Wetlands (2026) 46:45
https://doi.org/10.1007/s13157-026-02058-3

ORIGINAL RESEARCH ARTICLE

From Model to Action: Identifying the Gaps in Coastal Marsh Models for Decision Making

Amanda D. Stoltz[1,8] · Dawn M. Kotowicz[2] · Christine Addison Buckel[3] · Davina L. Passeri[2] · Renee Collini[4] · Nina Woodard[5] · Sara Martin[5,6,7]

Received: 25 August 2025 / Accepted: 23 March 2026 / Published online: 9 April 2026

Abstract
Coastal salt marsh modeling projects are designed to answer questions about where salt marshes may migrate, how they can migrate, and how they will be impacted by changing water levels. While this information is vital for climate-resilient marsh conservation, translating these findings into actionable results remains a challenge. The authors examined the actionability of marsh modeling efforts in the United States by analyzing data collected from semi-structured interviews of marsh model users ($n = 24$) across two ongoing projects along the U.S. East Coast and the Gulf of America (Gulf of Mexico). By qualitatively analyzing the interview data, the authors found that the tasks of practitioners who use coastal marsh model outputs fall into three major themes: (1) marsh restoration, (2) planning with uncertainty, and (3) conserving habitat for marsh-reliant species. For each of these themes, the authors identify unmet needs, including high spatial resolution information for local planning, accessible descriptions of uncertainty to increase user confidence, and the incorporation of human dimensions data (e.g., human alterations to the landscape such as impoundments and culverts) for a comprehensive understanding of the coastal salt marsh. Marsh modeling projects should strategize how to fulfil these unmet user needs so that marsh modeling outputs can better support decisions related to marsh conservation and restoration.

Keywords Marsh migration · Coastal wetlands · Coastal marsh model · Decision support · Coproduction · User needs · Climate change

✉ Amanda D. Stoltz
adstoltz@gmail.com

1 Disaster Research Center, University of Delaware, Newark, DE 19716, USA

2 U.S. Geological Survey, St. Petersburg Coastal and Marine Science Center, St. Petersburg, FL 33701, USA

3 National Oceanic and Atmospheric Administration, Beaufort, NC 28516, USA

4 The Water Institute, Vancleave, MS 39565, USA

5 Mississippi State University Coastal Research and Extension Center, Biloxi, MS 39532, USA

6 Mississippi-Alabama Sea Grant Consortium, Ocean Springs, MS 39564, USA

7 Mississippi Sound Estuary Program, Biloxi, MS 39632, USA

8 EqualSea Lab, Cross-Research in Environmental Technologies, University of Santiago de Compostela, Santiago de Compostela 15782, Spain

Modeling Coastal Marsh Response to Sea-Level Rise

Coastal salt marshes sequester carbon, protect communities from storms through wave attenuation and reduced flooding, and provide habitat for a wide array of economically and culturally important species including fin and shellfish, aquatic invertebrates, and birds (Barbier et al. 2011; Gittman et al. 2014; Bilkovic et al. 2016; Kirwan et al. 2016; Taylor-Burns et al. 2024). Managing these critical wetlands is a complex process, as they are dynamic systems governed by elevation, tidal inundation, hydroperiod, sediment supply, and biological feedback (Stralberg et al. 2011) and are increasingly threatened by sea-level rise (SLR), which can result in changes in tide ranges and tidal prisms (Passeri et al. 2016).

A salt marsh can keep pace with SLR through vertical accretion and biophysical feedbacks; however, if the rate of SLR exceeds the rate of accretion, the marsh will drown and be converted to open water (Reed 1995). Higher sea levels may also result in marshes migrating landward as higher elevations are inundated, transgressing into low-lying forests, agricultural fields, and suburban areas (Fagherazzi et al. 2019). The relative balance of accretion in the marsh platform versus landward migration is key to marsh resilience (Morris et al. 2024). Migration can only occur if the marsh can keep pace with SLR and there are no topographic or anthropogenic barriers to migration such as steep uplands, built environment, or shoreline armoring (Linhoss et al. 2015; Molino et al. 2022). These barriers to migration can lead to coastal squeeze and the loss of marshes and the ecosystem services they provide (van der Wal and Pye 2004).

Wetland models can be used to understand the evolution and resilience of salt marsh systems under rising seas (Fagherazzi et al. 2012). Several of the more well-known models for assessing decadal-scale salt marsh evolution in response to SLR include mathematical biological models such as the Marsh Equilibrium Model (MEM) (Morris et al. 2002) and Wetland Accretion Rate Model for Ecosystem Resilience (WARMER) (Swanson et al. 2014; Buffington et al. 2021), spatial models such as Sea-Level Affecting Marshes Model (SLAMM) (Clough et al. 2016), and coupled numerical approaches that incorporate geophysical processes (Mariotti and Fagherazzi 2010; Alizad et al. 2016; Kirwan et al. 2016; Mariotti 2020). These models differ in their methods ranging from the ability to resolve complex marsh processes including feedback between sedimentation, vegetation, and tidal hydrodynamics, to using simplified geometric and conceptual relationships to predict ecosystem response to SLR.

Current Marsh Modeling Efforts and Considering User Needs

Federal, state, and local practitioners such as resource managers, community planners, and environmental communicators who are tasked with short- and long-term marsh stewardship can use the information from coastal marsh models to inform decisions. However, there have not been as many large-scale research projects that directly support site-specific decision making, which can result in a perceived lack of usability as additional information is often needed for site-specific decision contexts (Burman et al. 2024). Marsh practitioners make many decisions on short time horizons (e.g., years) and small spatial scales (e.g., parcel scale), and while existing marsh models can be applied in these contexts, practitioners may require explicit data collection and modeling studies with focused questions and geographic scope to provide site-level decision support. As coastal marsh models and user needs evolve along with rising sea levels, ensuring strong connectivity between model projections, model advancements, and the translation to actionable outputs is essential to maintaining our coastal ecosystems and protecting coastal communities.

The mismatch between marsh researchers' modeling objectives and the diverse needs of marsh model users highlights a critical gap: insufficient communication between users and modelers throughout both model development and data utilization. Sustained engagement before, throughout, and after a project is essential to advancing marsh modeling that generates actionable results, building confidence in marsh model predictions, and supporting scientifically informed climate adaptation decisions. Over the past two decades, efforts to understand and integrate the planning and adaptation needs of marsh model users have been undertaken by several large-scale marsh modeling projects (Fagherazzi et al. 2012; DeLorme et al. 2016; Stephens et al. 2020) and community of practice-level engagements (Martin et al. 2022; Woodard, Martin, and Collini 2023). A cornerstone of this advancement ran from 2010 to 2016 and explicitly advanced capacity to model marsh response to SLR in collaboration with a suite of potential data users (Kidwell et al. 2017). The project, "Ecological Effects of Sea Level Rise in the Northern Gulf of Mexico (EESLR-NGOM)", used a high-resolution coupled hydrodynamic-marsh equilibrium model (Hydro-MEM; Alizad et al. 2016) to assess salt marsh evolution under different SLR scenarios for estuaries in the Florida Panhandle, Alabama, and Mississippi. This project identified tasks that could be supported by Hydro-MEM including understanding where marsh can migrate; deciding how to mitigate changes; deciding where to relocate infrastructure; identifying which infrastructure could restrict or inhibit migration; projecting marsh transformation based on accretion forecasting; and justifying permits for projects (Collini et al. 2018; DeLorme et al. 2018; Stephens et al. 2020).

Research into the human dimensions of designing decision support tools has identified best practices for effectively supporting decisions including repeatedly engaging with end users and collecting feedback to be incorporated into tool design which is iterative and adaptive to user needs (Stoltz et al. 2023a; Collini et al. 2022). With an abundance of decision support tools available, developing new resources requires understanding of the context from which potential users approach a new decision support tool (Stoltz et al. 2023b). Issues like scale mismatch, when tools are presented at a different scale than that which practitioners need to make decisions, can be identified when engaging with potential data users and addressed prior to designing a decision support tool (Guerrero et al. 2013; Cumming et al. 2006). DeLorme et al. (2016) describe how repeated discussions between scientists and data users throughout the research process can make decision support tools more accessible. Morris et al. (2024) illustrate the value of repeated sustained engagement with coastal community members in identifying joint priorities for coastal decision making that meet the needs of coastal communities and coastal decision makers. Although sustained engagement with decision makers is not always possible or practical, Bamzai-Dodson et al. (2021) present a continuum of engagement for coproduction to inform actionable science with natural resource managers. This continuum presents consultation as one approach to coproduction including, for example, obtaining practitioner input about certain parts of a project to identify desired model outputs (Bamzai-Dodson et al. 2021).

While practitioner needs and models continue to evolve, there are not yet models that can meet every need due to constraints such as funding, project scope, or computational limitations. For example, federally funded research projects may be focused on developing higher complexity models to resolve marsh processes more holistically, or conducting regional vulnerability assessments to identify hotspots, whereas land managers may be focused on assessing how potential restoration strategies such as thin layer placement may affect a targeted area of marsh within a specific estuary. Discrepancies in project scope (research versus feasibility assessments) are governed by the funding source, project duration, available resources and limitations in model applicability. It takes time to understand the emerging needs and then advance the science and modeling logistics to a point where they can serve those needs. Additionally, there are settings where the data or computational capability is not available. This highlights the value of engagement that facilitates an improved understanding of actionable model outputs between the researchers and practitioners, and even compromise on output resolution (through communication about why parcel-scale data may introduce more uncertainty) and frequency (10 year versus 5 year versus 1 year).

Here we present an analysis of practitioner needs from two separate marsh modeling projects as an example of collectively analyzing information from consultation with data users to improve and continue alignment between data users and modelers. Decision-making needs are discussed under three overarching themes: (1) marsh restoration (2) planning with uncertainty, and (3) conserving habitat for marsh-reliant species. These themes are explored to answer the following questions: What are the decision-making needs of marsh model users, which needs are unmet by existing models, and what priorities should guide future modeling efforts?

Methods

Projects of Focus

To better understand the needs of practitioners and how they align with marsh modeling project objectives, we used a qualitative approach by leveraging two marsh modeling projects that are currently underway on the U.S. East Coast and the Gulf of America (Gulf of Mexico). These projects include: (1) the Effects of Sea Level Rise-South Atlantic Bight (ESLR-SAB) Project; and (2) the Marsh Model Retrospective Initiative. We focus on these two projects because their inter-disciplinary teams included social scientists and engagement specialists who were tasked with understanding user needs.

The objective of the ESLR-SAB Project is to assess the evolution of salt marshes in South Carolina, Georgia, and Florida under future SLR scenarios using Hydro-MEM (Alizad et al. 2016). It is planned as a four-year project, scheduled to be completed in 2026. The stated project deliverables include detailed assessments of marsh vulnerability to future SLR, including the potential for marsh migration, loss of habitat for critical species, designation of future land use, and strategies to mitigate marsh loss. For this project, the first planned model is a regional, multi-state application of Hydro-MEM with moderate spatial resolution (10-m resolution). For the ESLR-SAB project, interview participants were members of the Management Transition Advisory Group (MTAG), which is an advisory committee of marsh model users who are engaged throughout the project in one-on-one interviews and periodic meetings. Participants were selected for the MTAG based upon: (1) their need to make decisions about marshes in the SAB region; (2) their potential for using the outputs of the ESLR-SAB research project; and (3) collectively, their representation of various levels of management and geographies within the region. These MTAG members include practitioners from federal, state, academic, and non-governmental organizations who make marsh-related decisions at state, regional, and broader scales[1].

Our second source of data comes from the Marsh Model Retrospective Initiative, an effort to understand how well different marsh models predict observed conditions today in various environments to help inform how different existing models are suited to different decision contexts. This ongoing effort began in 2018 at a Gulf of America Alliance (Alliance; formerly Gulf of Mexico Alliance) workshop for modelers and marsh stewards across the region. The workshop was attended by over 45 Gulf of America (Gulf of Mexico) practitioners in federal, state, and non-profit

[1] All guidelines related to the Paperwork Reduction Act were followed, and additional review was not required.

organizations. A follow-up workshop was held in 2022, and modelers established the technical requirements of a marsh model retrospective informed by user needs (Martin et al. 2022). Data presented here are practitioner needs and challenges collected to support the 2022 workshop. The authors working on this project interviewed 10 practitioners from across the Southeast, including species managers, stewardship coordinators, researchers, land managers, and consultants. Participants were identified based on their participation in the EESLR-NGOM project, stewardship of coastal lands in the region (e.g., National Estuarine Research Reserve stewardship coordinators), or their participation in the Alliance Habitat Resources Team. This work was funded by the U.S. Geological Survey's Southeast Climate Adaptation Science Center.

Both the ESLR-SAB project and the Marsh Model Retrospective Initiative involve generating marsh projections with SLR, and while the underlying purpose and science (assumptions and mechanisms within the underlying models) of the projects differ, it is unknown if the outputs will differ in their ability to meet the needs of data users for decision making. Here, the authors use qualitative data collected from marsh model users across both projects to identify unmet needs and guide potential next steps for marsh modeling efforts.

Study Design and Interview Instruments

For both projects, interviews of marsh data users were semi-structured and designed to support the coproduction of resulting marsh modeling products. For the ESLR-SAB project, we virtually interviewed each member of the MTAG ($n = 14$; Table 1) in June 2023, asking about topics such as: (1) what decisions do [they] make about marshes?; (2) how do [they] use marsh models [in their work]?; and (3) what types of information is helpful in [their] decision making (e.g., high vs. low marsh, upland migration potential, conversion to other habitats)? (Kotowicz, Stoltz and Woodward 2025). These interviews were each 45 min to 1 h long and were recorded and transcribed in Microsoft Teams. Informed consent was obtained verbally for each interview prior to recording, and interviewees were made aware that any resulting scientific publications would identify the type of organization they work at but would not include further identifying information.

In support of the Marsh Model Retrospective Initiative, semi-structured interviews were conducted between March and July 2021 in the Gulf of America ($n = 3$) and coastal North Carolina ($n = 7$) (Table 1). Marsh model users were asked questions encompassing topics such as if and how they apply marsh modeling outputs in their decision making, which inputs and outputs are most important for decision making, and how much they trust model outputs. Interviews were conducted based on a pre-established interview guide. These interviews were each 45 min to 1 h long, recorded, and the interviewer took detailed notes focused on how participants described barriers in accessibility and usability in marsh modeling products. Verbal consent was provided for each recording and participants were aware that the information would be used to help improve marsh modeling outputs overall, with an emphasis on retrospective analyses.

With the goal of producing marsh modeling outputs that better address practitioner needs, these two data sources were combined and analyzed to answer the following research questions: What are the decision-making needs of marsh model users, which needs are unmet by existing models, and what priorities should guide future modeling efforts?

Data Analysis

The transcriptions and notes taken during the interviews across both projects were analyzed in Microsoft Excel by the lead author, a social scientist with qualitative coding expertise. Themes were developed inductively and then organized into categories of user needs, which were then finalized by the engagement specialists and social scientists on the author team who worked in the projects of focus (Kotowicz, Stoltz and Woodward 2025). The codebook consisted of user need categories including Restoration Activities, Planning and Management, Format of Modeling Outputs, Species and Vegetation Monitoring, Communication, Uncertainty, Freshwater Marshes, and Historical and Cultural Resources. The analysis of the Marsh Retrospective Initiative data revealed 46 mentions of discrete needs, and the analysis of the ESLR-SAB project data included 64 mentions of discrete needs (Table 2).

By comparing the interview results across both projects, we were able to further confirm the validity of the codebook as the majority of needs found across both projects were in the categories of Restoration Activities, Planning and Management, Format of Modeling Outputs, and Species and Vegetation Monitoring, answering the first part of our driving research question: What are the decision-making needs of marsh model users? These findings were then split into three overarching themes: (1) marsh restoration (2) planning with uncertainty, and (3) conserving habitat for marsh-reliant species. These three themes are discussed in detail in the following sections.

Table 1 List of research participants including their role and agency across both the ESLR-SAB project and the marsh model retrospective initiative

Project	Research Participant Role	Agency	Category
ESLR-SAB	Regional Wetland Ecologist	National Park Service	Federal
ESLR-SAB	Science Coordinator	Fish and Wildlife Service	Federal
ESLR-SAB	Geologist	U.S. Army Corps of Engineers	Federal
ESLR-SAB	Sustainability Liaison	Sea Grant/Department of Defense	Federal
ESLR-SAB	Conservation Coordinator A	U.S. Fish and Wildlife Service	Federal
ESLR-SAB	Regional Geomorphologist	U.S. Fish and Wildlife Service	Federal
ESLR-SAB	Interdisciplinary Research and Partnerships Lead	Sea Grant	Federal
ESLR-SAB	Conservation Coordinator B	North Florida Land Trust	NGO
ESLR-SAB	Coastal and Marine Director of Conservation	The Nature Conservancy	NGO
ESLR-SAB	Reserve Manager A	National Estuarine Research Reserve	State
ESLR-SAB	Research Coordinator	State Department of Natural Resources	State
ESLR-SAB	Reserve Manager B	National Estuarine Research Reserve	State
ESLR-SAB	Research Associate Professor	Florida International University	University
ESLR-SAB	Environmental Scientist	State Water Management District	State
Marsh Model Retrospective Initiative	Project Manager	The Nature Conservancy	NGO
Marsh Model Retrospective Initiative	Research Marine Biologist	National Oceanic and Atmospheric Administration	Federal
Marsh Model Retrospective Initiative	Stewardship Coordinator A	State Department of Environmental Quality	State
Marsh Model Retrospective Initiative	Associate Professor	University of North Carolina, Wilmington	University
Marsh Model Retrospective Initiative	Director of Ecological Restoration	State Department of Marine Resources	State
Marsh Model Retrospective Initiative	Reserve Manager C	National Estuarine Research Reserve	State
Marsh Model Retrospective Initiative	Stewardship Coordinator B	National Estuarine Research Reserve	State
Marsh Model Retrospective Initiative	Biologist	U.S. Fish and Wildlife Service	Federal
Marsh Model Retrospective Initiative	At-Risk Species Coordinator	U.S. Fish and Wildlife Service	Federal
Marsh Model Retrospective Initiative	Refuge Manager	U.S. Fish and Wildlife Service	Federal

Table 2 User needs and tasks for marsh modeling products identified across both projects of focus. The number of mentions refer to tasks and needs mentioned across the interview data from both projects of focus

Marsh modeling user needs/tasks identified during interviews	Number of mentions in ESLR-SAB project data	Number of mentions in the Marsh Model Retrospective Initiative data	Total number of mentions
Restoration Activities	16	4	20
Planning/Management	15	10	25
Format of Modeling Outputs	14	12	26
Species/Vegetation Monitoring	7	11	18
Communication	3	3	6
Uncertainty	3	3	6
Timescale	3	3	6
Freshwater Marshes	2	0	2
Historical and Cultural Resources	1	0	1
Total	**64**	**46**	**110**

Findings on Marsh Model User Needs

The results of the analysis of the interview transcripts from the ESLR-SAB project and the Marsh Model Retrospective Initiative provide insights about decision making of marsh model users that are presented in this section. We found that marsh practitioner decisions fall into three thematic categories: (1) marsh restoration, (2) planning with uncertainty, and (3) conserving habitat for marsh-reliant species. For each of these themes, we identify user needs that are not currently being met by the outputs of marsh modeling efforts. These include high spatial resolution information for local planning, accessible descriptions of uncertainty to increase user confidence, and the incorporation of human dimensions data (e.g., human alterations to the landscape such as impoundments and culverts) for a comprehensive understanding of the marshes.

Marsh Restoration

Marsh model users reported completing tasks associated with marsh restoration, usually with the goal of restoring habitat connectivity and ecosystem functions. These tasks include identifying areas for restoration, recreating wetlands, installing and removing culverts, and planning nature-based solutions for restoration (e.g., living shorelines or thin layer sediment placement). To complete these tasks, marsh model users reported needing a detailed understanding of the marsh including the locations of human disturbances such as drive-line ditches, impoundments, dikes, and navigational dredging. For example, a marsh model user who works for a state agency needed this information to understand where to remove dikes or install culverts to maintain a hydrological connection (6/6/2023; Oral Communication; ESLR-SAB Project). Another state agency researcher expressed that they need information on human disturbances because, “marsh that is human-impacted is the most vulnerable” (6/20/2023; Oral Communication; ESLR-SAB Project).

However, there are barriers to including human impacts in marsh models: (1) the information may not exist; (2) the information may not be in a format that can be easily incorporated into a model; (3) the information may be inaccessible or not made public; or (4) the model may not have the ability to incorporate the information due to model processes or resolution. As detailed by Lazarus and Goldstein (2019, p. 696) integrating real-time human interventions into geomorphic processes is “a phenomenon that no off-the-shelf numerical model of morphodynamics is built to capture”.

As described by marsh model users, completing local-scale restoration tasks also requires high spatial resolution data, below 10-m (i.e., 100 m^2), and parcel-scale data. For example, high spatial resolution data are needed to understand where and how to restore a site (e.g., application of thin layer placement), where to make hydrologic modifications, where to focus shoreline protection efforts based on observed rates of erosion, and to determine whether the land is sloped enough for the marsh habitat to migrate. Additionally, parcel scale information is needed by many state agencies for communicating and working with property owners. A representative from the U.S. Fish and Wildlife Service emphasized that while they use regional data to prioritize marsh restoration, they need more high spatial resolution marsh projection data to precisely locate restoration projects (6/8/2023; Oral Communication; ESLR-SAB). Lacking model outputs with high spatial resolution information, either due to limitations in funding or resources, research participants reported relying on local knowledge to make many of their decisions regarding restoration and conservation rather than large-scale modeling outputs (6/20/2023; Oral Communication; ESLR-SAB). This can result in suboptimal selection or placement of resiliency measures, which may increase long-term maintenance costs or have other detrimental effects such as increased erosion.

Conveying the resolution of the data required for the scale of the question being asked is an essential part of communicating marsh science to community members. Coastal practitioners at environmental NGOs and National Estuarine Research Reserves (NERRs) reported needing detailed, local or parcel-scale information to better communicate with the landowners with whom they work. However, a marsh model user stated, “I want an individual parcel-level output… but that is just not realistic when it comes to models. You can average the parcels over a certain drainage basin… but it must be tailored to your audience” (6/14/2021; Oral Communication; ESLR-SAB Project). They went on to explain that getting communities to understand that they do not need data on a parcel level is a challenge. A NERR’s representative shared this perspective and argued that if there were marsh data with a 1-m spatial resolution, for example, that it would likely be less accurate and therefore less meaningful than data that are provided on a larger scale because they do not provide a broader picture unless summarized at a coarser scale (Summer 2021; Marsh Model Retrospective Initiative). An outstanding challenge is conveying to users that finer scale data may be less reliable for decision making.

Some marsh model users do not work directly on restoration projects but instead help local managers in their efforts to restore marshes, create living shorelines, write grants, and acquire land. A downstream need in this category is better access to monitoring data that can be used to evaluate the performance of past restoration efforts. The efficacy of accessible monitoring data is twofold: it can support users by showing when and where restoration efforts have been effective and it can assist modelers with evaluating their model projections thereby decreasing uncertainty and improving user confidence in model predictions. The need for greater availability of monitoring data, especially in reference to nature-based solutions, is well-documented (Kabisch et al. 2016; Kumar et al. 2021; Stoltz et al. 2023b) and yet, when funded, usually as part of a restoration effort, it is short-lived (about three years or less).

Planning with Uncertainty

The second category of user needs is related to planning with uncertainty. Marsh model users want to know where marshes will migrate, which wetlands are projected to survive and for how long, and how that will affect the use and vulnerability of coastal areas. Model outputs inform their planning efforts, such as land acquisition, and help them prioritize where to focus their resources. However, these users have difficulty considering how to integrate uncertainty in the models when making decisions based upon model outputs.

Making decisions informed by future marsh migration or loss requires a clear understanding of uncertainty. In marsh models, uncertainty is calculated with a range of methodologies and presented in a range of formats or, sometimes, not presented at all. A practitioner from a federal agency expressed concerns that uncertainty is not often included in modeling products, "Uncertainty does not get included nearly enough. Park managers want something simple but they need to know about uncertainty and it needs to be conveyed" (6/9/2023; Oral Communication; ESLR-SAB Project).

Calculating and communicating uncertainty is complex, especially regarding the overlapping assumptions associated with SLR and different time horizons for planning (e.g., decadal predictions vs. predictions every five years). Uncertainty is also present in the underlying elevation dataset, which is often derived from light detection and ranging (lidar) which has reduced accuracy due to dense marsh vegetation in coastal fringe environments (Hladik and Alber 2012). These factors make it hard to provide users with accessible uncertainty estimates that can be clearly communicated. The practitioner went on to say that "the variability needs to be clear and communicated in a more digestible, user-friendly way. Maybe visually would be helpful, like a graph with confidence intervals" (6/9/2023; Oral Communication; ESLR-SAB project). Several users also called for spatially explicit uncertainty, such as a map of the areas of uncertainty with high and low bounds, an option that has been developed for several marsh modeling efforts (6/8/2023; Oral Communication; ESLR-SAB). Marsh model users understand uncertainty at various levels depending upon their modeling expertise, but overall, they want uncertainty to be communicated up front, easy to understand for non-experts, and displayed visually.

What gets lost in translation between the modelers and the marsh model users, is what 'uncertainty' means to different types of users. Two users (ESLR-SAB Project) with modeling expertise reported that they need to know exactly how uncertainty was calculated because they want the ability to rerun the model themselves, while other users, with limited modeling expertise, described wanting to know how confident they can be about how the marsh will change over time so that they can make planning decisions, accordingly, based on an identified level of certainty. Users in the first category want to have access to understandable metadata to better understand model outputs. A research participant who works at an NGO detailed, "I think the biggest issue with modeling is that the models and outputs consistently change if you're updating your model. Knowing not just which model, but which model and model output and where it is and who's running and understanding the metadata – that's all really important to me. The last thing we want to do is work with a model that's 10 years old [when there's a] newer model output that we could be using instead. It's hard to keep track of all this stuff" (8/2018; Oral Communication; Marsh Model Retrospective Initiative). Many users in the latter category expressed struggling with detailed descriptions of how uncertainty is calculated and need more simplistic, visual depictions of uncertainty. In other words, detailed descriptions of model assumptions may not help increase user confidence across the board. Another way of potentially meeting decision makers' needs surrounding uncertainty could be to clearly communicate which management decisions are and are not appropriate for a product, especially with respect to a model's resolution. In general, marsh modelers could clearly communicate that while models are useful for understanding marsh processes and vulnerabilities, they cannot make exact predictions of the future and may contain outdated vegetation data (Woodard et al. 2023b).

Conserving Habitat for Marsh-Reliant Species

The third category of needs is conserving habitat for species that rely on marsh, such as birds, fish, and other marsh associated species. Marsh model users who work to protect marsh-reliant species, including species of concern, want models that have detailed information on the presence of different habitats, the presence of marsh-reliant species, and how management interventions, such as impoundments, will impact habitat and foraging areas. The species most mentioned by research participants was often a type of bird, but

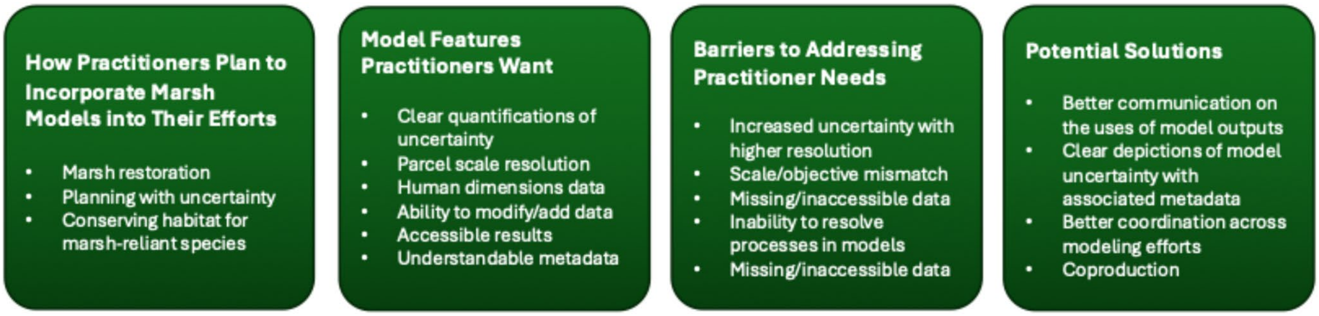

Fig. 1 How practitioners plan to incorporate marsh models into their efforts, the model features practitioners want, barriers to addressing practitioner needs, and potential solutions. Adapted from DeLorme et al. (2018)

interest in protecting marsh species also extends to fisheries and the need to understand fish passage and connectivity.

Many species of coast-associated birds depend on high marsh in some form for their survival (Bayard and Elphick 2011; Roach and Barrett 2015; Roberts et al. 2019; Stevens and Conway 2021). However, when marsh habitat converts to another habitat due to changes in inundation, it remains valuable for other species that may also be of interest to conservationists. For example, a representative from an environmental NGO remarked that the most vulnerable marsh areas make for the best Black Rail (*Laterallus jamaicensis*) habitat and a representative from a NERR described how tidal flats that convert into low sand spits become important habitat for seabirds and shorebirds (6/20/2023; Oral Communication; ESLR-SAB). These examples highlight the importance of including additional habitat classifications in modeling outputs like distinctions between high and low marsh. While a variety of marsh models do include multiple habitat classifications, these statements suggest that not all data users are aware of this possible output, indicating a need for more outreach on the topic.

The presence of certain species in wetlands can also drive decision making beyond species conservation. Representatives from the U.S. Fish and Wildlife Service and a NERR representative emphasized that understanding the threats to endangered species, such as loss of foraging habitat, are the main drivers of their land protection work. Several practitioners who do not focus on species of concern described how working in areas designated as critical habitat can provide more leverage for projects as these areas are more likely to get funding (6/20/2023; Oral Communication; ESLR-SAB).

Marsh model users also have an interest in monitoring invasive species. Several users included in this research are tasked with understanding how invasive plant species, like *Phragmites australis*, are holding the soil together and preventing erosion (8/2018; Oral Communication; Marsh Model Retrospective Initiative). These users need marsh models that consider these invasive species in addition to traditional marsh species.

Discussion

Considering the needs of users is an important step toward better utility of marsh modeling products. This paper presents results of complimentary efforts to identify and address marsh model end user needs. Our results show that needs exist around three main categories: restoration, planning with uncertainty, and conservation for marsh-reliant species. While a model does not need to address every need to be useful, perceptions that these models cannot support marsh practitioners may prevent model uptake.

Previous research has shown that managers want models that: (1) are easy to understand; (2) are specific to their managed lands; (3) include outputs for various time intervals; (4) are transparent about the input data; and (5) are clear about uncertainty and what it means (Martin et al. 2022). Our research builds upon these efforts to explore unmet needs across three major decision-making themes (i.e., marsh restoration, planning with uncertainty, and conserving habitat for marsh-reliant species) and offers suggestions that will encourage the use of these models (Fig. 1).

Across all categories, there are opportunities to close gaps through clear, frequent, and early communication between data users and modelers. We found that research participants were confused by the goals of existing marsh modeling projects and in some cases had difficulties understanding the differences between projects. The advent of information overload leading to decision paralysis is common in the coastal data and decision-making ecosystem (Stoltz et al. 2023b). Land managers who need site-specific data felt that regional-scale marsh modeling projects may assist them in communicating with their stakeholders and "starting the conversation," but they did not rely on the models to provide detailed information necessary for some of their tasks related to marsh restoration. While the need for more high spatial resolution, site-specific data is documented in this paper, the resulting data gap is frequently not due to a lack of science support or user engagement. Rather, this gap results due to a lack of collaboration and communication as regional-level modeling efforts are not intended to or able to support site-specific assessments; however, the existing models are able to provide that information when the study is appropriately designed and tailored to those purposes. To support data users navigating the difference between regional assessments and site-specific assessments, clear communication and supporting materials around the purpose of different model outputs will help build understanding and trust. Further, data users and modelers collaboratively seeking funding and project design will help ensure that studies meet the intended need and scope.

For planning with uncertainty, a key consideration is communicating the uncertainty in the models. The ESLR-SAB project is exploring several options for communicating uncertainty that will be tested in beta products to determine user preferences. The ELSR-SAB efforts to generate and user-test uncertainty information will respond to an immediate user need, and more broadly, it will provide insight into ways of successfully communicating this kind of information. Future marsh modeling projects should continue to build from these efforts to capture and translate uncertainty and what it may mean for data users in applying the model outputs. Further, the efforts of the Coastal Ecosystem Prediction System and the Marsh Model Retrospective Initiative were specifically designed with and at the request of data users to advance our understanding of what kind of models are best suited for which kind of decision-contexts. However, for these efforts to ultimately reduce uncertainty and support marsh model use, the dialogue with data users must continue. Currently, they are doing so through the Marsh Modeling Community of Practice which brings together modelers and practitioners[2].

Another key strategy for improving needs across different categories was inclusion of specific types of data in the models. These data needs ranged and included things such as understanding freshwater marshes, the human impacts to the marshland, and the ability for users to run the model with their own data. Preserving marshes is more likely to be successful when employing strategies including human communities and an understanding of the ecological, social, and cultural risks of losing marsh habitat (Morris 2024). While some modeling projects are working towards an understanding of the economic benefits and losses of marsh migration, many of the social and cultural risks have not yet been incorporated in large-scale marsh modeling projects. In practice, studies that combine coastal hazard modeling with data on social vulnerability are rare but growing (Arkema et al. 2017; Bilskie et al. 2022; Fox et al. 2023; Stoltz et al. 2025). Further, models that integrate social and biophysical aspects of coastal hazards and vulnerabilities remain a data gap for those interested in considering community vulnerability in marsh stewardship. Studies show that understanding how the most vulnerable communities experience marsh migration is an essential part of a socially-just coastal socio-ecological systems approach, and efforts to protect wetlands could be considered alongside efforts to protect people (Linhoss et al. 2015; Bhattachan et al. 2018; Dudley et al. 2021). However, coastal resilience work within wetlands has historically not engaged with the impacts that migrating marshes have on people. Rural communities have watched as their land—their homes, churches, critical infrastructure, and burial grounds—routinely flood and slowly convert into wetlands (Van Dolah et al. 2020). These communities often do not have the financial capital to relocate, especially without the ability to sell their property for pre-marsh-encroachment values, and they are often not able to adapt their property because of regulations enacted to protect marsh habitat (Van Dolah et al. 2020). While not a focus of the interviews, concerns about historical and cultural resources were mentioned by a representative from a state agency who argued that in South Carolina, future conservation plans could consider maintaining access to places of historical and cultural importance for all peoples, especially for African descended people who have been overlooked before (6/16/2023; Oral Communication; ESLR-SAB). How marsh migration will impact human communities was not expressed by the other interviewees, which may have been due to the focus of the interview protocol on data delivery or the overall composition of the interviewees which were skewed toward land and species managers. Projects that work to meet the needs of previously overlooked communities could begin by engaging with these communities to better understand their needs, so that their needs are considered at the project's impetus (Stoltz et al. 2025). Efforts to engage previously overlooked communities after a project has been conceived can lead to distrust between the researchers and the populations they hope to serve and can worsen stakeholder fatigue (Morris et al. 2024). Further, regardless of the sociocultural context of the community, in all instances of needing specific data to be included - early, frequent, and clear communication serves to close the gap if those data are available and compatible with the model structure.

When assessing how marsh model projects meet marsh data needs, the issue of scale mismatch is prevalent. In the natural resource management literature, scale mismatch refers to a lack of alignment between the extent and resolution of management actions and the ecological system of interest (Lee 1993; Cumming et al. 2006). This term could be used broadly to describe how marsh migration happens on a large scale and over a long timeframe, while marsh conservation actions happen on a comparatively small scale and a shorter time frame. More specifically, challenges in

[2] https://msucoastal.com/marsh-modeling-community-of-practice/.

marsh conservation related to scale mismatch include limited availability of high spatial resolution data and the lack of understanding social-ecological system components (Guerrero et al. 2013). While the overall problem of scale mismatch may not have a resolution, as most conservation actions cannot match the scale of marsh migration across U.S. coasts, understanding the multiscale nature of conservation problems is essential so that marsh models are created and applied at appropriate temporal and spatial scales (Guerrero et al. 2013). It should also be used to guide conversations around expectations, needs, and compromise outputs.

The findings from this work also support the existing body of literature around the importance of co-developing decision-support tools with end users (Bamzai-Dodson et al. 2021; Collini et al. 2021; Collini 2022; Stoltz et al. 2023a). Without coproduction, scale and objective mismatch can result in model outputs that have reduced benefits or contribute to perceived lack of reliability. Given that developing predictive models often takes years, as demonstrated in the ESLR-NGOM project, and models need to continuously be refined as new data and knowledge become available, it is essential that all opportunities to make them beneficial and trusted are acted upon. Engaging with end users can provide a better understanding of local knowledge and management needs and permit effective refinement, enhancement with best available data, and testing of models to ensure they are appropriately tailored to meet management objectives. This approach is fundamental for establishing the required knowledge, methods, and tools that can be used to assess marsh processes, transitions, and vulnerability to drivers such as SLR. Although limitations in project scope may result in not all end user needs being met, the developed models create the foundation for future detailed feasibility assessments of local restoration actions that can be targeted with future funding opportunities.

The findings here are limited to two projects in similar regions of the United States. It is important to continue exploring location-specific needs that may require additional advancements in modeling capacity in order to integrate them. For example, in Hawai'i where they have much smaller marsh extents and different physical systems, there may be different specific data types that would require altering the specific capacity or framework of the marsh models. Understanding the different user needs across the U.S. is part of the Coastal Ecosystem Prediction System through the Marsh Modeling Community of Practice; however, this should not replace ongoing, site-specific conversations with local marsh stewards or model output users for each effort. Additionally, the study represents a moment in time of modeling capacity and outputs. Regular assessments of modeling advancements and data availability should be considered to determine if activities or data that were previously considered unable to be completed are now possible or if new needs or gaps have emerged.

Conclusion

This paper provides an overview of marsh model user needs based on two projects within the Gulf of America (Gulf of Mexico) and Southeastern United States and discusses how these needs are met by current marsh modeling projects. User needs described here were summarized into three main categories of interest - marsh restoration, planning for sea-level rise, and conserving habitat for marsh reliant species. Crucially, the authors find that current marsh modeling projects can inform some of these needs but not others, and that there are several gaps that can be addressed through clear, frequent, and early communication. These gaps include the lack of high spatial resolution model outputs, the lack of information on the human dimensions of wetland habitats, and the need for more relevant and detailed information around model uncertainty. These needs go unmet due to a range of factors including computational and data limitations, limited funding and resource capacity at the local level to create site-specific flood models, and a mismatch in the goals of research-funded marsh model efforts (scientific progress) and those of land managers (site-specific marsh stewardship). Closing the latter gap will involve coproduction on both the development of marsh models and their outputs and how they are communicated.

When marsh modelers and marsh model users work iteratively throughout the modeling process, marsh models can better meet user needs and product developers can better clarify how to produce outputs that meet those needs. This collaboration, especially if it occurs at the early stages of project formation, can alleviate some of the challenges in conservation planning related to scale mismatch and uncertainty (Lee 1993; Cumming et al. 2006; DeLorme et al. 2016). The findings presented here are meant to inform future marsh modeling efforts and outreach. If marsh modelers more clearly catalog and communicate what model outputs are built to provide, then there will be more confidence in use of these models for their intended purposes.

Acknowledgements The authors are grateful to all our research participants for sharing their time and expertise. We'd also like to thank Jenny Thomas for her review of the data release, and Nicholas Enwright, Alyssa Dausman, Kara Doran, and the anonymous journal reviewers for their time and effort in reviewing this manuscript. Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Author Contributions All authors contributed to the study conception and design. Material preparation and data collection were performed by Amanda D. Stoltz, Dawn M. Kotowicz, and Sara Martin. Data analysis was performed by Amanda D. Stoltz and Dawn M. Kotowicz. The first draft of the manuscript was written by Amanda D. Stoltz and edited by Dawn M. Kotowicz, Christine Addison Buckel, Renee Collini, Davina Passeri, Sara Martin, and Nina Woodard. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This research was funded in part by NOAA's National Centers for Coastal Ocean Science Competitive Research Program under award NA22NOS4780175.

Data Availability USGS Data release Kotowicz, D.M., Stoltz, A.D., and Woodard, N., 2025, Modeling marsh migration—User needs for decision-making collected in 2021 and 2023: U.S. Geological Survey data release, https://doi.org/10.5066/P13JMCBZ.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

Alizad K, Hagen SC, Morris JT et al (2016) Coastal wetland response to sea-level rise in a fluvial estuarine system. Earths Future 4:483–497. https://doi.org/10.1002/2016EF000385

Arkema KK, Griffin R, Maldonado S et al (2017) Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. Ann N Y Acad Sci 1399:5–26. https://doi.org/10.1111/nyas.13322

Bamzai-Dodson A, Cravens AE, Wade A, McPherson RA (2021) Engaging with stakeholders to produce actionable science: a framework and guidance. Weather Clim Soc 13:1027–1041. https://doi.org/10.1175/WCAS-D-21-0046.1

Barbier EB, Hacker SD, Kennedy C et al (2011) The value of estuarine and coastal ecosystem services. Ecol Monogr 81:169–193. https://doi.org/10.1890/10-1510.1

Bayard TS, Elphick CS (2011) Planning for sea-level rise: quantifying patterns of Saltmarsh sparrow (*Ammodramus Caudacutus*) nest flooding under current sea-level conditions. Auk 128:393–403. https://doi.org/10.1525/auk.2011.10178

Bhattachan A, Jurjonas MD, Moody AC et al (2018) Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. Environ Sci Policy 90:122–134. https://doi.org/10.1016/j.envsci.2018.10.006

Bilkovic DM, Mitchell M, Mason P, Duhring K (2016) The role of living shorelines as estuarine habitat conservation strategies. Coast Manage 44:161–174. https://doi.org/10.1080/08920753.2016.1160201

Bilskie MV, Angel DD, Yoskowitz D, Hagen SC (2022) Future flood risk exacerbated by the dynamic impacts of sea level rise along the Northern Gulf of Mexico. Earths Future 10:e2021EF002414. https://doi.org/10.1029/2021EF002414

Buffington KJ, Janousek CN, Dugger BD et al (2021) Incorporation of uncertainty to improve projections of tidal wetland elevation and carbon accumulation with sea-level rise. PLoS One 16:e0256707. https://doi.org/10.1371/journal.pone.0256707

Burman E, Merrill N, Mulvaney K et al (2024) This land is your land, this could be marsh land: property parcel characteristics of marsh migration corridors in Rhode Island, USA. J Environ Manage 351:119657. https://doi.org/10.1016/j.jenvman.2023.119657

Clough J, Polaczyk A, Propato M (2016) Modeling the potential effects of sea-level rise on the coast of New York: integrating mechanistic accretion and stochastic uncertainty. Environ Model Softw 84:349–362. https://doi.org/10.1016/j.envsoft.2016.06.023

Collini RC, Heming MC, Mohrman C et al (2022) Utilizing an end-user driven process to identify and address climate-resilience tool needs in the U.S. Gulf of Mexico. Coast Manage 50:197–214. https://doi.org/10.1080/08920753.2022.2022975

Collini RC, Heming MC, Mohrman CF, et al (2021) Understanding end-user adoption of an online climate resilience tool. Environmental Science & Policy 124:247–253. https://doi.org/10.1016/j.envsci.2021.06.022

Collini R, DeLorme D, Hagen SC (2018) NGOM+N2E2 Management Team Advisory Group (MTAG) 2018 Workshop Report

Cumming GS, Cumming DHM, Redman CL (2006) Scale Mismatches in Social-Ecological Systems: Causes, Consequences, and Solutions. Ecol Soc 11(1):14. https://www.ecologyandsociety.org/vol11/iss1/art14/

DeLorme DE, Kidwell D, Hagen SC, Stephens SH (2016) Developing and managing transdisciplinary and transformative research on the coastal dynamics of sea level rise: experiences and lessons learned. Earths Future 4:194–209. https://doi.org/10.1002/2015EF000346

DeLorme D, Stephens S, Hagen S, Bilskie M (2018a) Communicating with coastal decision-makers and environmental educators via sea level rise decision-support tools. J Sci Commun 17:A03. https://doi.org/10.22323/2.17030203

Dudley PN, Rogers TL, Morales MM et al (2021) A More Comprehensive Climate Vulnerability Assessment Framework for Fisheries Social-Ecological Systems. Frontiers in Marine Science Volume 8-2021

Fagherazzi S, Anisfeld SC, Blum LK et al (2019) Sea Level Rise and the Dynamics of the Marsh-Upland Boundary. Front Environ Sci. https://doi.org/10.3389/fenvs.2019.00025

Fagherazzi S, Kirwan ML, Mudd SM et al (2012) Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. Rev Geophys. https://doi.org/10.1029/2011RG000359

Fox N, Tilt JH, Ruggiero P et al (2023) Toward equitable coastal community resilience: incorporating principles of equity and justice in coastal hazard adaptation. Cambridge Prisms: Coastal Futures 1:e36. https://doi.org/10.1017/cft.2023.24

Gittman RK, Popowich AM, Bruno JF, Peterson CH (2014) Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a category 1 hurricane. Ocean Coast Manage 102:94–102. https://doi.org/10.1016/j.ocecoaman.2014.09.016

Guerrero AM, McAllister RRJ, Corcoran J, Wilson KA (2013) Scale mismatches, conservation planning, and the value of social-network analyses. Conservation Biology 27:35–44. https://doi.org/10.1111/j.1523-1739.2012.01964.x

Hladik C, Alber M (2012) Accuracy assessment and correction of a LIDAR-derived salt marsh digital elevation model. Remote Sens Environ 121:224–235. https://doi.org/10.1016/j.rse.2012.01.018
Kabisch N, Frantzeskaki N, Pauleit S et al (2016) Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecol Soc 21
Kidwell DM, Dietrich JC, Hagen SC, Medeiros SC (2017) An Earth's future special collection: impacts of the coastal dynamics of sea level rise on low-gradient coastal landscapes. Earths Future 5:2–9. https://doi.org/10.1002/2016EF000493
Kirwan ML, Temmerman S, Skeehan EE et al (2016) Overestimation of marsh vulnerability to sea level rise. Nat Clim Chang 6:253–260. https://doi.org/10.1038/nclimate2909
Kotowicz DM, Stoltz AD, Woodard N (2025) Modeling marsh migration: user needs for decision-making collected in 2021 and 2023. U S Geol Surv data release. https://doi.org/10.5066/P13JMCBZ
Kumar P, Debele SE, Sahani J et al (2021) An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. Earth-Sci Rev 217:103603. https://doi.org/10.1016/j.earscirev.2021.103603
Lazarus ED, Goldstein EB (2019) Is there a bulldozer in your model? J Geophys Res Earth Surf 124:696–699. https://doi.org/10.1029/2018JF004957
Lee KN (1993) Greed, scale mismatch, and learning. Ecol Appl 3:560–564. https://doi.org/10.2307/1942079
Linhoss AC, Kiker G, Shirley M, Frank K (2015) Sea-level rise, inundation, and marsh migration: simulating impacts on developed lands and environmental systems. J Coastal Res 31:36–46
Mariotti G (2020) Beyond marsh drowning: the many faces of marsh loss (and gain). Adv Water Resour 144:103710. https://doi.org/10.1016/j.advwatres.2020.103710
Mariotti G, Fagherazzi S (2010) A numerical model for the coupled long-term evolution of salt marshes and tidal flats. J Geophys Res Earth Surf. https://doi.org/10.1029/2009JF001326
Martin S, Cameron C, Collini R et al (2022) Marsh Model Retrospective Workshop. Program for Local Adaptation to Climate Effects
Molino GD, Carr JA, Ganju NK, Kirwan ML (2022) Variability in marsh migration potential determined by topographic rather than anthropogenic constraints in the Chesapeake Bay region. Limnol Oceanogr Lett 7:321–331. https://doi.org/10.1002/lol2.10262
Morris A, Baird-Zars B, Sanders V et al (2024) Advancing equitable partnerships: frontline community visions for coastal resiliency knowledge co-production, social cohesion, and environmental justice. Geoforum 154:104051. https://doi.org/10.1016/j.geoforum.2024.104051
Morris JT, Sundareshwar PV, Nietch CT et al (2002) Responses of Coastal Wetlands to Rising Sea Level. Ecology 83:2869–2877 10.1890/0012-9658(2002)083%5B2869:ROCWTR%5D2.0.CO;2
Passeri DL, Hagen SC, Plant NG et al (2016) Tidal hydrodynamics under future sea level rise and coastal morphology in the Northern Gulf of Mexico. Earths Future 4:159–176. https://doi.org/10.1002/2015EF000332
Reed DJ (1995) The response of coastal marshes to sea-level rise: survival or submergence? Earth Surf Process Landforms 20:39–48. https://doi.org/10.1002/esp.3290200105
Roach NS, Barrett K (2015) Managed habitats increase occupancy of black rails (*Laterallus jamaicensis*) and may buffer impacts from sea level rise. Wetlands 35:1065–1076. https://doi.org/10.1007/s13157-015-0695-6
Roberts SG, Longenecker RA, Etterson MA et al (2019) Preventing local extinctions of tidal marsh endemic Seaside Sparrows and Saltmarsh Sparrows in eastern North America. Condor 121:duy024. https://doi.org/10.1093/condor/duy024
Stephens SH, DeLorme DE, Hagen SC (2020) Coastal stakeholders' perceptions of sea level rise adaptation planning in the northern Gulf of Mexico. Environ Manage 66:407–418. https://doi.org/10.1007/s00267-020-01315-3
Stevens BS, Conway CJ (2021) Mapping Habitat Quality and Threats for Eastern Black Rails (Laterallus jamaicensis jamaicensis). Waterbirds. https://doi.org/10.1675/063.044.0211
Stoltz AD, Cravens AE, Herman-Mercer NM, Hou CY (2023a) So, you want to build a decision-support tool? Assessing successes, barriers, and lessons learned for tool design and development: U.S. Geological Survey Scientific Investigations Report 2023–5076, 32 p., https://doi.org/10.3133/sir20235076
Stoltz AD, Cravens AE, Lentz E, Himmelstoss EA (2023b) User Engagement to Improve Coastal Data Access and Delivery. Report 2023–5081. Scientific Investigations Report. Reston VA. USGS Publications Warehouse. https://doi.org/10.3133/sir20235081
Stoltz AD, Won OM, Gee EKC, Seto KL (2025) No coastal justice without environmental justice: a systematic literature review of climate and coasts. Clim Change 178:206. https://doi.org/10.1007/s10584-025-03999-0
Stralberg D, Brennan M, Callaway JC et al (2011) Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied to San Francisco Bay. PLoS One 6:e27388. https://doi.org/10.1371/journal.pone.0027388
Swanson KM, Drexler JZ, Schoellhamer DH et al (2014) Wetland accretion rate model of ecosystem resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco Estuary. Estuaries Coasts 37:476–492. https://doi.org/10.1007/s12237-013-9694-0
Taylor-Burns R, Lowrie C, Tehranirad B et al (2024) The value of marsh restoration for flood risk reduction in an urban estuary. Sci Rep 14:6856. https://doi.org/10.1038/s41598-024-57474-4
Van Dolah E, Hesed C, Paolisso M (2020) Marsh migration, climate change, and coastal resilience: human dimensions considerations for a fair path forward. Wetlands. https://doi.org/10.1007/s13157-020-01388-0
Wal D, Pye K (2004) Patterns, rates and possible causes of saltmarsh erosion in the Greater Thames Area (UK). Geomorphology 61(3–4):373–91. https://doi.org/10.1016/j.geomorph.2004.02.005
Woodard N, Martin S, Collini R (2023a) Land Managers Want Marsh Models That… Mississippi-Alabama Sea Grant Publication – MASGP-22-065. https://placeslr.org/wp-content/uploads/2023/01/LandManagersWantMarshModelsThat.pdf
WoodardN, Martin S, Collini R (2023b) Marsh Modelers Want Land Managers to Know… Mississippi-Alabama Sea Grant Publication – MASGP-22-065. In: https://placeslr.org/our-work/activeprojects/enhancing-marsh-model-applications-through-intersectional-stakeholder-engagement/marsh-model-comparison/. Accessed 8 Aug 2025