastal change along sandy beaches (Stockdon *et al.* 2023). They are also used to investigate flooding under future climate conditions (Anderson *et al.* 2021; Wang *et al.* 2025) for predicting coastal change hazards (Leung *et al.* 2024). Overall, while model performance has improved, challenges remain in adequately representing small-scale features, uncertainty, and feedback related to land use, morphology, and hydrodynamics.

Coastal flooding observations

Flood monitoring and observation have progressed significantly in recent years due to advances in technology and data analysis methods, and can broadly be categorized into in-situ observations, remote sensing, and crowdsourcing. In-situ observations provide real-time measurements from water level sensors such as pressure gauges (Temple *et al.* 2020), acoustic sensors (Park *et al.* 2014), and microwave radar (Fiorentino *et al.* 2019). NOAA and USGS have expansive permanent in-situ water level networks throughout the coastal U.S. that provide real-time data for monitoring flooding and inundation events (Miller and Luscher 2018; McCallum *et al.* 2013).

Rapid deployment of sensors along the coast ahead of storm and flood events provides more detailed coverage of impacts in areas predicted to be affected (U.S. Geological Survey 2025b). Recent increased access to low-cost ultrasonic acoustic (Silverman *et al.* 2022; Hernandez *et al.* 2025), and storm-drain sensors (Gold *et al.* 2023) enhance measurement of flooding both at and near the coast and in nearby coastal communities (Hino *et al.* 2025). Remote-sensed observations include measurements made from satellites (Vignudelli *et al.* 2019; Schumann 2024), crewed aircraft, uncrewed aerial systems (Over *et al.* 2021), and stationary cameras (Dusek *et al.* 2019).

Crowdsourcing, such as social media posts (Moore and Obradovich 2020; Eilander *et al.* 2016), geotagged images and web-applications (Harley and Kinsela 2022), can also provide localized and real-time information on water levels and flood conditions.

MORPHODYNAMICS AND SEDIMENT TRANSPORT

Most coastlines are composed of sediment or have sediment fronting, or are adjacent to, built features. Other coastlines consist of or are fronted by cliffs or rocky environments (Hapke *et al.* 2014); both are less studied than sediment-covered coasts. Cliffed/bluffed shoreline (Earlie *et al.* 2017) processes are dominated by cliff base erosion and collapse due to wave action/run-up and rainfall (Zhao *et al.* 2025). Rocky coastline (MacMahan *et al.* 2024; Marques *et al.* 2025) morphology tends to be more static, where the dominant processes are longer-term rock degradation under wave forcing and/or deposits of boulders and cobbles (Trenhaile 2016). This section focuses on coastlines composed of sediment.

Sediment can be mobilized by hydrodynamic processes, leading to elevation changes referred to as morphodynamics (Wright and Short 1984), or the interaction between morphology (shape and structure) and hydrodynamics (waves, currents, tides). These processes occur across a range of scales. Small-scale, short-term processes underpin all coastal morphodynamics. All larger-scale features are the cumulative result of small-scale sediment-transport processes. These processes occur at the granular to wave orbital or swash excursion length scale, of Order (O) millimeters to meter (10^-3 m to 10^1 m). Corresponding short-term temporal scales range from much less than ~3 s (wave period or swash durations) up to 1-2 minutes on the infragravity time scale (O 10^-2 s to 10^2 s). Prediction of sediment transport at small temporal/spatial scales is required to understand how it affects biological, ecological, and nature-based/built structural systems, which informs the estimation of medium- and long-term processes (Gallop *et al.*, 2015; Murray *et al.* 2002; Vowinckel 2021).

Fundamental processes

Understanding how sediment moves in coastal environments requires an understanding of geomechanics, or mechanical processes at the grain to bulk sediment scale, and geotechnical sediment properties (Bagnold 1966; Brilli *et al.* 2024). Liquefied sediment lacks particle-particle stress and is readily available for transport, potentially enhancing sediment transport rates (Florence *et al.* 2022). Sediment strength and textural properties vary at different coastal sites and even across a single beach profile (e.g., Sassa *et al.* 2014; Stark *et al.* 2022; Brilli *et al.* 2024). Measuring these properties remains challenging (Albatal *et al.* 2019; Brilli and Stark 2024), and the interaction between sediment dynamics and geomechanical properties is not fully understood. Furthermore, once the threshold of motion is exceeded and grains are mobilized, their response to external fluid forces changes considerably (Guazzelli and Pouliquen 2018).

There are a variety of other processes and effects that can influence sediment movement. Some examples include organism secretions and bioturbation that can alter sediment properties (Murray *et al.* 2002), boundary layer structure that alters bed shear stresses, and groundwater-surface water interaction, particularly in the swash zone (Turner and Nielsen 1997; Nielsen *et al.*

2001). Sediment transport properties in heterogeneous sediment environments (Holland and Elmore 2008), or high latitudes where cryospheric effects and freeze-thaw cycles alter sediment conditions and mobility (Korte *et al.* 2020), are less well studied. Regardless of composition, hydrodynamic and sediment-scale processes may locally reshape the bed depending on forcing intensity. For example, foreshore areas under swash zone forcing tend to be planar with sediment transport occurring as sheet flow via large bed-shear stresses (Chardon-Maldonado *et al.* 2016; Masselink and Puleo 2006). Rippled bedforms are common in the wave shoaling zone and surf zone (Hay and Mudge 2005), enhance turbulent coherent structures (Zhou *et al.* 2014), and can modify transport or even reverse net transport direction (van der Werf *et al.* 2006; Pedocchi and García 2009). Hydraulic-jump-driven antidunes may also be present at the inner-surf to swash zone transition on dissipative beaches (Broome and Komar 1979).

Medium-scale processes

Medium-scale processes are defined as spanning from tidal (12-24 hours) to multi-year fluctuations (O 10^1 to 10^3 days) and spatial scales of up to 1 km O (10^1) to O (10^3) m. Medium-scale process knowledge is needed for understanding sediment budgets within a littoral system, the evolution of sand bars, berms, inlets, beach-dune recovery, and the role of vegetation within coastal systems (ecomorphodynamics). Importantly, engineering and management decisions are often made at the medium scale, impacting coastal planning, risk perceptions, and policy (Ferreira *et al.*, 2024). Predicting medium-scale morphodynamics remains challenging due to complex interactions between small-scale sediment transport, human engineering interventions, ecological feedback, and seasonal to interannual variability (Lazarus and Goldstein 2019; Moore *et al.* 2025). Furthermore, multi-year observations of medium-scale change in the nearshore are difficult and expensive to collect and are inevitably limited, sometimes undersampling the variability in smaller-scale processes (Banno 2023).

Large-scale coastal change

Large-scale coastal change integrates the shorter-term processes, with all of their non-linear feedback, and is forced by weather and oceanic conditions, including all of their variability. These processes increase through small- and medium-scale and manifest at geologic scale with time frames up to 100 years (O 10^1 to 10^2 years) and spatial scales from 1 km-1000 km (O 10^3 to 10^6 m) or more. Prediction of sediment transport and morphodynamics at this temporal/spatial scale is required to develop and adapt holistic engineering solutions, including nature-based and hybrid structures. One aspect of this interconnectedness includes how the relevant spatial scales can dynamically change with conditions; for example, the size of a large littoral cell can expand as wave energy increases (George *et al.* 2022). Attention has been devoted to important drivers of coastal morphodynamics, including the response of sandy barrier islands to extreme storms (Sherwood *et al.* 2022), island stability and migration over centennial timescales (Reeves *et al.* 2022), and SLR impacts on beaches (Vousdoukas *et al.* 2020) and river deltas (Nienhuis *et al.* 2023). Some of these large-scale changes have been investigated through global mapping of sandy shorelines from satellite imagery (Luijendijk *et al.* 2018; Vos *et al.* 2019a, b).

Morphology and sediment transport observations

The general approach for "measuring" sediment transport happens at the small scale and is derived from coupled velocity and concentration measurements. Velocity measurements are now routinely acquired using acoustic Doppler and other sensors; particle image velocimetry (PIV) is a nonintrusive method; however, these rely on optimal illumination and are mainly limited to use in the laboratory (Cowen *et al.* 2003). In contrast, few commercial optical backscatter and acoustic sensors have been used for sediment suspension (Beach *et al.* 1992; Wilson *et al.* 2024), and they are prone to error in turbulent, aerated environments. Several custom-made conductivity (Lanckriet *et al.* 2013; van der Zanden *et al.* 2013) and acoustic (Hurther *et al.* 2011; Hay *et al.* 2012) sensors for bed load/sheet flow concentration have been used with success in laboratory and field experiments; however, no commercially available sensor exists. Overall, these sensors have improved sediment transport understanding, including how the different transport aspects (bedload/sheet flow and suspended load) may be partitioned (Mieras *et al.* 2019; Puleo *et al.* 2016). Yet, there are still challenges in measuring sediment transport and geotechnical properties that can be addressed by developing new sensors and measurement techniques (Brand *et al.* 2020; Brilli and Stark 2024).

Capabilities for collecting observations at medium to large scales, which are critical for linking event-driven sediment transport to long-term recovery, morphologic evolution, and land and resource management-relevant change, have advanced significantly through satellite remote sensing, autonomous platforms, and operational imaging. Satellite remote sensing has shifted coastal science from studying a small subset of the world's beaches to capturing daily, high-resolution, global coverage (Vitousek *et al.* 2023a). Satellite-based approaches now underpin global shoreline change monitoring, exemplified by open-source tools like CoastSat (Vos *et al.* 2019a, b) and CoastSeg (Fitzpatrick *et al.* 2024), which extract shorelines from imagery to track long-term trends that can be integrated into data-driven models for predicting future shoreline changes at event scale to long-term time frames (Vitousek *et al.* 2023b). Recent use of optical satellite imagery includes estimating topography and bathymetry from successive images (Bergsma *et al.* 2021) and applying structure-from-motion photogrammetry to measure beachface morphology (Brown *et al.* 2025). Regional coastal survey coverage can be achieved with airborne light detection and ranging (Lidar) or aerial imagery combined with structure-from-motion processing for rapid event response data collection (Warrick *et al.* 2019); however, these surveys can only be conducted infrequently. Autonomous-based platforms can also extend survey coverage to subaqueous morphology (Bak *et al.* 2022, 2023; Francis and Traykovski 2021).

Terrestrial systems, such as the continuously operating Lidar at the USACE Field Research Facility (O'Dea *et al.* 2019), Argus camera systems (Holman and Stanley 2007), and USGS Coast Cams, provide near-real-time hourly observations to monitor changing beachface morphology. Remote-sensed imagery combined with ML enables landcover classification (Buscombe and Richie 2018), backshore morphology estimations (Mao *et al.* 2022), and roughness

parameterization for flood models (Sherwood *et al.* 2022). Coordinated strategies for combining remote sensing and in-situ measurements are essential, as ground-truth data are needed for high quality image processing, model training, and validation (Splinter *et al.* 2018). Coordinated observing efforts, including research facilities such as the USACE Field Research Facility and the Hazaki Oceanographical Research Station, along with sustained (e.g., Ruggiero *et al.* 2016) and intermittent field campaigns (e.g., Cialone *et al.* 2019), continue to support critical coastal morphological data collection despite cost and logistical challenges. Together, these innovations deliver multi-scale, high-resolution observations of coastal change, transforming monitoring from episodic surveys to continuous, integrated systems.

Morphodynamic and sediment transport models

Numerical modeling tools span small- to large-scale approaches by explicitly resolving physical processes. Small-scale discrete element models may resolve individual grains (Calantoni *et al.* 2004), but they are impractical to simulate entire beach profiles over long-time scales. Medium-scale models resolve hydrodynamics and sediment processes over beach and nearshore scales, enabling simulation of depth-dependent sediment concentration and morphodynamic response, often using Computational Fluid Dynamics (CFD) approaches such as the OpenFoam platform (Kim *et al.* 2019). Other medium-scale frameworks resolve key wave processes including infragravity motions (e.g., COAWST with InWave; Olabarrieta *et al.* 2023), and wave-resolving (non-hydrostatic XBeach and SWASH, Zijlema *et al.* 2011; McCall *et al.* 2014) or Boussinesq approaches (FUNWAVE; Shi *et al.* 2012). Wave-averaging methods (e.g. XBeach hydrostatic, Roelvink *et al.* 2009) enable longer-term simulations but require additional parameterization for both higher-order wave statistics (van Thiel de Vries 2009; Ruessink *et al.* 2012; Rocha *et al.* 2017), and wave-breaking turbulence on sediment transport (Roelvink and Stive 1989; van Thiel de Vries 2009).

In large-scale modelling, there are some tradeoffs between physical fidelity and computation costs, with some models using turbulence submodels (e.g., COAWST, SCHISM, Telemac) and others using model coupling are capable of simulating morphodynamics on scales up to weeks and tens of kilometers (e.g., Bertin *et al.* 2020; Hegermiller *et al.* 2022; Villaret *et al.* 2013, Warner *et al.* 2010). Recent work has used reduced-complexity hydrodynamic models with simplified physics for simulating large numbers of storm events over a large spatial area (Leijnse *et al.* 2021), and simplified approaches to forecast coastal change over large scales in real time (Birchler *et al.* 2024).

Data-driven modeling approaches will be further enhanced with the increased use of ML (Goldstein *et al.*, 2019), which is already being leveraged to classify landcover in aerial and satellite imagery (Hoonhout *et al.* 2015), map shoreline locations and beach slopes (Fitzpatrick *et al.* 2024; Tsiakos and Chalkias 2023; Vos *et al.* 2019a, b, 2020), predict shoreline change (Fogarin *et al.* 2023; Gómez-de la Peña *et al.* 2023), and simulate estuarine morphology (Weber de Melo *et al.* 2022). Data-driven models leverage dense observational records to efficiently predict coastal morphodynamic change that would be computationally prohibitive for fully physics-based models, but their applicability is constrained by data availability, limited generalizability beyond the training domain, and reduced physical interpretability.

ECOSYSTEM CHANGE AND HEALTH

Healthy coastal ecosystems act as natural infrastructure that mitigates coastal hazards, supports fisheries and tourism economies, and regulates key environmental conditions such as water quality, carbon storage, and nutrient cycling. These systems safeguard human health by mitigating eutrophication, hypoxia, acidification, harmful algal blooms, and pathogen contamination, yet are increasingly threatened by development, SLR, and intensifying storms that erode the land-water interface, or "resilience zone." Protecting and restoring this dynamic interface of dunes, marshes, tidal flats, and estuarine and nearshore waters is critical, as these habitats underpin essential physical and ecological processes and collectively enhance coastal and community resilience (Bridges *et al.* 2022). Nature-based and hybrid engineering approaches are being advanced to recover lost functionality; for example, dunes with healthy vegetation buffer storm surges (Radfar *et al.* 2024), marshes filter pollutants and sequester carbon, and oyster reefs and seagrass beds attenuate waves and reduce inundation. Solutions like these provide environmental, economic, and social benefits (Bridges *et al.* 2021; Tritinger *et al.* 2024; Sigren *et al.* 2014; Morton *et al.* 2025).

A healthy ecosystem is one that maintains biodiversity, structure, and function under stress, consistent with United Nations' Sustainable Development Goal (UN SDG) 14, "Life below water" (Rapport *et al.* 1998; UNEP 2021). Water quality is a key indicator, assessed through integrated indices combining multiple geophysical, chemical, and biological parameters (EPA 2023; Uddin *et al.* 2021). Maintaining and evaluating coastal ecosystem health thus requires interdisciplinary monitoring and modeling to capture dynamic feedback across varying scales and to guide sustainable management. The following sections summarize the state of the science in monitoring and modeling coastal ecosystem change and water quality, which together provide the basis for understanding and managing these vital systems.

Monitoring ecosystem change and water quality

Environmental monitoring of coastal waters has greatly benefited from technological advances over the past several decades (e.g., Pellerin *et al.* 2016). The deployment and operation of sensors now takes place at unprecedented spatial and temporal frequencies, and the generation of vast datasets is now routine (Butts-Wilmsmeyer *et al.* 2020). Even with these advancements, there remains a need for intensive maintenance in coastal regions due to biofouling and human interference. This is particularly true for temperature, conductivity, salinity, turbidity, oxygen, pH, and chlorophyll, but the maturity of these technologies varies, with physical and chemical parameter sensors generally being much more deployment-ready than biological parameter sensors (Graham *et al.* 2022). Therefore, traditional sampling schemes involving field sampling and laboratory processing persist with major environmental quality parameters such as fecal indicator bacteria (Hannides *et al.* 2021). The resulting demands on trained professionals are supplemented by increasingly sophisticated community science (citizen science) programs and volunteer monitoring networks that engage the public in data collection (Ramírez *et al.* 2023).

Targeted process studies led by research institutions play a crucial role in illuminating how different environmental parameters interact and vary over time and space. These studies, sometimes limited in duration or scope, help disentangle natural variability from anthropogenic impacts and reveal connections between drivers (like river discharge or land-use changes) and responses (like algal blooms or oxygen depletion; Gunderson *et al.* 2016). Meanwhile, long-term operational monitoring programs are primarily driven by government mandates and are funded at national, state, or local levels to fulfill regulatory requirements (such as the federal Clean Water Act or state water quality standards; e.g. the Beaches Environmental Assessment and Coastal Health Act of 2000). Recent collaborations between the U.S. Environmental Protection Agency (EPA) and U.S. Geological Survey (2025a) highlight both the potential and the complexity of integrating these datasets. Although historical records exist for many water-quality parameters, significant spatial and temporal gaps (especially for biological and chemical measurements) limit the development of robust, operational models for ecosystem processes (Butts-Wilmsmeyer *et al.* 2020). Addressing these gaps will require coordinated data standards, expanded sensor networks, and cross-agency integration to ensure that coastal monitoring systems can fully support reliable forecasting and management (Cooley *et al.* 2022).

A variety of pollutants and water-quality indicators illustrate the evolving state of coastal monitoring. Among the most well-documented are legacy contaminants, including heavy metals such as lead and mercury, banned pesticides such as DDT, and persistent industrial chemicals such as PCBs. Historical data are available for lead, mercury, pesticides such as DDTs, and industrial organics such as PCBs (UNEP 2023). In the case of macro- and micro-plastics and "forever" chemicals, analytical techniques and monitoring systems are developed and refined further, supported by targeted funding campaigns (U.S. Environmental Protection Agency 2025b). However, ecosystem-wide impacts of these less-studied and less-monitored organics are not well known.

Nutrient pollution remains one of the most widespread anthropogenic stressors affecting coastal ecosystems (McDowell *et al.* 2025). Excess nitrogen and phosphorus, typically delivered through agricultural runoff, urban wastewater, and stormwater discharges, drive cultural eutrophication in estuaries and nearshore waters (Bricker *et al.* 2007). Sensors for these parameters are commercially available, but they are either unaffordable for most entities or suffer from significant interference when used in the coastal zone. For example, chromophoric/colored or fluorescent dissolved organic matter can affect the optical sensor detection of nitrate (Johnson and Coletti 2002; Pellerin *et al.* 2016). Despite these technical challenges, the extensive historical datasets available for major watersheds allow for reliable calculations of nutrient loads to coastal waters and support efforts to model and mitigate their impacts (Hyer *et al.* 2020; Stackpoole *et al.* 2021).

Microbial contaminants and harmful algal blooms (HABs) also pose significant public health and environmental concerns. Fecal indicator bacteria (FIB), such as *Escherichia coli* and *Enterococcus* spp., are routinely monitored in coastal waters to assess risks to swimmers and shellfish consumers (Russo *et al.* 2020). In the case of FIB, several methodological approaches rely on time-consuming laboratory incubations and are often non-source (human) specific. This has led to increasing interest in rapid molecular techniques, such as quantitative PCR (qPCR), which can detect bacterial DNA within hours (Holcomb and Stewart 2020). Similarly, HAB monitoring programs now use a mix of traditional cell counts, toxin assays, and newer tools such as eDNA sampling, remote sensing, and pigment sensors on autonomous platforms to detect toxic algae more rapidly (Brenckman *et al.* 2025). However, the expansion of genetic screening applications will accelerate the detection and consequently the public notification of these threats (see reviews in Elko *et al.* 2022; Hannides *et al.* 2021).

Monitoring of coastal habitats and living resources has also advanced rapidly with the growth of remote sensing and autonomous technologies. Whereas habitat mapping once depended on aerial photography and field surveys, today's efforts increasingly use drones, autonomous surface vessels, underwater ROVs, and high-resolution satellite imagery to assess the extent and condition of wetlands, seagrass meadows, coral and oyster reefs, mangroves, and dunes (e.g., Ventura *et al.* 2023). Extensive datasets on the presence, abundance, and biomass of indicator or "keystone" species, commercially important groups, and critical invasive species are available (e.g., see references in Shukla *et al.* 2023; NOAA 2026; Simpson *et al.* 2021), and allow for temporal analysis of population patterns and, to a lesser degree, spatial distributions. Advances in species monitoring, such as eDNA, may revolutionize how species distribution surveys are conducted (Goodwin *et al.* 2024). Coordination may be needed to monitor species expansions across latitudes, in the same vein as monitoring for commercially -important species (Hollowed *et al.* 2013; Campana *et al.* 2020; Slesinger *et al.* 2021).

Monitoring efforts also must increasingly account for coastal squeeze (e.g., Doody 2013; Pontee 2013), and associated habitat conversion, where rising water levels, sediment deficits, and constrained landward migration drive shifts among coastal and estuarine ecosystems. Studies warn that without space to migrate, many high marsh areas will drown or erode, essentially compressing the ecosystem into a narrower zone and reducing overall wetland extent (Day *et al.* 2024). These transitions are further complicated by nonlinearity in climate- and chemistry-driven vegetation change (i.e., the northward expansion of mangroves into historically grass dominated marshes) raising critical questions about whether such conversions maintain, enhance, or fundamentally alter coastal biodiversity and ecosystem function over time (Osland *et al.* 2022; Saintilan *et al.* 2025). Maintaining a mosaic of marsh and mangrove communities (each with different biomass structures and soil-building capacities) is thought to enhance overall resilience and biodiversity (Osland *et al.* 2022), underscoring the importance of long-term monitoring to understand and manage these dynamic transitions.

Despite these advances, sediment dynamics and groundwater processes remain under-monitored yet critically important for understanding ecosystem health. Coastal sediments act as long-term repositories for both pollutants and pathogens. Many contaminants, particularly hydrophobic compounds, bind to sediment particles and can persist for years, creating a latent source of

pollution that may be resuspended by storms or bioturbation (Gellis *et al.* 2024). Moreover, sediments harbor high microbial populations that can influence local water quality and biogeochemical cycling (Halliday and Gast 2011). Monitoring changes in sediment accumulation and erosion is essential, not only for understanding contaminant fate but also for tracking sediment hot spots, which are areas experiencing localized accretion or erosion that can drastically alter habitat structure and shoreline stability (Tritinger *et al.* 2025). Tools such as sediment traps, surface elevation tables, and repeat surveys with remote sensing platforms can reveal long-term trends, but capturing rapid sediment fluxes during storm events remains technically difficult.

Groundwater, particularly submarine groundwater discharge (SGD), is another key but understudied pathway for nutrient and pollutant delivery to coastal waters (Charette 2007, 2013). In coastal areas with permeable soils and widespread septic system use, SGD can carry significant loads of nitrogen and other dissolved substances, potentially fueling eutrophication or contaminating shellfish beds (e.g., Herren *et al.* 2021). Unlike surface runoff, these flows are harder to observe, requiring specialized techniques like seepage meters, tracers, or geophysical surveys. On larger scales, shelf-wide groundwater exchange also plays a role in moving freshwater and solutes from land to sea (e.g., Kwon *et al.* 2014). Fully incorporating sediment processes and groundwater dynamics into coastal monitoring networks is a critical next step for achieving a more holistic and predictive understanding of coastal ecosystem health.

Modeling ecosystem change and water quality

The USCRP has been instrumental in sponsoring studies toward predictive nowcasting/forecasting models that aim to identify risks to ecosystems and humans. The effectiveness of data-driven models has been greatly enhanced by ML advances and near-real-time data streams. Through calibration and validation, these models are evolving into reliable predictive systems, such as those used for FIB and HABs (Francy *et al.* 2020). The assessment of cultural eutrophication and associated coastal hypoxia has benefited from modeling nutrient loads from the watershed to the coast, but this is possible only for major, well-studied watersheds and the availability of decades-long datasets. The role of groundwater transport, even in these cases, still lags behind surface runoff transport.

Effective decision-making on issues pertaining to water quality and ecosystem health relies on the availability of relevant and timely information (Cooley *et al.* 2022). This often implies the application of ICON (Integrated, Coordinated, Open, and Networked) and FAIR (Findable, Accessible, Interoperable, and Reusable) data and model generation and dissemination (e.g., Graham *et al.* 2022). However, simply providing data or model results is not enough for decision-making — expert interpretation remains crucial (Ncube and Ngulube 2024). Many local decision-makers (e.g., municipal officials, resource managers) rely on scientists and technical experts to help translate model outputs into implications for policy or action. Thus, partnerships among federal, state, academic, and citizen-science experts are key to turning complex model forecasts into clear guidance. Public outreach and citizen engagement have also expanded in this context. New web-based portals and smartphone apps now communicate forecasted conditions, health risks, or resource status directly to the public; for instance, apps that notify users of HAB risks or poor beach water quality based on model-data systems (e.g., EPA 2024; USC *et al.* 2025). These innovations show great promise for increasing situational awareness and enabling more proactive responses. Nevertheless, continued improvements in public-health warning systems are needed, especially to minimize false alarms and ensure messages reach the right audiences in a timely manner (Sadiq *et al.* 2023).

Looking beyond short-term forecasting, long-term planning to sustain ecosystem health is increasingly incorporating complex interactions and feedback, such as the interaction between hydrodynamics, morphology, and marsh ecology (Passeri *et al.* 2015). The timely processing of high-resolution habitat mapping data (e.g., from Lidar, drones, satellite) and analysis of trends are crucial to detect early signs of habitat degradation or recovery. Providing these insights to decision-makers in an actionable format (e.g., maps of marsh-loss hot spots or coral reef condition trends) can prompt intervention before irreversible damage occurs. Management approaches are gradually embracing the fact that multiple stressors act simultaneously on coastal ecosystems; for example, warming, acidification, pollution, and physical habitat disruption all interact. Tools like the Ecosystem-Based Management (EBM) approach by NOAA (2025a) give a great example of a holistic approach, integrating ecological and social data to guide decisions that balance use and conservation across an entire ecosystem. Despite these advances, addressing ecosystem pressures through broad measures, for example, pollutant reductions at the watershed scale using Soil and Water Assessment Tool (SWAT) modeling (e.g., Bieger *et al.* 2017), presents substantial complexity for decision-making processes, especially when weighing socioeconomic tradeoffs.

Modeling and monitoring tools for coastal ecosystem health are advancing rapidly, but their full potential depends on the collaboration of multisector and multidisciplinary teams (Cooley *et al.* 2022). Sustained partnerships among federal, state, and local agencies, academic institutions, private industry, and community science networks are essential to achieve the scale, standardization, and longevity required for meaningful ecosystem assessment. These collaborations enable consistent data collection methods, shared modeling frameworks, and unified indicators that extend across geographic and jurisdictional boundaries. By coupling innovation with coordination, these teams expand the reach and relevance of coastal monitoring. This reduces uncertainty in ecosystem health predictions, leading to management decisions that enhance the adaptive capacity and resilience of coastal systems.

ADAPTATION TO COASTAL HAZARDS

The translation of coastal research into actionable insights is central for providing information for decision-making to coastal communities, protecting national security assets, and sustaining coastal economies. The coastal research community enables this translation through a range of cross-cutting components. For instance, there has been considerable progress made around understanding, modeling, and communicating strategies for community adaptation to

coastal hazards (e.g., Berrang-Ford *et al.* 2021). However, determining when to adapt, how to adapt, and the ultimate goals of adaptation remain challenging for many coastal communities intent on creating positive coastal futures (Leung *et al.* 2024).

Adaptation decisions made today can dramatically influence the extent to which communities incur negative impacts of future coastal hazards, including those driven by climate change. A community's adaptation preparedness for coastal natural hazards can be quantified by the level of risk knowledge, plans in place, actions implemented, existing institutional and financial capacities, risk reduction mechanisms, and strategies for long-term adaptation pathways. A recent global assessment of the state of progress toward coastal adaptation (Magnan *et al.* 2023) found that coastal societies across the spectrum from urban to rural have reasonable risk knowledge and societal awareness of risk. However, coastal communities typically lack effective plans and actions for risk reduction, lack evidence of coastal hazard risk reduction, and lack pathway-like approaches for mitigating risk.

Adapting to coastal hazards is a societal grand challenge as coastal systems are experiencing the compounding effects of rising sea levels, changing patterns of storminess, and mounting human stressors on coastal resources and ecosystems. Simpson *et al.* (2023) found that most responses to compounding risks are either reactive or maladaptive, while relatively few responses are anticipatory. Many communities may have options to adapt but do not have mechanisms in place to leverage those options when natural hazards strike.

Adaptation pathways

The paradigm of Dynamic Adaptation Policy Pathways (DAPP) (Haasnoot *et al.* 2013) was developed to assist with decision-making under conditions of deep uncertainty. Adaptation pathways are a decision-making approach that identifies and implements actions to prepare for and respond to coastal hazards, consider future uncertainties, and allow for flexible, progressive adaptation strategies (Werners *et al.* 2021). The DAPP framework incorporates plausible future scenarios and their development over time, sequences of adaptation measures, corrective actions to address vulnerabilities, and monitoring to determine when to activate new measures (Valente and Pinho 2025). The approach allows for a wide variety of uncertainties to be explored dynamically while identifying near-term low-regret adaptation measures and keeping future options open via ongoing learning from evolving knowledge (Haasnoot *et al.* 2013).

To facilitate the uptake of adaptation pathways by coastal communities facing SLR, Haasnoot *et al.* (2019) generalized the approach for common coastal archetypes (open coasts, deltas, and estuaries in urban and rural settings), resulting in generic pathways available for adjustment to local conditions. The wide portfolio of adaptation options available for SLR and other coastal hazards are canonically divided into three categories following the IPCC (Dronkers *et al.* 1990): protect (e.g., dikes, seawalls, natural and nature-based solutions [NNBS]), accommodate (e.g., floodproofing and pumps), and retreat (e.g., managed retreat from the shoreline). Applying the adaptation pathways approach aids coastal communities in identifying when to start planning adaptation measures — typically earlier than anticipated — and can be used in tandem with deep stakeholder engagement to determine what adaptation measures are acceptable based on local values and constraints.

Coupled natural human systems modeling

More than a decade ago, Elko *et al.* (2015) asserted that numerical "models incorporating coupled anthropogenic alterations and physical morphological dynamics are in their infancy…" Citing early coupled natural human systems modeling successes (e.g., McNamara and Werner 2008a,b), and suggesting that the further development of coupled models is crucial to addressing pressing societal needs around long-term coastal sustainability, Elko *et al.* (2015) posed the following research question: "What drives human interventions, how do mitigation strategies couple with natural processes, impact system dynamics, and long-term sustainability, and how might these factors evolve as physical, economic, and policy forcings change?" Explorations of future hazard impacts and uncertainty are incomplete without the inclusion of human systems into modeling frameworks (Kopp *et al.* 2019; Sandifer *et al.* 2021; Peek *et al.* 2020; Lazarus and Goldstein 2019). Human decision-making can drastically influence projections of hazard exposure and costs (e.g., Hinkel *et al.* 2014; Lincke and Hinkel 2021). So, integrated systems modeling approaches that incorporate societal evolution models in combination with coastal processes, climate change, and hazard models are necessary to provide a more complete picture of future hazard impacts and the efficacy of various adaptation options to reduce risk (Leung *et al.* 2024; Schroder *et al.* 2022). Models that combine hurricane forecasts and damage estimates based on building inventories with economic analyses, policy interventions, and household decisions to engage in risk mitigation actions, provide more holistic insights into how hazards, adaptations, and economic and policy systems interact (Guo *et al.* 2022; Wang *et al.* 2020).

Significant progress has been made incorporating the adaptation pathways with modeling frameworks that combine human dynamics with physical processes. For example, adaptation measures implemented to protect roadways and communities (e.g., construction of large dunes, emplacement of beach nourishment, and removal of washover) can modify characteristics of barrier island systems that ultimately, over time scales of decades to centuries, will limit their habitability (Anarde *et al.* 2024). Additionally, dissimilar management priorities such as protecting roads and nourishing beaches, can increase erosion rates at neighboring communities (Anarde *et al.* 2024), highlighting the importance of understanding coupled human-natural interactions through multidisciplinary modeling approaches (Barnard and Passeri 2024).

Agent-based and future visioning models (computational tools used for simulating the actions and interactions of individual and/or collective agents in order to understand the behavior of a system and what governs its outcomes) are also promising. Particularly when they use stochastic models to assess probabilistic sequences and magnitudes of coastal hazards, agent-based models can further help coastal communities understand the role policy decisions can play in shaping future coastal hazards exposure, impacts, and equity (Fox *et al.* 2023; Nalau and Cobb 2022; Zhuo and Han 2020). These techniques provide

powerful tools to allow communities to visualize feedback within the coupled natural-human systems and identify decision pathways to achieve more desirable futures under uncertainty (e.g., Mills *et al.* 2018; Lipiec *et al.* 2018). Understanding the impacts of adaptation decisions and coastal hazards both as individual drivers and coupled within scenarios can allow for more robust and informed determination of best practices with respect to various adaptation pathways — within the constraints of the modeled representation of coastal community drivers and processes (Mills *et al.* 2021). Agent-based and future visioning models can also be critical for marrying theoretical adaptation models with the political, social, cultural, and economic realities of coastal communities (Kopp *et al.* 2019). They have been demonstrated to improve adaptation literacy, motivation, and capacity within participating communities (Nalau and Cobb 2022; Jagannathan *et al.* 2023).

APPLIED RESEARCH

Observations

Coastal observations to address a range of interdisciplinary research and operational use cases have significantly expanded over the past decade. Here operational use cases are defined as systems running in a real-time, production environment that generate outputs to inform decision-making. Close-range remote sensing data collected from sensors affixed to crewed and uncrewed aerial systems and tall coastal infrastructure are burgeoning in private, government, and academic entities. For instance, increasingly large networks of fixed optical cameras are being implemented in coastal communities (Dusek *et al.* 2019; Harley and Kinsela 2022; Palmsten and Brodie 2022), and the advancement of commercial structure-from-motion software has led to an increasing amount of 3D datasets produced by photogrammetry in coastal areas (Conlin *et al.* 2018). Ocean currents just outside the nearshore (1 km-200 km) are continuously observed along much of the U.S. coast via the NOAA IOOS high frequency radar network (Paduan and Washburn, 2013; Roarty *et al.* 2019), which may be able to provide wave observations as well (Wyatt and Green 2024). Lidar data continue to be an important component of coastal data over large spatial scales, and Lidar time series extending over three decades are now available, building a time series of high-resolution 3D datasets of coastal change (Doran *et al.* 2017). The cost and size of Lidar instruments have decreased by several orders of magnitude, largely brought about by advances in self-driving cars and smartphone technology, whose sensors have been adapted to new applications in close-range sensing of waves and morphology from fixed and mobile platforms (Baker *et al.* 2023; Feddersen *et al.* 2023; Luetzenburg *et al.* 2024; Martins *et al.* 2025). Satellite observations of the coastal zone have also increased with improvements in resolution and data analysis methods — in particular, monitoring shoreline position (Vos *et al.* 2019a, b), measuring waves and currents (Hauser *et al.* 2023), and even estimating coastal bathymetry (O'Dea *et al.* 2025).

Relatively low-cost, expendable, or miniature sensors have become widely available using Internet-of-Things technology. There are distributed networks used for near-real-time model assessment and assimilation of waves and water levels (Houghton *et al.* 2022; Son *et al.* 2023), which greatly increase the volume and efficiency of coastal observational data. These low-cost networks are being actively supported by NOAA (e.g. Hernandez *et al.* 2025), and supplement existing networks of wave buoys and water level gauges (Behrens *et al.* 2024; Miller and Luscher 2018; Riley 2024; U.S. Geological Survey 2025b). Uncrewed systems continue to provide new data from air, water surface, and subsurface. Platforms include wave gliders, bottom-crawling amphibious vehicles, uncrewed surface vessels, or even hybrid uncrewed aircraft and surface vessels to measure a range of coastal oceanographic parameters from waves, currents, atmospheric properties, near-surface turbulence, bathymetry, and other water column properties (Amador *et al.* 2023; Bak *et al.* 2023; Francis and Traykovski 2021; Mercado *et al.* 2019). As in previous decades, large, coordinated field experiments measuring wave, water level, and morphological change are being conducted. Recent experiments also include hydrodynamic, morphologic, and structural damage forecasting during extreme events and are leading to new understanding of community forecasting capabilities and the development of rapid storm response capabilities (Houghton 2025; Raubenheimer 2020; Straub *et al.* 2023). Finally, the last decade has seen a significant increase in the sharing of open data repositories, including publication of long-time series data (Ludka *et al.* 2019; National Oceanic and Atmospheric Administration, 2025; Turner *et al.* 2016; U.S. Geological Survey, 2025a; U.S. Army Corps of Engineers, 2025).

Applied models and forecasting

ML was mentioned only in passing in Elko *et al.* (2015), but the field has grown significantly since. According to a Web of Science search, the number of published manuscripts with "machine learning" and "coastal" as subjects has increased from 16 in 2014 to 683 in 2024. Primary applications of ML in nearshore work include computer vision, prediction and forecasting, and data analysis. Computer vision applications of ML include detecting marine debris, shoreline positions, and HABs (Hardison *et al.* 2019; Parrish *et al.* 2023; Vicens-Miquel *et al.* 2022), segmenting and classifying of imagery from flooded areas, land, water, and benthic features (Parrish *et al.* 2023; Wang, Y. *et al.* 2024; Williams *et al.* 2019), and developing regression models to estimate wave heights and bathymetry (Buscombe *et al.* 2020; Collins *et al.* 2021). ML applications for prediction and forecasting include predicting non-tidal residuals and settling velocities (Bruneau *et al.* 2020; Goldstein and Coco 2014), surrogate models for flooding and waves (Chen *et al.* 2021; Zahura *et al.* 2020), projecting future coastal conditions (Anderson *et al.* 2021) and post-processing forecasts (Campos *et al.* 2020). ML models can also be used to process data, including detecting and extracting features (Collins *et al.* 2021; de Silva *et al.* 2023), recognizing patterns (Mahmoudi *et al.* 2024), and generating synthetic or super resolution data (Lütjens *et al.* 2024; Wang *et al.* 2022).

The coastal research community has made significant advancements in nearshore operational forecasting since 2015. National-scale and regional-scale operational modeling systems with local resolution include storm surge (Kohno *et al.* 2018), coastal compound flooding, including storm surge fluvial and pluvial contributions (Cosgrove *et al.* 2024), rip currents (Dusek *et al.* 2014), nearshore waves (van der Westhuysen *et al.* 2013), water levels at the shoreline and dune erosion (Stockdon *et al.* 2023), and beach erosion (Turner *et al.* 2016). Refined, local-scale forecasts designed to support local decision-making are also now avail-

able in some communities (Georgas *et al.* 2016; Harley *et al.* 2016; Merrifield *et al.* 2021). The technology enabling these forecasts includes development of model coupling methods and open-source code, improved computational power and cloud computing, improved data and model access (netCDF, ERDDAP), development of meta models and ML, and availability of improved boundary conditions. These developments allow for longer forecast lead times and opportunities for near-real-time data assimilation in forecasts.

Decision support

Decision Support Tools (DSTs) harness advances made in identifying coastal hazards by leveraging data to build models across short and long-term timescales, so that communities can tailor adaptation responses to their distinct vulnerabilities, such as acute storm events, erosion, and chronic high tide flooding. DSTs can be time-intensive and challenging to execute, especially for communities with limited resources and expertise, yet these tools can facilitate informed decision-making and promote broader participation and acceptance of decisions within local communities (Newth *et al.* 2017; Palutikof *et al.* 2019a).

Effective DSTs not only require data, physical modelling of acute processes across differing spatial and temporal scales, inclusion of regulatory practices, and cost-benefit analyses, but also an understanding of end-user needs and constraints. End users often operate with limited time, budgets, or technical training, yet are expected to make high-stakes decisions (Refulio-Coronado *et al.* 2021; Simm *et al.* 2021; Collini *et al.* 2022). Further, sustained technical support for DSTs can be challenged by personnel turnover at both the community and federal level. Tools that ignore these practical considerations risk remaining underused regardless of their scientific sophistication. Recent studies have shown that DSTs are significantly more effective when end users are engaged early and often in the development process (Raub and Cotti-Rausch 2019; Refulio-Coronado *et al.* 2021; Simm *et al.* 2021; Collini *et al.* 2022). For instance, Gulf TREE, a climate resilience platform for coastal decision-makers, was co-designed with users to guide tool selection. While users may rate platforms highly in terms of usability and relevance (Collini *et al.* 2022), these strengths did not necessarily lead to widespread adoption (Collini and Smallegan 2021), highlighting a critical gap between tool quality and real-world uptake. Similarly, NOAA's National Water Model delivers valuable data for short-term resilience planning, but adoption remains limited due to a lack of stakeholder inclusion during development and insufficient accessibility for users from diverse backgrounds, many of whom lack specialized expertise in coastal processes (Raub *et al.* 2024). Findings underscore the importance of communication strategies tailored to diverse disciplinary backgrounds and user contexts, and of co-production when building stakeholder tools for coastal adaptation (Sweetman *et al.* 2024).

Tools that consider trade-offs, feedback loops, ecological functionality, and mitigation performance from a systems approach are especially valuable for informing robust, long-term strategies (Refulio-Coronado *et al.* 2021; Tritinger *et al.* 2025). One example of leveraging data to assess action is the Resilience-Increasing Strategies for Coasts Toolkit (RISC-KIT). The RISC-KIT tools provide a valuable foundation for enhancing forecasting, early warning, and long-term coastal risk assessment, offering a scalable example that can be built upon to optimize prevention, mitigation, and preparedness strategies across local, regional, and national levels (van Dongeren *et al.* 2018). The Bayesian Network-based decision support system (DSS) within RISC-KIT is designed to manage coastal risk during prevention and serve as an early-warning system. The approach is grounded in the source-pathway-receptor (SPR) framework and extends prior work by Poelhekke *et al.* (2016). Developed as part of the RISC-KIT project, the DSS predicts real-time impacts of extreme coastal events and evaluates potential disaster risk reduction (DRR) measures, with flexibility to address a range of natural hazards beyond marine storms (Jäger *et al.* 2018).

Similarly, the U.S. Army Corps of Engineers' Engineering With Nature® (EWN®) program hosts a comprehensive platform for building resilience coastlines utilizing NNBS with guidance on engaging with stakeholders, mitigation performance, adaptive management, cost-benefit analyses, and specifics based on coastal system type: beaches and dunes, coastal wetlands and tidal flats, and islands (Bridges *et al.* 2021). An application of EWN was assessed at Deer Island, Mississippi, with a goal of reducing risk in coastal systems through integrated, NNBS approaches. The systems-based framework addressed erosion, habitat loss, and storm vulnerability by integrating ecological functions and operating effectively at both local and regional scales (Tritinger *et al.* 2025).

Another example is CoastAdapt, a comprehensive framework designed to support coastal managers in addressing current and future risks through adaptation planning (Palutikof *et al.* 2019b). In this framework, the DST teaches users necessary concepts related to climate change science, projected impacts, and available adaptation strategies (Palutikof *et al.* 2019b). CoastAdapt walks users through six stages of adaptation from understanding their risk and challenges, monitoring protocols, and evaluation of mitigation efforts. However, the team reported that the framework required substantial time, effort, and financial resources, and the perceived benefits were not always evident to end users (Palutikof *et al.* 2019b).

CONCLUSION

Over the past decade, coastal research has advanced remarkably across the domains of coastal flooding, morphodynamics and sediment transport, and ecosystem change and health. These advances have deepened our understanding of fundamental processes, expanded our capacity to observe coastal environments, and improved our ability to forecast future environmental states. A particularly important development has been the rise of emerging technologies, such as low-cost sensors, which now enable higher-frequency and broader spatial coverage of coastal observations than ever before. At the same time, advances in physics-based numerical models and the rapid growth of artificial intelligence and machine learning have transformed our ability to simulate and predict coastal change. While many innovations leveraging artificial intelligence remain in their early stages, we are poised to leverage even greater improvements to further progress in the decade ahead.

It has also become clear that progress within individual disciplines is not enough. The coastal environment

is inherently interconnected: accurate flood prediction requires understanding changes in coastal morphology; modeling sediment transport depends on reliable forecasts of water levels and waves; and the health of coastal ecosystems is tied to physical drivers such as flooding extent, sedimentation, and erosion. Recognizing and integrating these linkages is essential to both scientific advancement and practical coastal management.

This integrated understanding is increasingly critical as coastal communities confront the compounding effects of sea level rise, shifting storm patterns, and mounting human pressures on coastal systems. Advances in modeling coupled natural–human systems are beginning to enable the design of dynamic adaptation pathways — approaches that allow communities to plan flexible, staged responses to uncertain future conditions. Enhanced observing networks, improved hazard models, and new decision-support tools are helping to translate scientific progress into actionable resilience strategies. As the pace of coastal change accelerates, however, continued innovation, collaboration, and communication will be vital. Ultimately, even perfect environmental predictions cannot ensure resilience unless communities have the knowledge, capabilities, and resources to apply this information in decision-making, adaptation, and action.

Addressing these challenges demands sustained cooperation among academic, governmental, and stakeholder communities, along with a research agenda that remains rigorous, responsive, and relevant. Together with Part 1, which identifies priority research directions for the coming decade, and Part 3, which places current advances in historical context, this *State of the Science* article provides a foundation for guiding the next generation of coastal research that is not only scientifically robust, but also deeply aligned with the needs of the coastal communities it serves.

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Training the next generation of U.S. coastal scientists and engineers: A 2024 & 2025 update

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The American Shore & Beach Preservation Association (ASBPA) has been committed to training the next generation of U.S. coastal scientists and engineers for nearly two decades. The 1999 National Research Council (NRC) report "Meeting Research and Education Needs in Coastal Engineering" cited concerns with reduced funding, shrinking academic programs, and an inadequate pool of trained professionals (NRC 1999). A 2012 policy statement issued by ASBPA expressed support of the implementation of an updated version of recommendations from the 1999 NRC report, suggesting that the academic community should establish a consortium to improve research and education through cooperative agreements, encouraging National Science Foundation (NSF) funding to support fundamental research on coastal engineering and science, and advocating for federal agency funding support for applied research and promotion of partnerships between academia, federal agencies, and private interests.

In response, ASBPA subsequently worked to support the creation of the U.S. Coastal Research Program (USCRP) with targeted goals to improve research and education opportunities through cooperative arrangements that would leverage major research facilities, educational capabilities, and distribute funding to support applied research and promote partnerships between academia, federal agencies, and the private sector.

In 2018, ASBPA revisited the policy statement from 2012 and benchmarked in an assessment via a survey of coastal academic researchers. The survey produced responses from 51 coastal academics representing U.S. institutions coast to coast on their five-year perspectives on topics including funding, course offerings, and graduate student populations (Elko *et al*. 2018). The main conclusions included reports of decreased funding (62%), "stable" course offerings (84%), and 75%-100% of effort in basic research. That same qualitative survey was revisited in 2024 to capture an update of the five-year trends reported in 2018, and then relaunched in 2025 motivated by reports of reduced funding, funding for projects being rescinded, a hiring freeze at many federal agencies, and other changes in the landscape of preparing for a career in the coastal sciences and engineering. This paper presents a comparison of the results from the 2024 and 2025 surveys.

METHODS

Survey questions established in the 2018 assessment were redistributed to the ASBPA and USCRP academic membership in 2024 to assess changes in the five-year trends. The survey was relaunched in 2025 to assess changes within the past year. The academic survey included questions regarding graduate programs, graduate student demographics and training, research funding, workforce development, and an open-ended comment section to share additional information about the respondent's experience and observations in U.S.-based trends in academia.

Participants: Participants were conveniently sampled through coastal newsletter mailing lists. In total, the 2024 and 2025 surveys garnered 31 and 28 unique responses, respectively. Participants were self-selecting.

Procedure: The academic survey questions from 2018 were updated to include "in the last five years" language for 2024 and changed to "in the last year" for 2025. Questions were formatted into an online form. The survey included 24 items. Five items addressed programmatic questions consisting of one free-response question and four multiple-choice questions. Nine questions were focused on graduate student training and demographics, with eight being multiple choice and one "select all that apply" question. Five questions looked at research funding with three multiple-choice questions, one yes-or-no question, and one "select all that apply" question. Finally, workforce development had two multiple-choice questions. Emails were sent out to ASBPA and USCRP membership, reminders were included in ASBPA and USCRP newsletters, and information was posted to the Coastal List email listserv. The surveys were open approximately three months each year. Additional responses were recruited from the USCRP's 2024 Decadal Visioning Workshop participants. Comparisons of the 2024 and 2025 results were normalized based on the percentage of respondents.

RESULTS

Academic survey results: Five-year trends (2024)

University trends

In 2024, there were 31 unique survey responses from institutions with Bachelor of Science (BS), Master of Science (MS), and Doctor of Philosophy (Ph.D.) programs related to coastal science, including Civil, Environmental, Ocean and/or Coastal Engineering, Marine Science, Marine Biology, Oceanography, Geosciences/Coastal Geology, and Environmental Sciences. Most reported there were between one and five tenured professors in their programs with about 20% indicating 10 or more tenured faculty. Approximately 40% reported having 2-5 non-tenured professors. Many of these programs either had zero post-doctoral fellows or reported 2-5 post-docs with

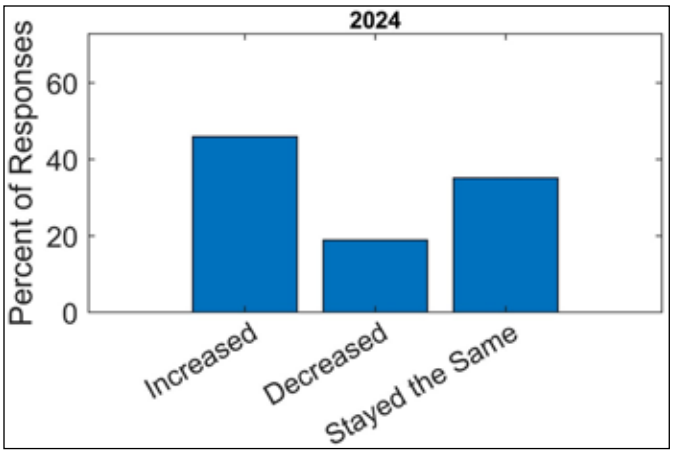

Figure 1. Responses to: Has overall coastal science/ engineering funding increased or decreased over the past five years?

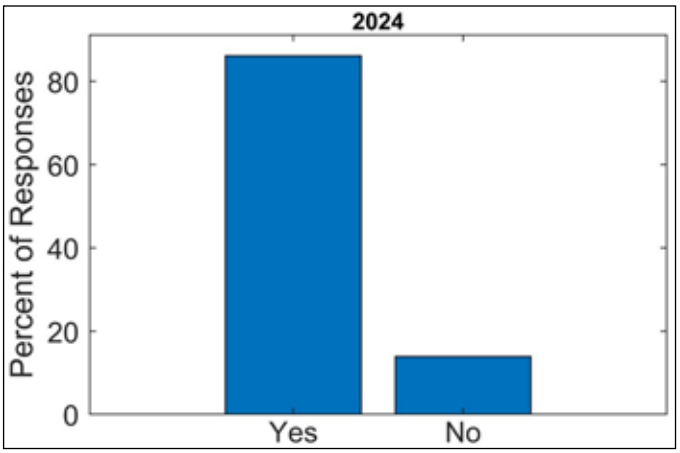

Figure 2. Responses to: Is funding difficult to obtain?

fewer programs supporting only one or more than six post-docs.

Research funding trends

In the area of funding for research, the majority of academics reported overall coastal science/engineering funding had increased or stayed the same over the past five years (Figure 1), but identified funding remains difficult to obtain (Figure 2). Agencies reported to be funding the majority of coastal academic research were cited as: National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), state agencies, U.S. Army Corps of Engineers (USACE), U.S. Coastal Research Program (USCRP), Sea Grant, and Office of Naval Research (ONR) (Figure 3). Other funding agencies included Bureau of Ocean Energy Management (BOEM), Environmental Protection Agency (EPA), National Fish and Wildlife Foundation (NFWF), Department of Energy (DOE), U.S. Geological Survey (USGS), Department of Defense Assistant Secretary for Research and Engineering [DoD ASD(R&E)], National Park Service (NPS), National Institute of Standards and Technology (NIST), U.S. Department of Transportation Federal Highway Administration (USDOT FHWA), and Private Foundations. Grant sizes reported were primarily in the $100,000-$500,000 range, with very few reported to be less than $50,000 or more than $1 million. Most academics reported their research is 25%-50% basic (rather than applied), but others also stated less than 25% or between 50%-75% is basic research (Figure 4).

Graduate training trends

The survey also assessed the state of graduate training. Most respondents reported their graduate programs had 25+ students in the program, followed by between 6-10 students. The number of responses saying their program had 1-5 students or 11-25 students was nearly equal with two respondents indicating they had zero students (Figure 5). The overwhelming majority of respondents indicated 25% or more students were domestic (less than 20% said their programs had 0 or <25% domestic students). Respondents reported students were recruited from various sources, with a slightly higher percentage coming from direct contact via email from prospective graduate students (Figure 6). Referrals from colleagues, undergraduate research collaborations, and academic conferences/seminars/workshops were reported more frequently as recruiting methods than graduate school admissions office or online platform advertising.

In terms of academic preparation, the majority of respondents indicated courses teaching fundamentals (e.g., the underlying physics, traditional nearshore oceanography, coastal geology or engineering curricula of waves, sediment transport, geomorphology, hydraulics, structural design, structures' effects on shorelines, etc.) are offered every semester at their university (Figure 7) and coastal science/ engineering courses have either increased or stayed the same over the past five years (Figure 8).

Workforce trends

Finally, the survey asked questions relating to workforce development. The percentage of international (non-U.S. citizen) graduate students and post-docs joining the non-academic U.S. workforce after concluding their training was mostly unknown or between 25% and 75% (Figure 9). When asked what percentage of graduate students joined the U.S. workforce remaining in academia, the overwhelming majority stated 0-25% (Figure 10).

The open-ended comment section provided some insight into the status of graduate student training and career preparation. Some academics expressed there was more funding to support graduate researchers in the last five years, while witnessing a decline in domestic student interest in post-graduate work. Another reported wage and job conditions after

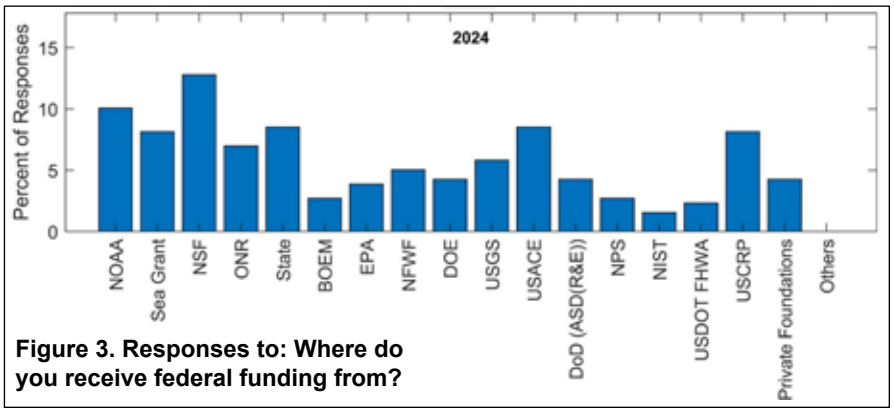

Figure 3. Responses to: Where do you receive federal funding from?

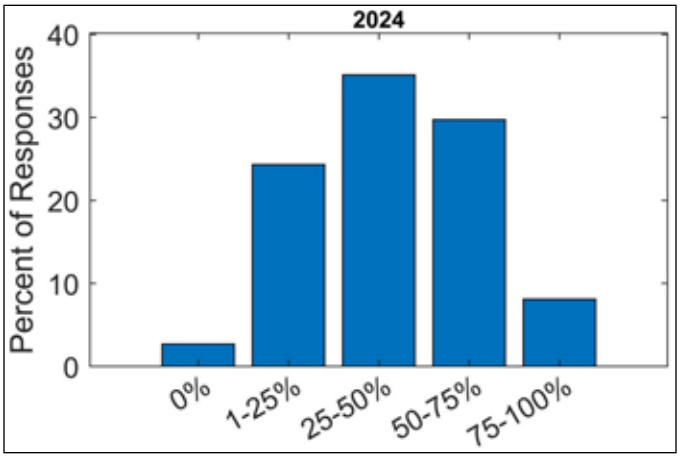

Figure 4. Responses to: What percent of your research is basic (rather than applied)?

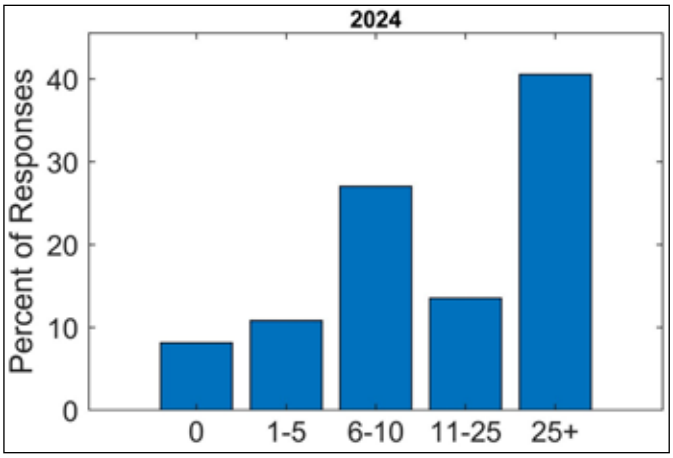

Figure 5. Responses to: How many graduate students are in your program?

undergraduate degrees were making it hard to attract and retain qualified graduate students. Another academic made note of the inverse relationship between costs of materials, living, and salaries with funding amounts.

Academic survey results: 2024 compared with 2025

University trends

The same survey was relaunched in 2025, with responses from 28 institutions with similar Bachelor of Science (BS), Master of Science (MS), and Doctor of Philosophy (Ph.D.) programs as the respondents in 2024. More than 50% of programs reported having between two and five tenured professors in their program with fewer reporting only one or six or more. Nearly 60% reported they had 1-5 non-tenured professors with more than 20% reporting they had more than six non-tenured faculty. Similar to 2024, many of these programs either reported zero post-doctoral fellows or 2-5 post-docs.

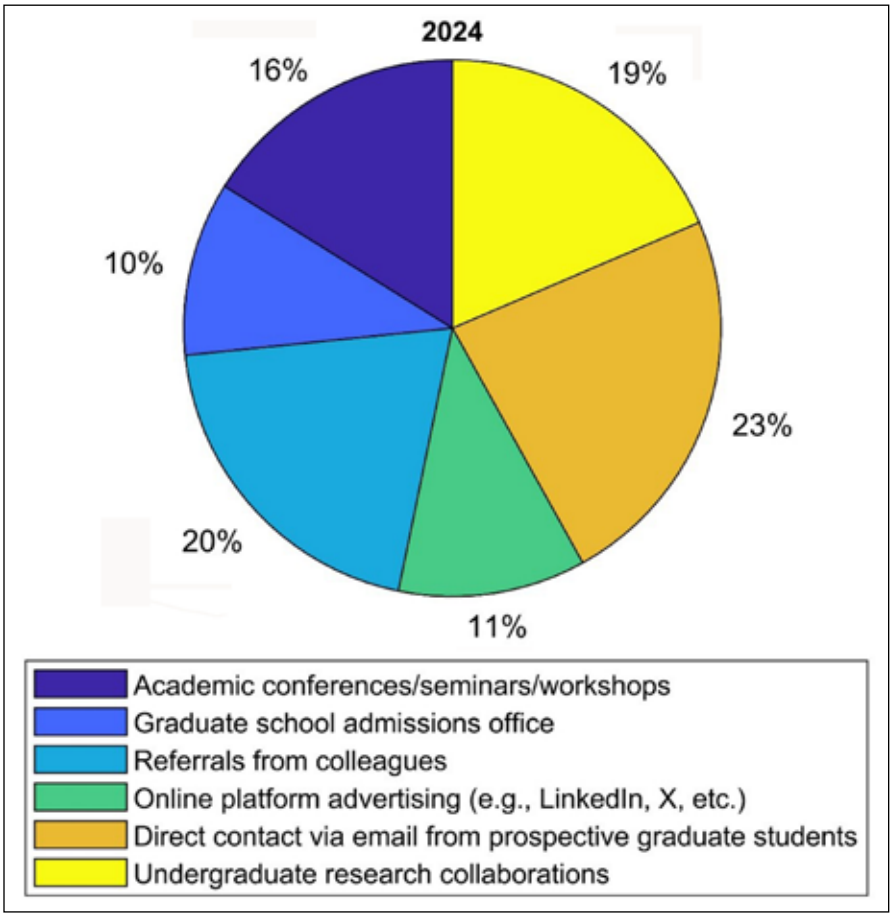

Figure 6. Responses to: What are the primary sources for recruiting graduate students (in the last decade)?

Research funding trends

In contrast to 2024, more than 60% of academics reported overall coastal science/engineering funding had decreased over the past year (Figure 11). Similarly to 2024, responses indicate funding remains difficult to obtain (Figure 12). The top funding agencies were the same as 2024 (e.g., NOAA, NSF, USACE, USCRP, Sea Grant, and state) (Figure 13). Grant sizes in 2025 were primarily in the $100,000-$500,000 range, with a slight increase in those reported to be less than $50,000 or more than $1 million. In 2025, there was a shift in the percentage of academics reporting their research is basic (rather than applied) with the majority stating 1%-25% is basic and a close split between others identifying 25%-50%, 50%-75%, or 75%-100% is basic (Figure 14).

Graduate training trends

The majority of graduate programs still had 25+ students in the program in 2025, with an increase in the number reporting 11-25 and a decrease in those reporting 6-10 (Figure 15). There was a slight increase in programs reporting 0 or 1-5 students. Additionally, the majority of respondents indicated 25% or more were domestic students. There was an increase in the percentage of respondents indicating they had 0, 0-25%, or 25%-50% domestic students and a decrease in those reporting 50%-75% domestic students. Student recruitment methods were nearly identical in the 2025 survey as reported in 2024.

Courses covering fundamentals shifted from mostly every semester in 2024 to mostly annually in 2025 (Figure 16), with the total number of coastal science/en-

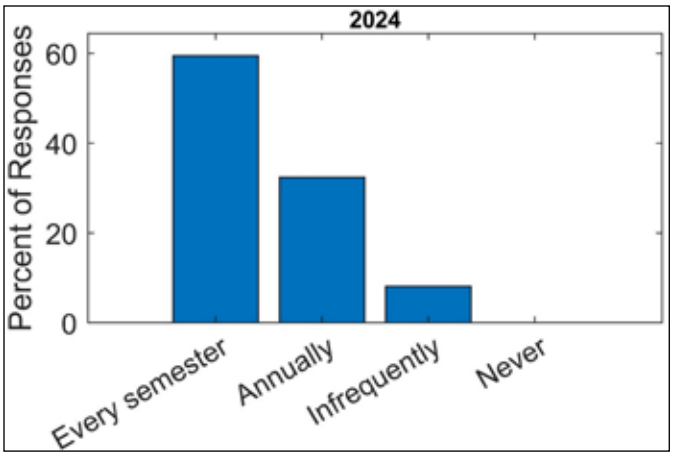

Figure 7. Responses to: How often does your university offer courses teaching fundamentals?

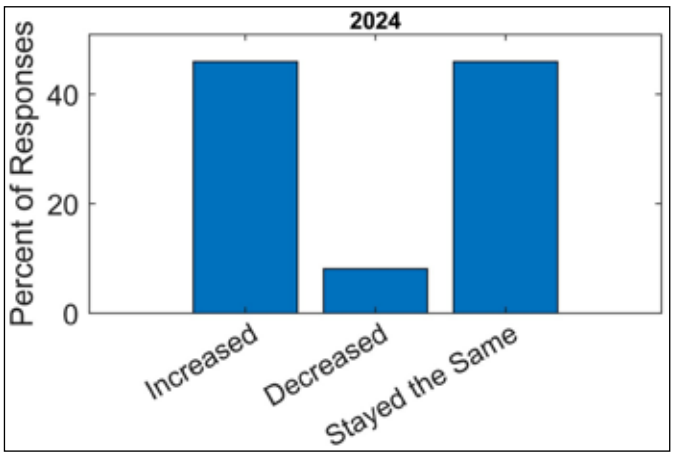

Figure 8. Responses to: Has the number of coastal science/engineering courses increased or decreased over the past 5 years?

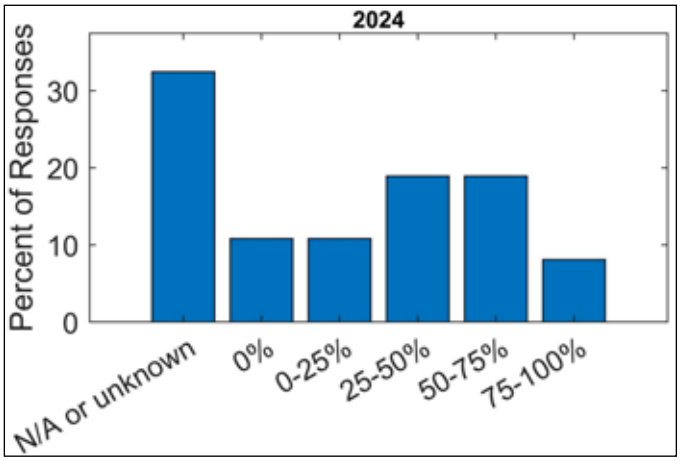

Figure 9. Responses to: What percentage of international (non-U.S. citizen) graduate students and post-docs joined the U.S. workforce (non-academic) after concluding their training?

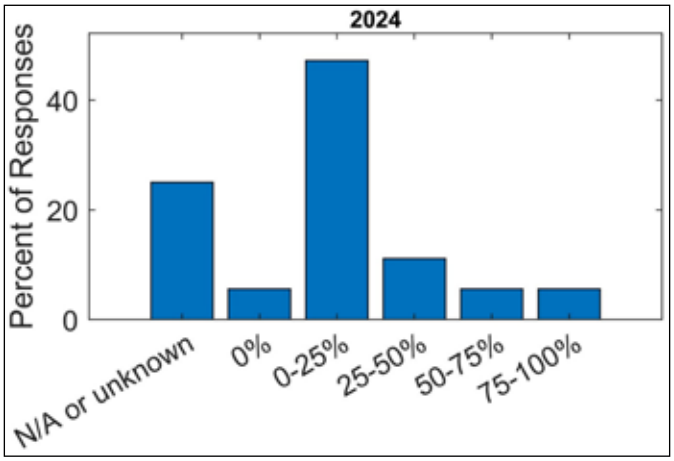

Figure 10. Responses to: What percentage of graduate students joined the U.S. workforce and remained in academia?

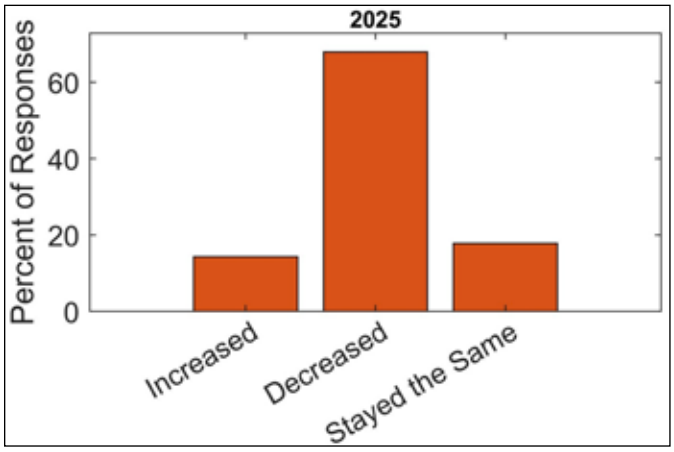

Figure 11. Responses to: Has overall coastal science/ engineering funding increased or decreased over the past year?

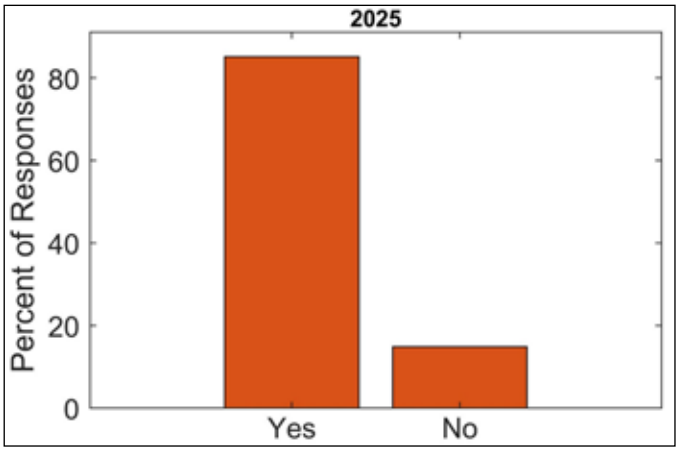

Figure 12. Responses to: Is funding difficult to obtain?

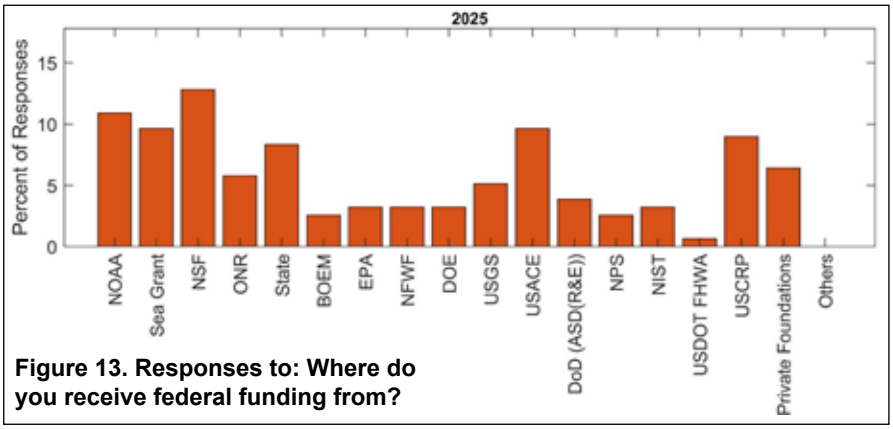

Figure 13. Responses to: Where do you receive federal funding from?

gineering courses still being reported as increased or stayed the same (Figure 17).

Workforce trends

The percentage of international (non-U.S. citizen) graduate students and post-docs joining the non-academic U.S. workforce after concluding their training reported in 2025 remained mostly unknown, with increased responses of 0-25% and decreased responses of 50%-75% (Figure 18). Far fewer respondents indicated 0-25% of graduate students joined the U.S. workforce remaining in academia, with more indicating either 0% or 50%-75% (Figure 19).

The general concern in 2025 was around funding and student support. Comments regarding the loss of project funding and the cost of supporting students relative to the opportunities for funding were expressed. There was also concern regarding loss of funding to support soft-money faculty, students, and post-doctoral fellows that, if sustained could lead to the loss of entire programs. A shift to corporate or private funding sources for academics, training the next generation, and workforce development was also suggested. Given the expressed concerns around domestic graduate student interests, another suggestion for growth and workforce development was to invest in more four-year BS program training of coastal practitioners.

SUMMARY AND RECOMMENDATIONS

The landscape of training the next generation of coastal scientists and engineers is dynamic. The ASBPA and USCRP Academic Surveys have attempted to track these trends by collecting responses on university programs, research funding, graduate training, and workforce development. Uncertainty in the assessment of trends should be considered given respondents self-selected, had the option to remain anonymous, the sample size varied between surveys, and it is likely respondents were self-motivated to provide their opinions. Future surveys could reduce uncertainty by soliciting emails from all respondents, directly inviting the same institutions to respond, and increasing the time between surveys to increase participation.

While funding opportunities were reported to increase between 2018 and 2024, there was a dramatic reversal of opinion in 2025 (i.e., funding decreased). Most academics continue to report funding is difficult to obtain and has or will impact their ability to support graduate research. The 2018 survey suggested most research was considered basic (i.e., 75%-100%). In 2024 and 2025 overall, academics were reporting higher amounts of applied research rather than basic. Given that the top funding agencies did not change, it is likely the difference in academic research is based on differences in self-reporting.

It is likely the variability in graduate training trends is due to some programs not being exclusively "coastal." Institutions reported varying numbers of graduate students across BS, MS, and Ph.D. programs receiving fundamental science and engineering courses. Survey results from 2025 indicate courses are being taught less frequently. Future research could include additional questions to investigate these factors. It is critical to capture how students are being trained both in the classroom and through their research.

Changes in responses of how many students are joining the academic and non-academic workforce suggest identifying program-specific employment outcomes for students is a priority. Identifying the post-graduate employer and programs successfully training students for a career in academia should be a priority for future surveys. Success in academia-agency partnerships continues to be strong, despite a decrease in available funding. However, given the uncertainty with funding, academic curricula, and types of research projects, it may be advantageous to pursue increased

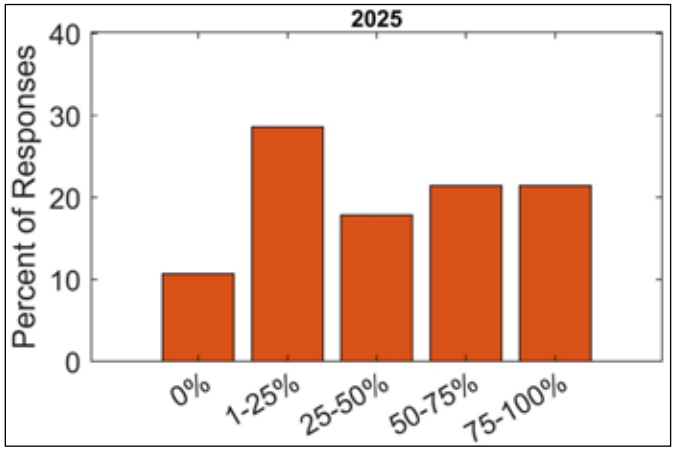

Figure 14. Responses to: What percent of your research is basic (rather than applied)?

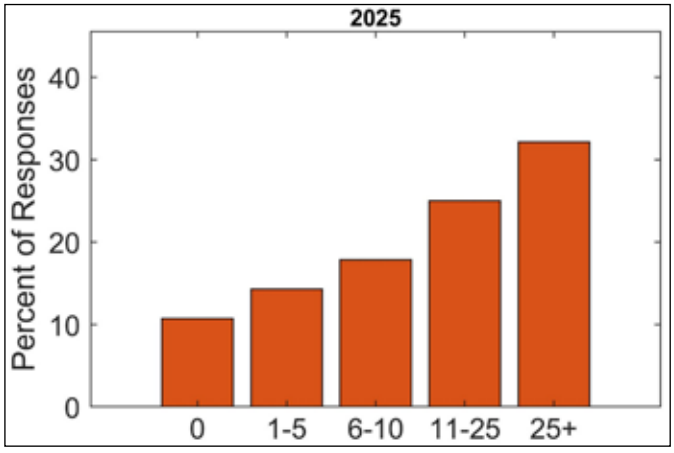

Figure 15. Responses to: How many graduate students are in your program?

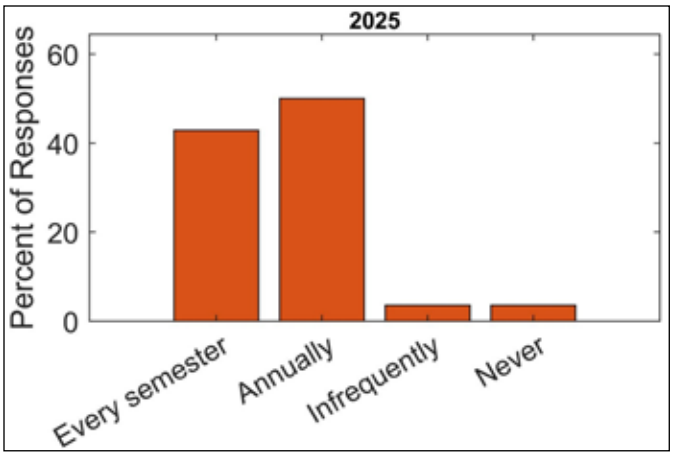

Figure 16. Responses to: How often does your university offer courses teaching fundamentals?

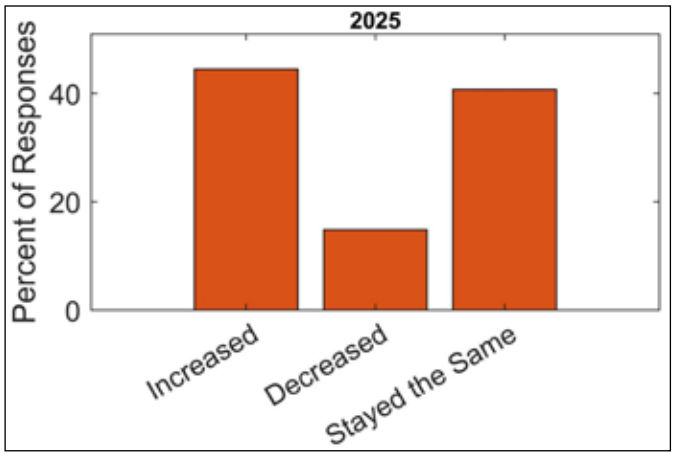

Figure 17. Responses to: Has the number of coastal science/engineering courses increased or decreased over the past year?

research and training partnerships with industry. Given that one of the USCRP goals includes sharing research facilities, future surveys might also include questions about research and training activities using shared facilities.

Finally, a coordinated effort to engage federal agencies and industry to determine current and future workforce needs would better position academic programmatic priorities and strengthen career preparation. Asking federal agencies what specific innovative student skills are needed for workforce development and identifying what discipline-specific skills they need from incoming employees (e.g., expertise on coastal structures) will also help better inform training the next generation of coastal scientists and engineers.

ENDNOTE

1) Responding academics were affiliated with, but not limited to: Old Dominion University, Oregon State University, University of California-Los Angeles, Louisiana State University, Stevens Institute of Technology, University of Puerto Rico, University of South Alabama, University of North Florida, University of South Florida, Florida Institute of Technology, University of Florida, Florida Atlantic University, Coastal Carolina University, University of Georgia, University of North Carolina-Wilmington, and the United States Naval Academy.

ACKNOWLEDGMENTS

The authors want to acknowledge the support of ASBPA and USCRP. We also want to thank all who responded to the survey to help us capture a glimpse of the state of academia, training the next generation, and workforce development for coastal scientists and engineers. Finally, we thank Dr. Nicole Elko for the continued support of this effort and the guest editors for their insights and review to improve this white paper.

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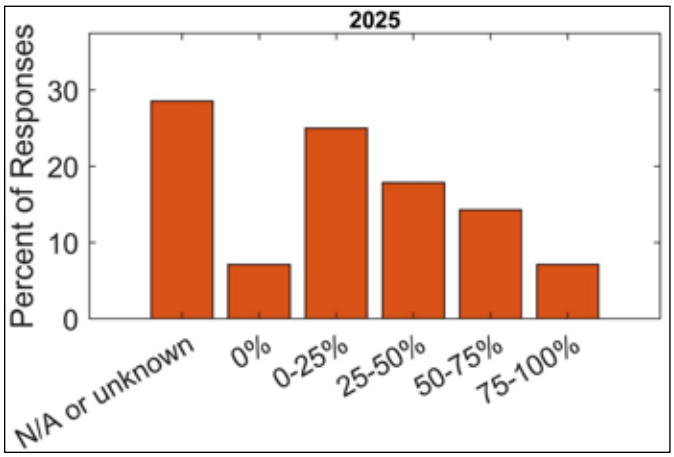

Figure 18. Responses to: What percentage of international (non-U.S. citizen) graduate students and post-docs joined the U.S. workforce (non-academic) after concluding their training?

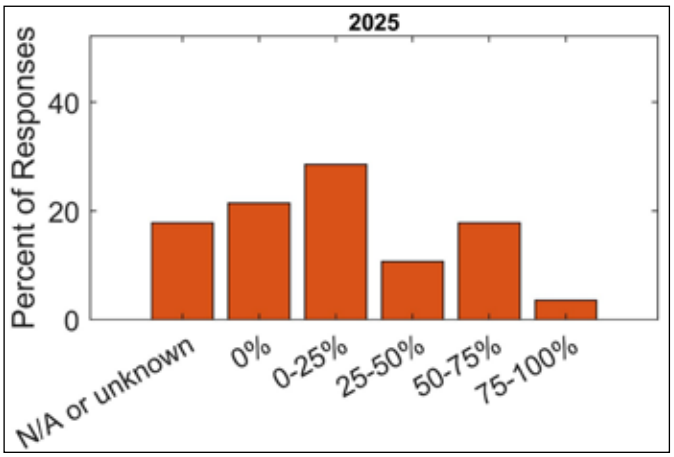

Figure 19. Responses to: What percentage of graduate students joined the U.S. workforce and remained in academia?

Barriers to co-produced coastal science for early-career researchers

By

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ABSTRACT

A significant portion of the global population lives in the near-coastal zone; these communities are often described as being on the front lines of climate change. In these communities, increasing hazards of flooding and erosion due to sea level rise and changing patterns of coastal storminess are exacerbated by aging or nonexistent infrastructure, loss of protective ecosystems, and inequities in community resources. Many coastal communities lack access to the expertise needed to understand local hazards and potential adaptation strategies. Research on coastal-coupled human-natural systems plays a critical role in filling this vital community need. Recognition of these gaps has resulted in a changing landscape of coastal research in which co-production and collaboration between academic disciplines and local communities have been highlighted as the way forward and are frequently required for funding. However, early-career researchers — who often have more formal training in interdisciplinary work compared to previous generations of scientists — face important structural limitations in their ability to participate in transdisciplinary research efforts. In this perspective, we outline barriers for early-career researchers, and researchers at large, to participate in co-produced science and suggest methods for mitigating these challenges at the individual, departmental, university, and national levels. These suggestions can provide guidance as scientific agencies consider priorities and funding structures.

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Approximately 37% of the global population lives in the near-coastal zone, within 100 km of the coast (Cosby *et al.* 2024). These communities are often described as on the front lines of climate change, where increasing hazards of flooding and erosion due to sea level rise and changing patterns of coastal storminess are exacerbated by aging infrastructure and inequities in community resources (Berman *et al.* 2020; Sandifer and Scott 2021; Griffin 2023). However, many coastal communities lack access to the expertise needed to understand local hazards, guide ongoing adaptation, and identify potential risk reduction strategies. In cases where expertise is available, communities often face political or other structural barriers to materializing their desired adaptive strategies (Jessee 2022). Even so, global coastal communities have reached a halfway point to full adaptation potential (Magnan *et al.* 2023); further advancement of adaptation sciences can realize this potential. Over the last decade, efforts between communities and scientists to engage in and evaluate the co-production of coastal hazards knowledge and solutions have demonstrated that the collaborative development of methods and products can increase community capacity (An *et al.* 2014; Robards *et al.* 2018; Griffin 2024).

There exists a full range of experiences that focus on the involvement of communities or end users in academic work. As the authors here represent a broad range of disciplines and practices, we engage with a broad definition of co-production and community-engaged work (Table 1). The terms "co-design," "co-development," and "co-delivery" are often lumped together as the "3D" components of co-production, where co-production is loosely defined as research that brings together a range of knowledge types to bring about a target outcome.

A related, but distinct term is community-engaged research, which can encourage community participation in all aspects of the process. This is different than co-production, which specifically aims to combine knowledges (Fleming *et al.* 2023). Further, there can be deeper discussions of what constitutes a community or end user, be it a coastal community, coastal land managers, or even tourists, depending on the specific context (Mitlin and Bartlett 2018; Vargas *et al.* 2022). Another related term is convergence research, which describes different academic disciplines working together to solve grand problems, but does not necessarily involve communities outside of academia (NRC 2014; Morton *et al.* 2015).

Due to the urgency of climate impacts for many coastal communities, co-production of knowledge has the potential to close the knowledge-action gap that exists between conventionally developed research and community and policy action (Bojovic *et al.* 2021; Muhl *et al.* 2023). Co-produced knowledge, which builds interpersonal trust between knowledge users and knowledge cre-

ators, has the potential for being more directly applicable (Nguyen *et al.* 2019). Co-production is critical for equitable management of coastlines and reduction of risks faced by communities. We believe it is the role and responsibility of natural and social scientists to partner with communities to co-produce actionable forms of knowledge. This calls into view what the larger goals are of both the academic institution and scientists as a whole.

Co-production is critically needed, particularly when handling environmental problems (Lemos *et al.* 2018). Although coastal science, both natural and social, towards adaptation and resilience has been an active area of research, much of this work is not implemented in communities (Shaw *et al.* 2013; Nursey-Bray *et al.* 2014; Dale *et al.* 2019). As important, previous work has found that science is more likely to be implemented when it is developed in a co-production framework (Fujitani *et al.* 2017). Additionally, co-production can be a tool for those communities most impacted by coastal hazards who are otherwise marginal to decision-making institutions. Overall, co-production methods can benefit academic science and coastal resilience in an age of rapid climate change.

Table 1.
Select definitions of co-production that encompass a broad understanding of this type of work.

Definition of co-production	Source
"An umbrella term for research engagement (which typically incorporates some or all of co-design, co-development, and co-delivery, often sequentially) that brings diverse knowledges together to create new knowledge, tools or products, activities, processes and/or outcomes."	Fleming *et al.* 2023
"… research is conducted collaboratively, inclusively, and in a respectful and engaged manner — from the identification of research needs to study design, data collection, interpretation, and even application — with the idea of creating actionable science and benefits to the partners involved."	Cooke *et al.* 2021
"Processes that iteratively unite ways of knowing and acting — including ideas, norms, practices, and discourses — leading to mutual reinforcement and reciprocal transformation of societal outcomes."	Wyborn *et al.* 2019
"…1) evolving communities of practice, 2) iterative processes for defining problems and solutions, and 3) presence of boundary organizations, such as a government agency, university, or co-management council, …4) the consistent provision of sufficient funds and labor that may transcend any one specific project goal or funding cycle, and 5) long temporal scales (sometimes decades) for achieving the co-production of actionable knowledge."	Robards *et al.* 2018

In response to the need for co-produced science and adaptation strategies, funding agencies have introduced programs that specifically target collaboration between communities and scientists. These include the NSF programs "Coastlines and Peoples (CoPes) Hubs," "Coastal Science, Engineering, and Education for Sustainability (SEES)," "NSF Confronting Hazards, Impacts, and Risks for a Resilient Planet (CHIRRP)," "Responsible Design, Development, and Deployment of Technologies (ReDDDoT)," and "Regional Resilience Innovation Incubator (R2I2)." NSF's "Navigating the New Arctic" (NNA) created and maintains its own "Community Office" to support co-production between interdisciplinary researchers and Arctic communities (Druckenmiller 2022). Other agencies, including Sea Grant (national and state) and the U.S. Coastal Research Program (USCRP), have offered similar calls that support co-production and collaboration between academic and nonacademic partners.

There are well-documented challenges to co-production in the literature and evidenced across disciplines (Briley *et al.* 2015; Grainger *et al.* 2021; Rölfer *et al.* 2022; McCabe *et al.* 2023; Callahan *et al.* 2024; Apine *et al.* 2026). Some of these include the devaluation of interpersonal and reflexive skills (Fleming *et al.* 2023), incompatible incentive structures (Boon *et al.* 2019), and hidden labor (Hartline 2023; Kolesar *et al.* 2024). Here, we expand upon these previously identified challenges, contextualize them within the field of coastal research, and propose transformational solutions spanning the institutional to individual levels. Substantial barriers to co-produced science are embedded in the institutions in which we work. For early-career scientists to be successful, serious consideration must be made about how the goals of co-production align or diverge from the expectations levied by academic institutions, disciplines, and funding structures. The purpose of this perspective is to outline common barriers for early-career coastal researchers in developing co-produced work and to identify practical mitigation strategies to support researchers in these efforts.

BARRIERS TO CO-PRODUCED SCIENCE IN COASTAL ENVIRONMENTS

In a review of reflections on co-production, Fleming *et al.* (2023) found that respondents grappled with the long timelines involved in co-production. One respondent stated: "I learned long ago that, when you start something that's based on science and management and evidence and all that stuff and you put it through for implementation, it's a decade of work. And that's the other issue that arises. Who's going to be there for a decade?" (Fleming *et al.* 2023). This comment highlights that, for both the scientist and the community, the development of co-produced outcomes is often a lengthy process.

A key barrier to the full participation and development of co-produced science in early-career academia is the misalignment of timelines. Processes such as grant writing, tenure evaluation, and the development of local networks often progress slowly, while communities frequently face an urgent need for timely solutions. Co-production and community engaged

work, by nature, take a longer time to create academic products (Plumb *et al.* 2004; Cargo and Mercer 2008; Flicker *et al.* 2008; Fleming *et al.* 2023). The long timeline can be compounded by the fact that early-career researchers often may be new to the geographic area in which they work. Given this, researchers may not have established relationships with communities and relevant local entities (such as tribes, local government agencies, boundary organizations) and have likewise not developed trust, knowledge-sharing agreements, or other critical components of co-production. Although these components of co-production will manifest given the engagement and drive by the researcher, more time is required compared to the spin-up for traditional natural-science approaches. Below we outline specific barriers to early career coastal researchers in developing co-produced work.

Grants

Most scientific research at universities is supported by external grants, which are typically awarded for periods of two to three years. This funding structure presents distinct challenges for community-engaged research and co-production. As stated above, co-production requires researchers to be responsive to community needs and priorities which emerge or may shift during the research collaboration itself (No'kmaq *et al.* 2021). For example, communities are often interested in long-term programs, facilities, and the like for their communities through co-production. Why should communities settle for short-term commitments from scientists and their associated grant structures? Previous research has highlighted that while projects can be a success, long-term sustainability becomes difficult for communities in which most users are concerned about continued financial support and flexibility with funds (Jaspers and Steen 2019; McMullin 2023).

Another critical barrier is that the grants that value co-production often require (reasonably so) that researchers and end users develop the grant together (Arnott *et al.* 2020). For early-career researchers, who are often new to the region in which they are working, co-developing a grant proposal takes a long time because it first requires building trust and familiarizing oneself with local issues. Relatedly, both standard grants and grants focused on co-production require upfront letters of support or collaboration from partner communities or organizations. Without dedicated funding for relationship-building activities, the requirement for up-front documentation of intent to collaborate can deter early-career researchers, who may not yet have the contacts or knowledge to request these letters. Again, without a funded co-design process, requests for letters of support can place an undue burden on communities themselves. Additionally, as many grants are not funded, the same groups can become exhausted due to repeated requests for letters. While researchers may expect some grant proposals to go unfunded, communities may be less able to recoup their time, labor, and other resources from the co-development of unsuccessful proposals. Communities may also be approached by multiple scientific groups conducting similar work; without clarity on the details of the work, this redundancy can create distrust and reduce meaningful engagements between communities and scientists (Clark 2008).

Grants necessarily involve administrative loads that burden all researchers, but these burdens are increased with grants that involve community engaged work (Carter-Edwards *et al.* 2021). This issue becomes acute particularly when paying community partners and participant support costs (Guo *et al.* 2026). Most universities are not set up to deliver these kinds of payments easily and thus require faculty to invest time in understanding and then navigating the rules and bureaucracy around these payments, sometimes involving community partners as well. In one of our projects, the process of gathering the documentation required to distribute participant support costs was burdensome enough for a small, understaffed community organization that they decided it was not worth distributing the funds specifically designated for this purpose in the grant. Likewise, given that co-produced work involves equal balance between academic researchers, community members, and other end users, grant sources and subcontracts may come from nontraditional sources compared to traditional academic grants. While it can be difficult for the universities to handle non-standard contracts, it is even more complex for the early-career researcher involved in co-production. These issues can become strong barriers to being able to participate in co-production.

Peer-reviewed publications

A key component of evaluation for early-career researchers is the number of peer-reviewed publications they have published. The role and production of publications is a complex issue in co-produced work. Firstly, developing projects with communities and entities outside of academia takes longer, as trust is earned and ideas are jointly formed. This necessarily means that the time to publication is extended. For example, an increase in the number of authors increases the time to publication (Taşkın *et al.* 2022) and, with co-produced work, there are likely even more contributors, as community members and end users themselves may be authors. In true co-produced work, all components should be shared between all partners, including authorship on scientific papers. Given more co-authors who are less versed in scientific writing and who likely value other outputs more, publications including communities and other end users are likely to take longer, exacerbating the timeline issue.

There may be misalignments between academic participants and end users that challenge the traditional publication model (Loseto *et al.* 2020). One significant barrier is that co-production requires clear agreements about how data will be shared and the ownership of said data. If all parties consent to the publication of data within a peer-reviewed scientific journal, the data sharing issue is minimized. However, in some co-production efforts, communities may not want the data published or may value other types of outputs rather than scientific publications. Our experience, and that of others (Beier *et al.* 2017; Norström *et al.* 2020), indicates that presentations, data sheets, reports, visualizations, and other nontraditional products may be more valuable to end users compared to scientific publications.

Furthermore, there are technicalities involved with publications that are problematic for co-produced work. Typically, co-authors are required to provide an email address, affiliation, and sometimes their scientific specialty. These requests can be barriers for inclusion of community members and end users to be listed on the publication. Additionally, scientific publications can be difficult to access for community members and end users. Paywalls and scientific jargon can limit the ability for end user use of this output. The

recent movement towards open-access publishing allows communities access to the papers their communities have contributed to; this is a great and critical step forward, but requires Principal Investigators to include that funding when submitting external grants.

For early-career researchers on the tenure track, the primary currency in evaluation for tenure is the number of peer-reviewed published papers. Depending on the institution, the number and quality of the papers may vary; likewise, depending on the researcher's discipline area, the number of expected papers may change given the time required to develop new ideas and experiments. More diverse "non-refereed" outputs, including those valued by communities (reports, policy documents, Best Management Plans) are often ascribed less value within traditional tenure evaluation structures.

Incentives, perception, and prestige

A primary goal for early-career faculty is to achieve tenure to secure their position and continue their research. Although tenure expectations and timelines vary substantially between, and even within, institutions, a typical faculty member is assessed on three components: research, teaching, and service. At least two (and perhaps all three) of these areas of evaluation are impacted when the scientist is actively engaged in co-produced research. The authors of this present work were or are all faculty at a research intensive (RI) university. While co-production has become more common, academics often adhere to incentive structures that privileges disciplinary science without or with less public engagement (Dilling and Lemos 2011). Popular advice given to early-career natural scientists is to delay engagement in co-produced science until after tenure. This advice can be frustrating, as this reinforces the system in which there are limited role models on how to achieve tenure while engaging in co-production. As most researchers are not trained to work directly with communities, poor implementation of co-production and fear regarding how to do so successfully can persist. Further, in many coastal communities, climate change and climate adaptation can be a highly politicized issue, which further complicates matters. Working in highly political contexts is also not something most early-career researchers are taught how to do.

For early-career scholars on the tenure track, external letters that evaluate a scholar's publications, grants, teaching, and national/international professional service over (most often) a five-year period can be another barrier. Co-produced research and its associated challenges can affect the perception of letter writers whose concerns might range from delays in expected publishing schedules to perceptions of the researcher's disciplinary impact. External letters are a critical part of tenure decisions despite having been shown to reflect more about the writer than the tenure candidate (Madera *et al.* 2024). Although co-produced science is increasing in use (Irwin *et al.* 2018; Naugle *et al.* 2020) and novel evaluations that incorporate diverse outputs for tenure are developing (Klein and Falk-Krzesinski 2017), letter writers tend to be senior researchers who have had less training in this area and, in our experiences, have certain expectations over what tenure involves (Lahsen and Turnhout 2021). These perceptions can prevent early career scientists from engaging in co-produced research.

Separation of knowledge from practice

While "applied" science is increasingly valued within the coastal research community, positivist interpretations of "fundamental" or "basic" science (i.e., empirical, measurable, and "objective") are most prevalent within such spaces (Lincoln and Guba 1989; Park *et al.* 2020). Positivist science is now more commonly complemented with post-positivist and/or interpretive social sciences, which emphasizes *how* knowledge came to be produced, *by whom*, and that our research generates incomplete representations of the world instead of objective and singular ones (Fox and Ramazanoglu 2008; Kanazawa 2023). Though vital for understanding environmental and ecological coastal processes, the epistemological assumptions of positivist and post-positivist research traditions can be in tension with, if not exclude, the kinds of shared or situated inquiry that ethical co-production may require (McMichael *et al.* 2021). Moreover, dominant knowledge systems may actively minimize, disregard, or erase the knowledge and experiences of diverse community partners. Within many Indigenous knowledge systems, for example, knowledge about the world cannot be separated from the values-laden obligations and responsibilities to the world and its people (Wilson 2008; TallBear 2014). Many scientific research traditions also presume that the production of knowledge, and its uptake by a rational public, can effectively inform policy or decision making, when in fact such mechanisms generate insufficient forms of action, especially when it comes to addressing the concerns, priorities, and needs of coastal environmental justice communities. Furthermore, there is a need to refine the ways that academics talk about "non-experts," "communities," or "end users"; some co-production research still diminishes the expertise that comes from lived experience and traditional ways of knowing.

SOLUTIONS LOOKING FORWARD

Grants

One helpful strategy could be for senior faculty members to introduce early-career faculty to nonacademic collaborators or even invite them to participate in larger projects that have established community partners or connections. This mentorship can also alleviate the difficulties in developing co-produced work. As discussed, early-career researchers usually are not established in their region, and long-term relationships are often needed to create successful co-produced science; an already-trusted senior mentor can help establish these relationships.

At the university level, grants management can ease the financial difficulties of co-produced work through expediting the processes of grants from nontraditional sources, independent of their dollar value, and creating ways for researchers to spend these grants through temporary budget lines before the grant is processed. Universities can also streamline the grant-spending processes related to co-produced work, easing the administrative work required of faculty and their community partners.

At a grant agency level, there are several pathways to creating a more supportive environment for early-career researchers engaged in co-produced research. Small seed funds, targeted at early-career researchers, that provide funding to develop partnerships with communities can provide early-career researchers the ability to build foundations of trust that allow them to successfully compete for large grants focused on co-produced research. This seed funding

should encourage spending on meetings, travel, participant support costs, and the creation of small, perhaps nontraditional, research projects to allow faculty to build relationships. In other words, seed funding should be focused on activities that create time and space for researchers and communities to get to know each other more than requiring research to be conducted.

More established researchers can rely on existing partnerships to develop these large grants, but early-career researchers without existing grants have few means to financially support themselves and their community partners as they forge their path. The presence of these small grants has been shown to be successful in supporting early-career work and co-production (Plumb *et al.* 2004; Kolesar *et al.* 2024). In addition, small grants for community engaged research to continue after a grant ends could allow for sustained commitment to the community and end users, building trust that is necessary for future co-produced endeavors. Ideally, funds would be available to follow up on existing larger projects with smaller-scaled data analysis to answer community questions. These grants should be targeted at developing local capacity where the researchers step back, nurturing an environment for true two-way knowledge production and sharing in co-production.

Both suggestions to grant agencies require capital investment, which may not be possible in all circumstances. There are other practices that grant agencies can employ to support early-career researchers' co-produced work that do not require this type of investment. For example, grant requirements could be more flexible in the submission of letters of support or collaboration. Letters of intent for grant opportunities that do not require upfront letters of support limit the burden to communities, end users, and early-career researchers in co-production, as many proposals will not continue to the next phase of review; in this way, only viable proposals will have to request letters. Additionally, given that most proposals are reviewed over a long time period, additional flexibility in the timeline for submission of the letters such as a longer or rolling deadline for submission of letters by end users and communities would minimize limitations.

Peer-reviewed publications

At the individual level, early-career researchers in co-production (and indeed, all researchers) should consider implementing clear guidance on authorship practices within lab groups and ensuring that these practices are equitable (Lancaster and King 2025). At the onset of co-produced research, authorship expectations and data-sharing agreements should be discussed by the researchers, community members, and other end users to ensure clarity, consistency, and equity (Miles *et al.* 2022). Additionally, individual academics can consider radically rethinking their authorship practices to include contextually or culturally specific authors such as place names being authors (Wilson *et al.* 2020).

There are several ways that journals can engage better with co-produced work to mitigate barriers. For example, in article submission additional categories for specialty can be incorporated to reflect a more diverse group of authors and be more flexible in author information by not necessarily requiring an email address for all authors. Another relatively simple change that some journals have already implemented is the use of a contribution statement that allows more diverse author groups to be able to state the type of contribution made to the manuscript. In this way, journals will pave the way to allow for expanded credited roles in accordance with specific project and community/researcher (co-researcher) relationships, alleviating another barrier for early career researchers engaged in co-produced work. Finally, journals can be more flexible about open-data requirements, particularly when communities or sovereign nations (tribes) own that data and may not want it fully published. While open data is important for reproducible science (Powers and Hampton 2019), journals must recognize contextually specific norms and allow for exceptions to open-data policies.

Lastly, the issue of open-access publications is a barrier that can be addressed at multiple levels. The individual early-career researcher involved in co-production should include publication costs into grant costs, as this allows community access to the work. Preprints can be used to share co-produced work without requiring a fee. As co-production has more players and requires more time, grant funding may be limited in its ability to provide full funding for open-access publications, so additional support may be required. Colleges and universities can either join consortiums that allow for the waiving of open-access fees (Pinfield *et al.* 2015) or create small grant funds to help cover open-access publication for co-produced work. Likewise, journals could waive fees for publications that have community-member or non-academic authors.

Tenure

While changing tenure timelines is not reasonable or beneficial, there are tactics across the levels of influence to reduce the burden of co-produced work on early-career researchers. On the individual level, an early-career researcher engaging in co-production can diversify their research portfolio to have smaller projects that do not require the same time investment required for co-production. Projects such as metadata analysis, reviews, and other projects can advance publications and ideas for proposals as co-produced research is pursued concurrently. At both the senior faculty and department levels, promotion and tenure expectations and standards can be revised to reflect the more diverse output created during co-produced research (Klein and Falk-Krzesinski 2017; Norström *et al.* 2020). For example, more products can be listed as "publications" including reports, flyers, and other common co-produced outputs in both the tenure package, curriculum vitae (CV), and in stated tenure and promotion guidelines provided by the unit. Some of these nontraditional academic products can even be published in scientific repositories, such as Figshare, and become citable objects with a Digital Object Identifier (DOI) that can also be linked to an author's Open Researcher and Contributor ID (ORCID). Another example is the publication of protocols with DOIs in protocols.io. Additionally, CVs could be amended to include a section for alternative products. In this way, these "nontraditional" products will be presented as a component of the package, properly seen by external letter writers, and included as part of one's scholarly work. In the past several decades, academia has revised standards to incorporate interdisciplinary research into tenure packages, acknowledging that interdisciplinary work takes longer and has more diverse outputs; these concepts can be logically extended into evaluations of co-produced work. We

note that at the institutional level, the development of communities of practice for co-production or community engagement, as well as the use of the Carnegie Foundation Community Engagement Classification, can lead to the development of mentor networks for early-career scientists involved in co-production and raise the perception of the value of co-produced work.

Role of practitioners, agencies, and local governments

Although we want to highlight that it is not the responsibility of communities to break the barriers imposed by higher education and by funders, practitioners, agencies, and local governments may also have the capacity to enable successful co-produced science with early-career researchers. We suggest there are some straightforward ways of enhancing successful co-produced science — with both early-career and more senior scientists. First, being aware of the point of view of academia and the structure in which early career academics operate can help clarify objectives, deliverables, and timelines. Through a joint understanding of the goals of all the partners in the development of a co-production relationship (including the early-career academics), expectations and norms can be properly developed for a more productive scientific process (Beier *et al.* 2016). Potential partners in co-produced work can increase their engagement with early-career academics to bring new researchers into co-production relationships. This can be as straightforward as networking events and local symposia that are managed in a way to promote new connections and engagements (Schulz and Schwaner 2024). The development of relationships in low-stakes settings can facilitate future partnerships.

TRANSFORMATION THROUGH CO-PRODUCTION

With the breaking down of barriers for development of co-produced work, we encourage researchers, including early-career researchers, to engage with coastal communities to work towards common goals. It is especially critical to co-produce coastal science and adaptation work with historically marginalized groups, as they are experts with both local knowledge and sophisticated understandings of material needs and governance priorities for coastal resilience. Co-produced research must also scale to match the structural nature of the challenges that coastal communities face.

Over the next several decades as co-production becomes more necessary, more widespread, and more accepted in the academic realm, we expect that end users and communities will build local capacity for the development of their own solutions for coastal adaptation. At that point, the role of scientists in implementing these solutions will diminish. Until then, we must support co-produced coastal science and solutions for an equitable and resilient world.

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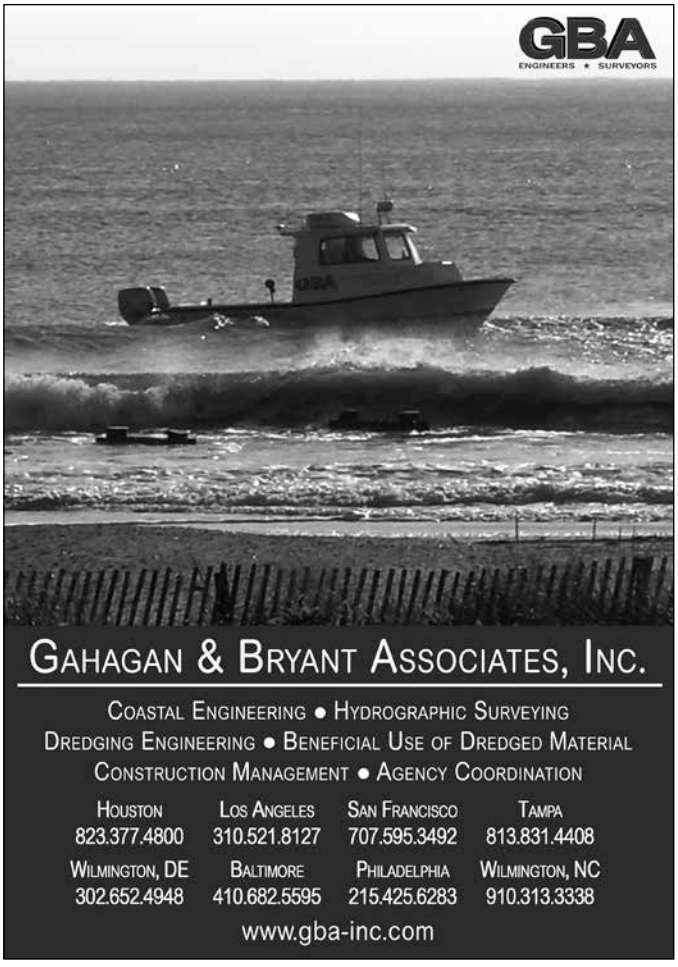

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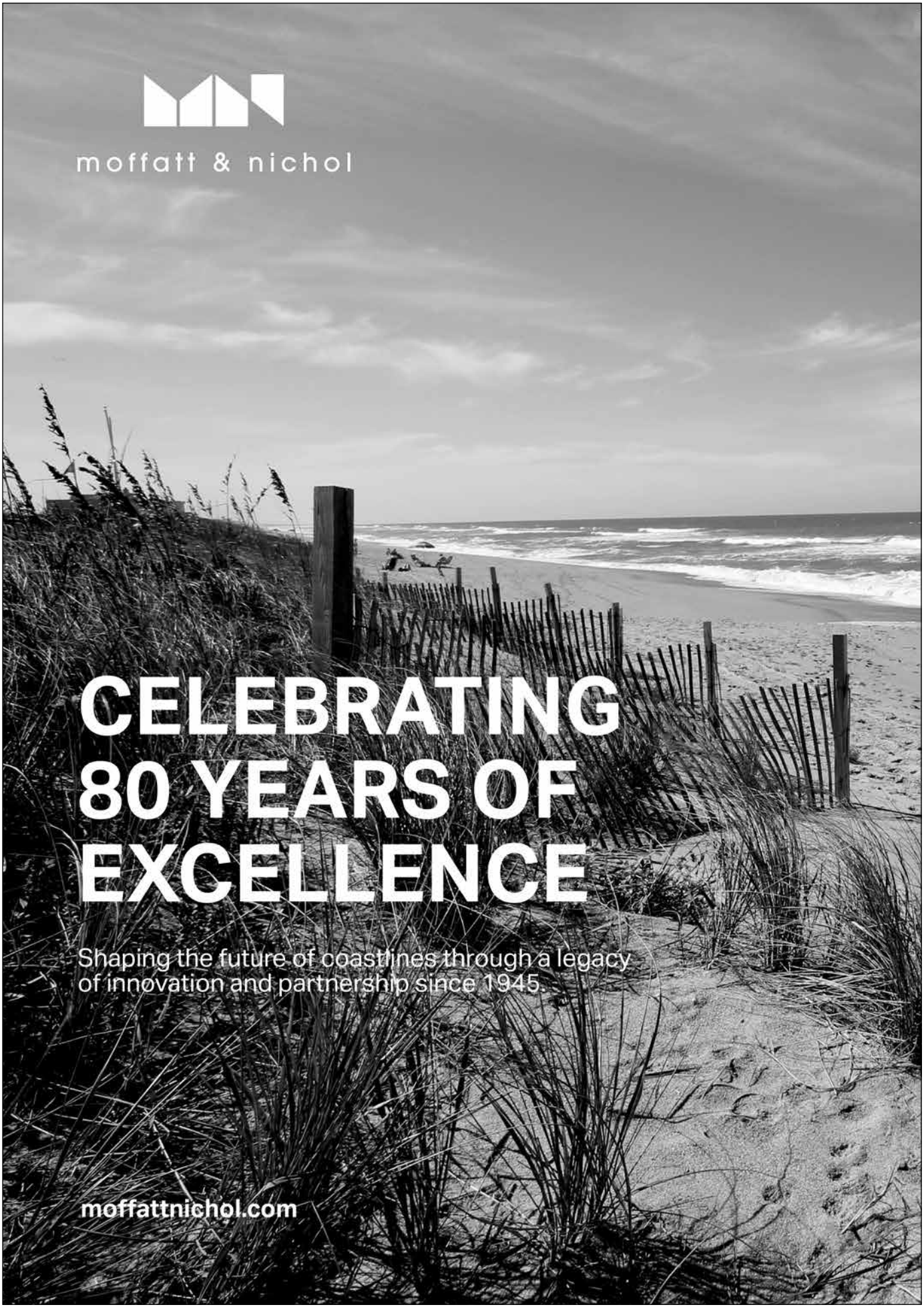
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Pre-conference workshop: Shaping Advancements to Federal Coastal Flood Hazard Information with NOAA, USGS and ASBPA: A Practitioner Workshop. Times TBD.
ASBPA board of directors meeting 2:30-5:00 p.m.
Coastal Champions Gala 6:30-8:30 p.m.

- **Tuesday, Oct. 6:**

Morning plenary session
Lunch
Afternoon concurrent sessions
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