Guidance on Using Models of Tidal Marsh Migration to Support Community Resilience to Sea Level Rise
WHAT’S AT RISK? THE VALUE OF TIDAL MARSHES

Tidal marshes provide important services for nature and people. Making way for marsh migration as the sea rises can help reduce the loss of these benefits:

<table>
<thead>
<tr>
<th>Service</th>
<th>Description</th>
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<tbody>
<tr>
<td>Fish Nurseries</td>
<td>Food and shelter for the young of many species of commercially and recreationally important fishes</td>
</tr>
<tr>
<td>Wildlife Habitat</td>
<td>Feeding and breeding areas for dozens of bird and mammal species, including rare species</td>
</tr>
<tr>
<td>Flood Protection</td>
<td>Reduction of storm surge and wave damage</td>
</tr>
<tr>
<td>Clean Water</td>
<td>Natural filtering that removes waterborne sediment and excess nutrients</td>
</tr>
<tr>
<td>Erosion Reduction</td>
<td>Stabilization of shorelines and reduction of erosion</td>
</tr>
<tr>
<td>Food Supply</td>
<td>Rich plant growth that builds marsh peat and supports the food web locally and regionally</td>
</tr>
<tr>
<td>Carbon Storage</td>
<td>Long-term removal of carbon from the atmosphere</td>
</tr>
<tr>
<td>Aesthetics and Recreation</td>
<td>Scenic vistas for recreation, relaxation, and tourism</td>
</tr>
<tr>
<td>Education</td>
<td>Living laboratories for teaching science at all grade levels</td>
</tr>
<tr>
<td>Self Sustaining</td>
<td>Natural capacity to continue providing ecosystem services despite many environmental changes</td>
</tr>
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Tidal marshes provide valuable habitat for fish, wildlife, and birds, such as these newly hatched saltmarsh sparrows in southern New England. This species nests only in tidal marshes, making it vulnerable to sea level rise. Credit: Margie Brenner/USFWS
Projected sea level rise presents unprecedented challenges to the survival of tidal marshes.

- Sea level is rising so quickly that it could outpace the natural processes that normally enable marshes to keep from drowning.
- Roadways, seawalls, and other features of land development will block some marshes from shifting landward.
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### Photograph

Photographs taken in 1976 (upper) and 2015 (lower) of the same site at Barn Island Wildlife Management Area in Connecticut show evidence of sea level rise and marsh migration.

*Credits: Coleman (upper), Ron Rozsa (lower)*

### On the Cover

*Photograph: Dead trees in a Connecticut tidal marsh suggest a history of marsh migration into previously forested upland. Credit: Chris Field*  
*Maps: Model results showing projections of marsh migration. Credit: RI CRMC*  
*Graph: Historical data on global sea level rise. Credit: IPCC*
ACKNOWLEDGEMENTS

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NROC thanks the many individuals who contributed their time and expertise to the planning and production of this report, including the project steering committee, members of the NROC Ocean and Coastal Ecosystem Health Committee, interviewees during the information gathering phase, workshop participants, reviewers, and those who provided ideas, information, and data. These individuals represented the following organizations:

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- Massachusetts Bays National Estuary Program
- Massachusetts Division of Ecological Restoration
- Massachusetts Office of Coastal Zone Management
- Merrimack Valley Planning Commission
- National Park Service
- National Oceanic and Atmospheric Administration
- New England Interstate Water Pollution Control Commission
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Tidal marshes in the northeastern United States have endured an array of human impacts since the 1600s. Not only have they lost 30 percent of their area to land development, agriculture, dredging, and filling, but the region’s marshes have been degraded by pollution, nonnative plants, channelization, and restricted tidal flow caused by culverts, bridges, and tide gates.

Today tidal marshes face an even greater challenge: rapidly rising seas. In the coming decades, the ocean will encroach on land at an increasing rate. Scientists expect that some marshes will undoubtedly drown, causing a loss of the many benefits provided by these ecosystems to people and wildlife. Yet tidal marshes boast a remarkable capacity to survive and thrive in the face of rising seas, as they have done many times in the geological past.

One way they survive is by shifting gradually inland with sea level rise onto formerly dry land. This landward movement—known as marsh migration—can happen only where rocky cliffs, roadways, seawalls, parking lots, and other natural and human-made features along the coastline do not block establishment of marsh vegetation. To sustain tidal marshes in the region, experts believe that an important strategy will be to make way for them—to make way for marshes as they shift onto present-day uplands.

A fundamental challenge is to understand where and how much tidal marshes are likely to migrate. A great number of factors play into marsh migration—the rate of sea level rise, topography of adjacent lands, availability of waterborne sediments, and localized nuances of tides, to name just a few. Natural resource managers and coastal stakeholders are asking many questions such as:

- Which coastal land parcels have the greatest potential to host marsh migration in the next several decades?
- What are the policies and practices that would best support marsh migration and help to sustain tidal marshes?
- To which marshes should organizations direct their limited funds for marsh restoration?

Government agencies and non-government organizations seek to answer those questions and many more in order to make management and policy decisions, but to do so requires new information. Increasingly, they are harnessing the power of computer-based models of marsh ecosystems. When used appropriately, models can provide valuable information about marsh migration and help to build a foundation of reliable information for decision-making and action.

The Northeast Regional Ocean Council (NROC) sponsored this report to advance the effective use of marsh migration models in the context of management and policy. The document offers expert guidance on the entire modeling lifecycle—from developing a modeling approach and working with data to communicating modeling results. While some of the information pertains specifically to NROC’s region of interest in the northeastern United States, the report is also intended as a useful resource for modeling of marsh migration in other regions.
Tidal Marsh Dynamics—Will the Marshes Move?

Tidal marshes are wetlands dominated by emergent vegetation that is routinely flooded and exposed by tidal waters. Species inhabiting tidal marshes are adapted to live in those conditions and indeed may require them to survive. Tidal marshes form in calm coastal waters, protected from waves, where fine sediments tend to be deposited. Where wave energy is too great, tidal marsh vegetation cannot persist. Three common types of tidal marsh are recognized: salt (greater than 18 parts per thousand salt concentration), brackish (0.5 to 18 parts per thousand), and freshwater tidal marsh (less than 0.5 parts per thousand). While each hosts a different set of plant species, the three types of marshes share the distinctive trait of flooding and draining with the tides.
A Matter of Inches: Key Role of Elevation in Tidal Marshes

Differences of scant inches in elevation can dictate which plants live in different parts of a tidal marsh, as each species is adapted to different amounts of flooding. This is important to consider because it means slight increases in sea level can cause big changes in the marsh ecosystem.

In New England’s salt marshes, a narrow belt of the tall salt marsh cordgrass (*Spartina alterniflora*) typically grows along the edges of creeks and ditches. This is the lowest elevation for marsh grasses. It is called the low marsh and is flooded daily by the tides. The rest of the marsh with higher elevations is called high marsh, where a number of shorter grasses and herbaceous plants are dominant, such as saltmeadow grass (*Spartina patens*). The boundary between low marsh and high marsh usually occurs near the elevation of mean high water. While the vertical difference between low marsh and high marsh may be modest, it has profound effects on plant life. Within the high marsh are shallow depressions called salt pannes and pools, where other plants prevail and many birds feed. Along the upland margin of a salt marsh, a brackish marsh belt influenced by groundwater and dominated by black grass (*Juncus gerardii*) may be present.

When the sea rises over a period of years, the frequency and duration of tidal flooding increases throughout the marsh. Eventually, the lowest areas of salt marsh cordgrass may die off, and those areas may become intertidal flats. Likewise, the boundary of low marsh and high marsh also shifts, so that salt marsh cordgrass replaces some of the saltmeadow grass. Along the upland margin, similar changes occur. As tidal flooding increases at those higher elevations, tidal marsh vegetation can grow farther uphill, replacing upland plants. That process is marsh migration.

**ELEVATION ZONES IN A TIDAL MARSH**

- Tidal Flat
- Low Marsh
- High Marsh
- Marsh/Upland Boundary

**LEARN MORE**

Two Ways for Marshes to Survive—for a Time

Tidal marshes in the Northeast have evolved and persisted in the face of rising seas for thousands of years. Natural feedback loops among biology, geology, and hydrodynamics in marshes enable them to survive when the rate of sea level rise is low to moderate. Two types of changes make this possible.

**Increase in Marsh Surface Elevation**

As sea level rises, marsh plants tend to respond by growing taller. In turn, the taller plants trap more waterborne sediment, which accumulates on the marsh surface. Taller plants also develop more roots and rhizomes, further building up the soil. Furthermore, greater flooding slows decomposition, causing dead organic matter to accumulate as peat. The combination of these processes can enable the marsh surface to increase vertically apace with sea level.

**Migration to Higher Ground**

Sea level rise causes tidal influence to reach farther uphill onto formerly dry land. The associated changes in soil moisture and salinity along the upland boundary can enable marsh vegetation to migrate laterally onto higher ground, essentially making it possible for the marsh to escape uphill from the rising sea. At sites across the Northeast, scientists are monitoring changes in the tidal marsh-upland boundary and documenting the rate of marsh migration. Studies are under way to understand the environmental characteristics and ecological processes in this transition zone that promote or prevent marsh migration.
What Will Happen to Our Marshes?
Understanding the Key Constraints

Scientists and resource managers have two main concerns regarding marsh migration: the accelerated rate of sea level rise and the presence of natural and human-made features that impede or block migration.

The rate at which the sea rises is a major factor determining whether a tidal marsh persists or disappears. If the sea rises faster than sediment and plant material can accumulate in the marsh, the marsh surface becomes flooded more often. Eventually, the increased flooding can cause plants to die and peat to break down, resulting in loss of marsh area. Scientists have observed marsh loss in some places already, and sea level rise is expected to accelerate further.

When features such as rocky cliffs, pavement, and seawalls lie adjacent to a tidal marsh, they can act as barriers that prevent tidal marshes from migrating inland as the sea rises. Many such features are permanent or extremely unlikely to be removed. They reduce the potential for tidal marshes to persist in the face of sea level rise. In other cases, barriers could be modified or removed to accommodate marsh migration.
Models: Tools to Explore Scenarios and Develop Solutions

The Role of Models

As the sea rises, a loss of tidal marshes could have a range of economic and ecological impacts, such as declines in commercial and recreational fisheries, increases in storm damage and flooding of property and infrastructure, reductions in water quality, and decreases in populations of birds and wildlife that live, breed, and feed in tidal marshes.

Models of marsh migration are increasingly being applied by government agencies and non-government organizations as they seek solutions. Using data on landscape characteristics and projections about future conditions, marsh migration models make it possible to explore different scenarios and see the general changes that may occur based on current understanding. In turn, the results can be used to gain insight into potential constraints on marsh migration and to identify strategies for accommodating migration.

It is important to keep in mind that all models are simplifications of the real world. They provide approximations of what might happen based on the assumptions, parameters, and data used. Care is needed in interpreting the results and using the findings. No individual model and no individual modeled scenario can definitively show how the future will unfold, which makes it necessary to use more than one type of model and many modeled scenarios to obtain dependable information. When applied appropriately and integrated with other types of information, models of marsh migration are valuable tools for building a foundation of information for decision-making.

Confidence and Interpretation of Model Results

A key challenge of marsh migration modeling is that the resulting maps may give the impression of more certainty in the outcomes than is actually present. Misinterpretation and misuse of the model results are common. Properly interpreting and clearly communicating the model outputs—and the associated assumptions and confidence levels—are essential when model results are used to make public policy and management decisions.

A Toolbox of Models

A range of models are available for investigating marsh migration. Some are relatively simple and need only a few types of data. Others consist of complex and detailed equations representing biological, geologic, and physical components of the ecosystem. Different models are suitable for different purposes. The next section, Getting Started with Marsh Migration Modeling, offers guidance on selecting a modeling approach.

Keep in mind that all models are simplifications of the real world. They may provide helpful insights—but not precise predictions.
Connecting Marsh Migration with Other Management Priorities

The issue of marsh migration is closely associated with other policy and management priorities such as infrastructure planning and maintenance, coastal hazard preparedness, and habitat restoration. Modeling can examine those issues jointly with marsh migration and produce management-relevant information for multiple purposes.

Management Challenges that Intersect with Marsh Migration Modeling

Protecting Roads and Other Infrastructure

Roadways, culverts, railroads, and other infrastructure located in coastal areas may face increased risk of inundation and damage from storms made worse by sea level rise. At the same time, these features are critical factors to consider in marsh migration modeling because they can be barriers to marsh migration, even if the right conditions are otherwise in place. Marsh migration modeling projects often include mapping and analysis of infrastructure to help define the physical processes; in turn, this information can be used to determine potential impacts of sea level rise on infrastructure.

Reducing Vulnerability of Communities to Storm Damage

Tidal marshes offer natural protection against storm surge, wave damage, and flooding. Modeling of marsh migration helps reveal where this natural protection might persist or be lost as the sea rises. Loss of marshes can exacerbate the increased vulnerability levels of coastal communities from sea level rise. Management decisions related to marsh migration can take into account the protective value of potential marsh sites in order to bolster community safety as well as ecosystem health.

Improving Water Quality

Tidal marshes intercept excess nutrients from land, and avoiding eutrophication is an important benefit of retaining tidal marshes in the landscape. Efforts to support marsh migration therefore align directly with initiatives by coastal communities to meet Total Maximum Daily Load (TMDL) requirements and otherwise improve water quality.

Maximizing Long-term Success of Habitat Restoration

Restoration of tidal marshes is a longstanding priority of many government agencies and non-government organizations. Marsh migration modeling can be used to evaluate the viability and suitability of candidate restoration sites in the face of sea level rise. For example, if a particular marsh were restored, would it be likely to migrate successfully in the face of sea level rise—or would the investment be lost because the marsh was blocked from migrating inland?
GETTING STARTED WITH MARSH MIGRATION MODELING

Marsh migration modeling is a way to explore a range of potential scenarios.

The old stone wall in the foreground of the photograph marks the historical boundary between pasture and marsh. Gradual sea level rise has resulted in the conversion of pasture to tidal marsh.
Modeling of tidal marsh migration is a rapidly evolving area of scientific investigation that is also being actively applied to management and policy decision-making. While the process of using marsh migration models as decision support tools will vary depending on the specific goals and objectives, this section provides an overview and framework that can be applied in any management context.

**The Modeling Process**

The decision-support value of modeling can be maximized by clearly defining the management questions, choosing and applying appropriate models with high-quality data, and producing outputs that clearly and accurately communicate the results, confidence levels, and assumptions in a useful form to managers and stakeholders.
GETTING STARTED WITH MARSH MIGRATION MODELING

Begin by Defining Overarching Goals

For modeling to be conducted efficiently and generate useful results, it is important to understand the overall context and define a set of long-term goals before diving into the modeling itself. In general, models of any type are most valuable as decision support tools when the decisions to be made, and the ways that model results will be used in the decision-making process, are clear. That information can be used to guide the model implementation.

Following these steps will help build a framework for a successful marsh migration modeling project:

- **Outline an overall vision for sustaining tidal marshes and how marsh migration fits into the vision.** Looking beyond the issue of sea level rise, consider the full range of current or anticipated threats to tidal marshes in the jurisdiction or study area. What are the threats, and what is being done or potentially could be done to address them? How highly does the potential for blocked or impaired marsh migration rank compared to other threats, including related but different issues such as changes in within-marsh habitats?

- **Look for ways to connect marsh migration modeling with other management issues** such as protecting infrastructure, reducing vulnerability of communities to storm surge and flooding, and increasing the long-term viability of habitat restoration projects.

- **Define the desired outcomes and long-term goals for marsh migration modeling.** For many organizations, the primary desired outcome of marsh migration modeling is to build a strong foundation of information about marsh migration since the issue is poorly understood at present. In what locations and how far are marshes likely to migrate? Where is marsh migration unlikely to occur? A longer-term goal is to use this understanding to take steps to sustain tidal marshes. If specific outcomes and goals are identified, they will be useful in shaping the modeling process.

- **Describe the decision-making process in which marsh migration modeling results may be used.** Who is involved, what issues are intended to be resolved, and what is the legal and regulatory framework? What types and formats of information will have the most impact on decision-making?
Engage an Advisory Group

Only recently has marsh migration emerged as a priority issue, and it is a complex and rapidly advancing area of interdisciplinary scientific study. To date, marsh migration has received little public attention in most places. For those reasons and others, practitioners of marsh migration modeling have found it important to engage an advisory group of people with a range of relevant expertise and perspectives. The advisory group can help focus the modeling project, define objectives, ensure technical and scientific validity, and translate the model results into useful, relevant products. Tips for assembling and working with an effective advisory group include:

- **Bring together managers, stakeholders, scientists, technical specialists, and communication specialists** at the beginning of the project to discuss the modeling process and desired products. Build an advisory group by drawing from these people and other interested parties who can contribute different viewpoints.

- **Consult with the advisory group periodically throughout the project** to ensure that pertinent questions are raised, problematic steps or results are discussed, and the project stays on target.

Set Specific Modeling Objectives

Models can be used to investigate many aspects of how tidal marshes might respond to climate change in general and to sea level rise in particular. It is crucial and often challenging to maintain a sharp focus on the goals and objectives so that the modeling process generates relevant, reliable, and actionable information. Take time to consider the following topics when developing modeling objectives:

- **Translate overarching management goals into specific questions for the modeling project to answer.** The questions serve to focus every aspect of the project—from selecting models and obtaining data to analyzing the results and creating communication products—and they help to ensure that the outputs are useful for management. See page 19 for examples of specific questions.

  - **Identify who will be receiving and using the modeling results.** If there is a plan in place for using the results and expectations for how the results will be used, this will be very helpful in focusing and streamlining the modeling effort. Also, consider whether it would be beneficial to align the modeling with related efforts, such as those in neighboring states or municipalities.

  - **Determine the information necessary and sufficient to answer the questions.** Recognize that adding detail and complexity usually means a higher cost for the project without necessarily providing more value for decision-making. Often the information needed for decision support is somewhat different from the information needed for scientific research.

  - **Define the geographic scale or scales for modeling.** Different modeling approaches might be chosen depending on whether the results are needed for a single marsh, or for all marshes along a state’s coastline. Spatial scale is an important consideration in how the modeling is carried out.

  - **Specify the acceptable level of accuracy for the intended use.** Do marsh migration areas need to be projected to within feet, or would lower accuracy be sufficient? High accuracy is often seen as desirable, but the tradeoff is that higher accuracy often means higher cost for the modeling project. The level of accuracy should be matched to the way the information will be used.
Getti Ng started with marsh migration modeling. Many modeling efforts focus on 50- to 100-year projections. When possible and appropriate, providing 20- to 50-year projections may be beneficial for raising awareness of the issue and aiding decision-making because it is easier for people to relate to the shorter timeframe.

Develop an implementation plan for the modeling project. Consider: (1) available data and information, (2) funding, timing, and staff resources, (3) purpose, audience, and planned use and communication of results, and (4) whether modeling will be done in-house or by a contractor. If a contractor is used, be sure a request for qualifications is fully vetted and require that model output and metadata will be delivered in a usable format.

Lay Groundwork for Communicating and Delivering Results

When marsh migration modeling is done for the purpose of providing information and decision support to people who are not experts in marsh ecology or modeling, it important from the outset to think about how the results will be communicated. Generally, the communication products will need to be very different from those typically produced for scientific purposes. If people are unlikely to look at a hundred different maps of model outputs, for example, what are the most important one, two, or three maps that they should have? It is much more efficient and effective to focus on communication objectives from the start of the project, rather than conducting the modeling and then thinking about communications. Taking the following steps up front will help ground the communication piece within the structure of the modeling project:

- Decide how far into the future the model projections should extend. Many modeling efforts focus on 50- to 100-year projections. When possible and appropriate, providing 20- to 50-year projections may be beneficial for raising awareness of the issue and aiding decision-making because it is easier for people to relate to the shorter timeframe.

- Develop an implementation plan for the modeling project. Consider: (1) available data and information, (2) funding, timing, and staff resources, (3) purpose, audience, and planned use and communication of results, and (4) whether modeling will be done in-house or by a contractor. If a contractor is used, be sure a request for qualifications is fully vetted and require that model output and metadata will be delivered in a usable format.

- At the beginning of the project, work with a communications specialist to plan an endgame for delivering the findings. Revisit the question of what information is most important for decision support. Define a strategy and portfolio of communication products that will effectively convey the information. Think backwards from those products to plan a process that will generate them.

- Budget time and resources to communication as an integral part of the modeling process. Keep in mind that products will need to be strategically planned and developed, writing and graphics will need to be accessible and engaging, and interactive products such as websites will need to be user friendly.

- Aim for a modeling approach that is transparent, understandable, and credible for non-experts. Think about how methods, assumptions, uncertainties, and results will be communicated, and when possible opt for methods that are easy to understand.

- Take time to cultivate understanding among stakeholders about what the modeling project can and cannot do. This is a way to proactively manage stakeholder expectations throughout the project.

- Obtain technical advice on the interpretation of modeling results and appropriate ways to use the results in decision-making. Think about how to explain these interpretations to stakeholders in clear and understandable language.

- Consider how data, metadata, and results will be stored and made accessible for future uses. Documentation and data resources represent valuable investments that should be readily discoverable and available for scientists and technicians.
EXAMPLES OF SPECIFIC QUESTIONS FOR MARSH MIGRATION MODELING

Marsh migration modeling is most useful and efficient when it focuses on answering one or a few specific questions, such as the following examples. Questions vary widely in their difficulty to answer and the types of models and data required.

- For the tidal marsh at a particular location—or for all tidal marshes along a coastline—which areas of adjacent land might become tidal marsh if sea level rises 1, 2, or 4 feet (without considering a specific rate of sea level rise or number of years)? Would the answer change if we project that sea level will rise 2 feet in 100 years?
- Where is marsh migration likely to be blocked by manmade barriers such as roads and seawalls? How many additional acres might become tidal marsh if those barriers were removed?
- Of all the tidal marshes in the Northeast region, which ones have the most (or least) potential to migrate into adjacent areas if sea level rises 1 foot by 2050 and 3 feet by 2100? Does the answer change if the amount of sediment in the water is low, moderate, or high?
- Which upland areas or parcels should we consider prioritizing for protection to accommodate migration of tidal marshes?
- Are proposed tidal marsh restoration projects viable as long-term investments based on likely migration scenarios?
- Where might there be opportunities to accommodate marsh migration as we build or repair coastal roadways and other infrastructure?
- Will the total acreage of tidal marsh in the study area expand or shrink if sea level rises 1, 2, or 3 feet? Will habitat types within marshes—such as high marsh, low marsh, and open water—gain or lose acreage?

BEYOND MARSH MIGRATION

The following are examples of questions that relate to but extend beyond the issue of marsh migration. Using models to help answer them would require other types of modeling, data, and analysis.

- Will coastal properties become more vulnerable to storm surge because of loss of tidal marsh?
- As sea level rise affects tidal marshes, will the value of these marshes as fish nurseries increase or decrease?
- How will sea level rise affect populations of birds and wildlife dependent upon tidal marshes?
- What would be the most beneficial actions to support long-term persistence of tidal marshes in the study area?
Overview of Marsh Migration Models

Three General Categories of Models

Many different models exist of tidal marshes, and all have utility as tools for understanding these coastal ecosystems. As with any tool, however, each model is well suited for some uses and not as well suited for other uses. It is important to select the right tool for the job. The universe of models relevant to marsh migration can be divided into three main categories: (1) conceptual models, (2) mechanistic models, and (3) rules-based models. We use these categories in this report, though it is possible to categorize the models in other ways. As decision support tools, rules-based models are generally the most suitable, but conceptual models and mechanistic models can play useful roles in decision-making, too.

Category 1: Conceptual Models

Conceptual models are non-mathematical representations of how an ecosystem works. They often take the form of diagrams, drawings, flow charts, or tables. Conceptual models are a tool to bring together and synthesize current scientific understanding of the ecosystem, illustrate linkages among ecosystem components and processes, and serve as touchstones for shared understanding and communication. A conceptual model may be developed for a specific tidal marsh site, or it can be a more generalized representation of tidal marshes. While conceptual models have an important role in advancing and broadening people’s understanding of marsh migration, they do not provide quantitative projections of marsh migration in particular places. They can be valuable communication tools for explaining how quantitative models work and what their results mean.
Category 2: Mechanistic Models

Mechanistic models consist of detailed mathematical equations representing processes in the marsh ecosystem and the linkages among those processes. They range from zero-dimensional models that show changes at a single point to two- and three-dimensional ecogeomorphic models that show changes along a line or within an area. Mechanistic models are valuable for basic and applied research because they excel at providing fundamental insights into how marsh ecosystems function. However, they may not be the best choice as decision support tools for management because the required investment in data and analysis can be very high without a commensurate increase in management value of the information. Mechanistic models must be calibrated for specific local conditions, need significant data inputs, and can require many assumptions that affect the final results. In addition, the model results can be highly sensitive to linkages among ecological processes in the model. The assumptions and sensitivity can make mechanistic models prone to incorrect results when the model is applied for long time periods into the future. Researchers are actively developing new and revised mechanistic models, including efforts to make them more readily applicable to management.

Examples of Mechanistic Models

The Marsh Equilibrium Model (MEM) is a web-accessible, one-dimensional model that was developed for Spartina alterniflora but can be calibrated for other vegetation. The model forecasts changes in marsh elevation at a single point, based on biological and physical inputs. Examples of the inputs are turnover rate of belowground biomass, root:shoot quotient, and settling trapping coefficients. The model produces a report with graphs and tabular results.

The Kirwan Model is an ecogeomorphic model incorporating marsh ecology, geomorphology, erosion, and hydrologic processes. Best suited for use in individual wetlands, the model requires extensive data inputs and includes many variables. Specialized programming is needed to use it. The model generates two-dimensional maps that show changes in marsh elevation and vegetation over time.

Hydrodynamic Models

Another Tool for Understanding Marshes

A hydrodynamic model is a set of equations that describe the movement of water in a particular geographic area. Hydrodynamic models can take into account parameters such as bottom friction, tidal harmonics, geometry of marsh channels, and size of culverts that restrict tidal flow. This type of model is developed for a specific tidal marsh based on the site’s unique characteristics. Considerable data collection and analysis must be done to build and validate hydrodynamic models. The detailed information they produce is typically of interest for engineering applications, rather than for decisions related to marsh migration.
**Category 3: Rules-based Models**

A rules-based model is a set of simple algorithms that serve as a decision-tree of major habitat changes associated with sea level rise without trying to capture all of the processes behind those changes. Rules-based models are a relatively economical way to produce useful results, especially given the many uncertain parameters associated with marsh migration. For this reason, they are the most commonly used models for management decision-making, and they are the focus of the remainder of this report. Rules-based models can be divided into three subcategories based on the number of variables they include: elevation-based models, elevation-and-time-based models, and geomorphic models.

**Category 3A: Elevation-based Models**

*Tide Levels + Sea Level Rise*

Often called bathtub models or simple inundation models, the simplest of the rules-based models consider only elevation and a user-defined change in sea level with no element of time. In this case, the “rule” is simply a determination of whether dry land will be flooded if the sea level rises by a specified height. These models essentially treat the ocean and coast as a giant bathtub, in which sea level rise is equivalent to adding more water to the tub. Bathtub models produce maps showing where the ocean may be expected to inundate land if sea level rises a defined amount. To interpret the model results with respect to marsh migration, one must look for inundated areas next to present-day tidal marshes and assume that they may turn into tidal marsh if soil, slope, and other conditions are suitable and there is nothing blocking marsh migration. Consequently, this type of model requires additional analysis or interpretation to understand the actual potential of marshes to migrate. However, the simplicity of bathtub models makes them easily understood by non-experts.

<table>
<thead>
<tr>
<th>Type of Model</th>
<th>Tide Levels</th>
<th>Sea Level Rise</th>
<th>Soil Buildup</th>
<th>Land Cover</th>
<th>Geomorphic/Empirical Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 3A:</td>
<td>☑</td>
<td>☑</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevation-based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category 3B:</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevation-and-time-based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category 3C:</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Geomorphic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**EXAMPLE OF ELEVATION-BASED MODEL**

Examples of outputs from an elevation-based model used by the Casco Bay Estuary Partnership. Colors indicate wetlands: existing (blue), lost (yellow), new without conflict with existing development (orange), and new with conflict (purple).

*Credit: Casco Bay Estuary Partnership*
Category 3B: Elevation-and-time-based Models

*Category 3A + (Time × Soil Buildup)*

These models add the element of time and show changes in habitat based on a set of transition rules. The marsh is divided into small blocks or cells, and rules determine the habitat within each cell based on elevation above or below tide levels. As sea level rises in each time step of the model, the rules determine whether the habitat in each cell has changed, such as from upland to marsh. These models require data on: (a) elevation, (b) land cover, and (c) rate of vertical change in the marsh surface from accumulation or compaction of mineral and organic matter in the soil. The rate of vertical change determines whether the marsh elevation increases at the same rate as within the marsh.

Category 3C: Geomorphic Models

*Category 3B + Land Cover + Geomorphic/Empirical Rules*

Compared to elevation-and-time-based models, geomorphic models add more detailed rules for habitat changes within the marsh, as well as rules based on simple sediment transport relationships. They begin to approximate the feedback loops and other linkages that exist in tidal marsh ecosystems. This can be a benefit but also requires more data and assumptions, making them more complicated compared to elevation-based and elevation-and-time-based models. The added complexities can have consequences and introduce errors into the results that are not as obvious as those in simpler models.

EXAMPLE OF ELEVATION-AND-TIME-BASED MODEL

Examples of outputs from an elevation-and-time-based model, the NOAA Sea Level Rise Viewer, for marshes (purple) near Portsmouth, New Hampshire. The Viewer allows users to adjust the amount of sea level rise, soil buildup, and number of years. *Credit: NOAA*

EXAMPLE OF GEOMORPHIC MODEL

Examples of outputs from a geomorphic model called the Sea Level Affecting Marshes Model (SLAMM) for Barn Island Wildlife Management Area, Connecticut. Colors indicate land cover categories from estuarine open water (blue) to undeveloped dry land (red). *Credit: Warren Pinnacle Consulting*
Do Models Differ Significantly in Their Results?

Various models of marsh migration are available (see Choosing Among Existing Models and Model-Based Tools, page 26), and each has its own set of assumptions, requirements, strengths, and limitations. An important question is whether different models generate significantly different results. This question is especially relevant when models are used as decision support tools in a policy and management context. Often a relatively coarse level of information is acceptable, rather than the detailed and precise information characteristic of scientific research. For example, resource managers may not need to know within inches where a marsh is likely to migrate. They may only need an accuracy of tens or hundreds of feet, so they can identify land parcels with the greatest potential to host tidal marshes in the future. If several different models can give them this information, then they might consider using the model that requires the lowest investment of money and time.

To answer this question definitively, one would need to apply different models to the same geographic areas—using identical assumptions about sea level rise and other factors—and then compare the results. There are few examples of this comparison being done in any systematic way. The images on this page offer an example of outputs from four models, run with similar parameters for the same area of marsh. They illustrate the types of information produced by the models, which differ in their data requirements, ease of use, and other factors. The Sea Level Affecting Marshes Model (SLAMM, image A) produced moderately high-resolution results showing land cover within and around the marsh. The SLAMM maps were produced by a consulting company under contract with the New England Interstate Water Pollution Control Commission, and this image was contained in a report to the NEIWPC. CoastalResilience.org (image B) provides high-resolution results that specifically indicate potential marsh migration areas on an aerial image. These maps are publicly available online for selected geographic areas. The NOAA Sea Level Rise Viewer (images C and D) offers lower-resolution results including a range of land cover types, and the results are publicly available online for most of the United States. The images above show results of four models for an area of Clinton, Connecticut, using approximately the same amount of sea level rise (3 or 3.3 feet) and, when included, time period (80 or 100 years). A: Sea Level Affecting Marshes Model (SLAMM). B: CoastalResilience.org. C: NOAA Sea Level Rise Viewer in basic Marsh mode. D: NOAA Sea Level Rise Viewer in Marsh mode with Advanced Options selected.
CONSIDER OTHER APPROACHES BESIDES MODELING

While models can be useful tools to provide information about potential marsh migration sites, other approaches are available that may be used with or instead of modeling. They are worth considering and could be good options depending on the management goals; types and precision of information needed; availability of data, funding, and technical resources; and timeline for project completion. These approaches may include:

- **Expert knowledge**: Obtaining information from experts through interviews, surveys, workshops, and other methods may provide information suitable for management purposes. In the scientific literature, methods are available for collecting, synthesizing, and analyzing expert knowledge regarding complex ecological topics.

- **Coastal Squeeze Index**: This index, developed by Dante Torio and Gail Chmura, reveals the degree to which marsh migration may be constrained by steep slopes and/or development. It can be used along the edge of an individual marsh or an entire coastline to help identify sites with the highest potential for marsh migration.

- **Geology and land cover**: Basic data on coastal geology can be used to quickly identify places that are well suited for marsh migration, such as glacial outwash plains. Readily available land cover data can reveal obvious constraints on marsh migration.

Any of these three approaches can be used to help focus marsh migration modeling and reduce the expenditure of time and money, or they may serve as alternatives to modeling.

Surficial geology data can be used to identify suitable and unsuitable areas for marsh migration. This section of the Connecticut coastline is dominated by low-lying sand and gravels, indicated with yellow and orange, which are favorable to marsh migration. Credit: Connecticut Environmental Conditions Online
Choosing Among Existing Models and Model-based Tools

Management- or conservation-oriented modeling of marsh migration does not usually require the creation of new models. Rather, existing models can be applied to the geographic area of interest. Several web- and desktop-based interactive tools make some marsh migration models broadly available and easily accessible.

The best choice of model depends on management goals, specific modeling questions, spatial scale, technical capacity, data availability, level of accuracy and precision needed in results, and plans for communicating and using the results. When the results will be used in decision-making, the selection and implementation of a model should be done by scientists and technicians with expertise in tidal wetland ecosystems, geospatial data collection, and modeling. However, some web-based interactive tools make it simple for non-specialists to quickly get a sense of the potential for marsh migration in a given area.

**Some Factors to Consider**

- What are the specific questions that model results are intended to help answer? What specific information is required to answer the questions?
- Who are the audiences for the model results? What information will be practical for them to use? In what format would they best receive the information?
- How far into the future do you need the model to provide information, recognizing that unknowns increase as the model projects farther into the future?
- What types of data already exist or are feasible to collect for your place of interest?
- How much time and money are you willing to invest, keeping in mind that a complex model is not necessarily better?
- How much inaccuracy are you willing to accept in model results?

A complicated model will not necessarily produce more accurate results than a simple model, especially if the additional complexities are poorly understood and suitable data and modeling techniques are not available.
Guide to Models and Model-based Tools

On the next several pages are descriptions of selected models and model-based tools. The term model-based tool refers to a website platform that makes it possible for users to view model results and even adjust some of the variables without digging into the actual model. Models and tools were selected for inclusion based on their relevance and practicality for management applications, and all are rules-based models.

Additional important models exist but are not included because they are not readily applicable to management at present. Examples are the Marsh Equilibrium Model and the Kirwan Model, both of which are expected to become more practical for use in management contexts in the future.

<table>
<thead>
<tr>
<th>Model</th>
<th>Main Use</th>
<th>Modeling Platform</th>
<th>Reporting Format</th>
<th>Data</th>
<th>Land Cover</th>
<th>Spatial Scale</th>
<th>Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maine Marsh Migration Team Model, p. 28</td>
<td>Providing initial information for town-level planning and state-wide general analysis</td>
<td>ArcGIS</td>
<td>Printed and electronic documents</td>
<td>Elevation. Highest Annual Tide. Sea level rise of 1, 2, 3, 6 feet.</td>
<td>Highest Annual Tide as proxy for upper boundary of coastal wetland (regulatory boundary) and state marsh mapping used to cross-check</td>
<td>Maine coastline (approximately 3,500 miles)</td>
<td>None specified</td>
</tr>
<tr>
<td>Buzzards Bay National Estuary Program Model, p. 29</td>
<td>Evaluating potential expansion and migration of existing salt marshes, particularly those in tidally restricted areas</td>
<td>ArcGIS</td>
<td>Online interactive map</td>
<td>Elevation. High Tide Line. Sea level rise of 1, 2, 4 feet.</td>
<td>Highest Annual Tide as proxy for upper boundary of coastal wetland (regulatory boundary)</td>
<td>Coastline of Buzzards Bay, Massachusetts (310 miles)</td>
<td>None specified</td>
</tr>
<tr>
<td>Casco Bay Estuary Partnership Model, p. 30</td>
<td>Identifying potential areas of marsh migration and possible impacts to existing developed areas</td>
<td>ArcGIS</td>
<td>Printed and electronic documents</td>
<td>Elevation. Tide levels. Sea level rise of 1, 2, 3 feet.</td>
<td>Wetland areas based on tide levels</td>
<td>More than 40 focus areas located in 10 municipalities around Casco Bay, Maine</td>
<td>None specified</td>
</tr>
<tr>
<td>Marsh Analysis and Planning Tool Incorporating Tides and Elevations (MAPTITE), p. 31</td>
<td>Providing information for restoration of tidal marsh vegetation</td>
<td>ArcGIS</td>
<td>Printed and electronic documents</td>
<td>Elevation. Tide levels. Tidal ranges of plant species.</td>
<td>Vegetation in marsh based on user-defined water-depth ranges for each plant species</td>
<td>Dependent on inputs</td>
<td>None specified</td>
</tr>
<tr>
<td>Marsh Adaptation Strategy Tool (MAST), p. 32</td>
<td>Evaluating and prioritizing potentially inundated sites based on values of interest</td>
<td>Global Mapper GIS</td>
<td>Electronic document</td>
<td>Elevation. Values of sites. Sea level rise.</td>
<td>Satellite imagery</td>
<td>Demonstration project included 3 land parcels</td>
<td>By 2100</td>
</tr>
<tr>
<td>NOAA Sea Level Rise Viewer, p. 33</td>
<td>Quickly and easily considering potential changes almost anywhere along the U.S. coastline</td>
<td>Internet</td>
<td>Online interactive map</td>
<td>No data input needed. Model uses: Elevation. Soil buildup. Tide levels. Sea level rise (0-6 ft).</td>
<td>Coastal Change Analysis Program (C-CAP)</td>
<td>National coverage with local, state, and regional applications</td>
<td>Default: None specified. Advanced Options: 0, 25, 50, 75, or 100 years</td>
</tr>
<tr>
<td>Marsh: Advanced Options</td>
<td>Identifying areas of land at the parcel scale onto which tidal wetlands may migrate, and possible impacts to existing developed areas</td>
<td>Internet, ArcGIS</td>
<td>Online interactive map; printed and electronic documents</td>
<td>No data input needed. Model uses: Elevation. Soil buildup. Tide levels. Down-scaled sea level rise (0-4.33 ft).</td>
<td>National Wetlands Inventory (NWI)</td>
<td>Varies: Selected international, regional, state, and municipal areas, and parcel level</td>
<td>2020, 2050, 2080 scenarios</td>
</tr>
<tr>
<td>Sea Level Affecting Marshes Model (SLAMM), p. 35</td>
<td>Understanding and quantifying potential changes in marsh locations and sizes</td>
<td>Standalone application</td>
<td>Varies: printed and electronic documents, online maps</td>
<td>Required: Elevation. Tide levels. Land cover. Optional: Soil buildup. Development footprints. Other parameters.</td>
<td>NWI</td>
<td>Varies: Less than 1 square mile to thousands of square miles; typically 5 to 50 square miles</td>
<td>Varies: Time increments of 5 to 25 years</td>
</tr>
</tbody>
</table>
Maine Marsh Migration Team Model

The Maine Geological Survey, Maine Natural Areas Program, and Municipal Assistance Program developed a relatively simple “bathtub” model of marsh migration as part of a NOAA Project of Special Merit conducted from 2004 to 2014. The project sought to raise public awareness of sea level rise and marsh migration, and to provide municipalities, conservation groups, and state and federal agencies with information that could be used in planning efforts to allow tidal marshes to migrate.

The model was intentionally kept relatively simple for several reasons: (1) a goal of modeling all of Maine’s lengthy coastline, (2) a goal of sharing results at the municipal level where simplicity is an advantage, (3) lack of available data on soil buildup, and (4) available budget. A foundational step in the project was a comprehensive review and improvement of tidal marsh maps for the state, which included extensive field surveys and reconnaissance of over 80 marshes. Based on 113 tidal prediction stations, the team created a dataset of Highest Annual Tide (HAT) elevations for the entire Maine coast. The project focused on HAT because the state’s shoreland zoning regulations use HAT as a proxy for the upper marsh boundary for all coastal wetlands.

Elevation data for the coastline were developed using LiDAR data collected and processed in 2012. Four scenarios of sea level rise were explored by adding 1, 2, 3.3, or 6 feet to the present-day HAT elevation.

### OUTPUTS
- Statewide dataset of tidal marsh areas (ArcGIS shapefile including 1,158 polygons)
- Maps of current HAT
- Reports for 6 towns on: (a) potential wetland expansion zones, (b) potential inundation areas based on sea level rise and 100-year storm levels, (c) potential impacts on infrastructure, and (d) potential impacts on land cover

### FOR MORE INFORMATION
- www.gulfofmaine.org/2/climate-network-climate-initiatives/maine/
- www.waterviewconsulting.com/marshmigration/mainemodel.pdf
Buzzards Bay National Estuary Program Study of Salt Marsh Expansion

The Buzzards Bay National Estuary Program (BBNEP) in Massachusetts developed a model to evaluate the potential expansion and migration of salt marshes, particularly those in tidally restricted areas, within the Buzzards Bay watershed. The model uses the highest annual tide (HAT) as a proxy for the marsh-upland boundary because that is how state regulations define the boundary. The HAT was derived from 18 tidal prediction stations. Three potential sea level rise scenarios (1, 2, and 4 feet) were simulated without any defined time period associated with them. To address a lack of accurate data on linkages among inundated and potentially inundated areas, the project team conducted site visits and created a Google Earth layer showing roads, culverts, and other tidal restrictions. An elevation algorithm was used to remove hydrologically unconnected inundation areas, which would likely remain freshwater or brackish without regular saltwater inundation.

BBNEP used a relatively simple elevation-based model in part because they wanted site-specific data at the parcel level. This required a higher level of resolution than was available in the then-current version of the widely used Sea Level Affecting Marshes Model (SLAMM, see p. 35). The project team was not concerned about excluding soil buildup from the model because the protected inland marshes in Buzzards Bay were assumed to be able to keep up with sea level rise.

**OUTPUTS**
- Interactive map with interim results: [www.climate.buzzardsbay.org/migrating-marsh-maps.html](http://www.climate.buzzardsbay.org/migrating-marsh-maps.html)

**FOR MORE INFORMATION**
- [www.climate.buzzardsbay.org/migrating-salt-marshes.html](http://www.climate.buzzardsbay.org/migrating-salt-marshes.html)
**Casco Bay Estuary Partnership Model**

The Casco Bay Estuary Partnership (CBEP) developed an elevation-based model to conduct a detailed study of potential marsh migration in 10 of the 14 municipalities that line Maine’s Casco Bay. Overarching goals were to analyze nearly all marshes in the bay to improve understanding of wetland gains and losses that might result from sea level rise and to enable municipal staff and decision makers to understand risk levels and potential impacts of sea level rise on infrastructure and habitats. In particular, CBEP intended the findings to be useful to towns, land trusts, conservation groups, and other groups that could protect upland areas to allow landward migration of the marshes. CBEP also used the model to evaluate the effects of culverts and other tidal restrictions on marsh responses to sea level rise and to determine whether priorities for tidal marsh restoration should be revised.

Although CBEP used a relatively simple “bathub” model for the study, they did test the sensitivity of the projected changes to soil buildup over time in selected locations, which provided additional context for interpreting model results. Additionally, CBEP invested considerable effort into groundtruthing and analytical methods to ensure that present-day marshes were mapped accurately in the model, given the inaccuracy of using elevation alone as a proxy for marsh presence.

**Outputs**

- GIS data
- Downloadable reports for 10 municipalities

**For More Information**

Marsh Analysis and Planning Tool Incorporating Tides and Elevations (MAPTITE)

The Marsh Analysis and Planning Tool Incorporating Tides and Elevations (MAPTITE) from NOAA was developed to facilitate successful habitat restoration projects in tidal wetlands. It aids in the selection of vegetation types to be planted in different parts of the wetland based on a digital elevation model, local tidal datums, and plant species tolerances. By delineating planting areas and providing point data that can be uploaded to GPS receivers for those areas, MAPTITE allows users to plant appropriate species accurately in areas where conditions are most amenable to growth, enabling native species to create or restore ecosystem functions of the marsh. Various sea level rise scenarios can be applied to investigate potential effects on where marsh plants are likely to grow in the future. Available as a free download, MAPTITE is an ArcGIS add-in tool that requires technical expertise in geographic information systems (GIS) to view the results on a map. A user guide provides information on datums and types of uncertainty.

**OUTPUTS**
- GIS shapefiles of planting zones for plant species
- Statistics such as number of plants suggested for each planting zone

**FOR MORE INFORMATION**
- tidesandcurrents.noaa.gov/maptite.html

Examples of MAPTITE inputs and results.
Marsh Adaptation Strategy Tool (MAST)

A consortium of public- and private-sector organizations in Maine developed the Marsh Adaptation Strategy Tool (MAST) to enable people to evaluate the future values of coastal land parcels under different sea level rise scenarios. MAST facilitates cost-benefit analysis of potential changes in land cover and habitat, and this information could be used in decision-making by government agencies and non-government organizations. The model runs on Global Mapper GIS and uses pre-made digital elevation models (DEMs) for four sea level rise scenarios (1, 2, 3.3, 6 feet) by 2100.

The consortium conducted a demonstration project in which they used MAST to evaluate three land parcels in Scarborough, Maine. For each parcel, a group of experts allocated initial values for 15 ecosystem services. Among the ecosystem services were carbon storage, habitat, flood prevention, and nutrient export. The model then created depth-benefit curves that estimated how those values would change with increasing water depth at each site. Importantly, the shapes of depth-benefit curves used in the model reflect the opinions of the experts who were interviewed; local residents or other people might value ecosystem services differently. The demonstration project suggested that the cumulative expected benefit approach used by MAST has potential to inform strategic land prioritization decisions for conservation and development.

OUTPUTS
- GIS maps and datasets for land parcels

FOR MORE INFORMATION
- northatlanticlcc.org/projects/demo-project-marsh-migration
- Contact: Sam Merrill, smerrill@geiconsultants.com, (207) 615-7523

A Marsh Adaptation Strategy Tool (MAST) test site in Scarborough, Maine.
NOAA Sea Level Rise Viewer

NOAA developed the Sea Level Rise Viewer to establish a nationally consistent platform that enables communities to examine the potential effects of sea level rise and to inform planning and decision-making at the local level. The Viewer has five modes that can be used to explore different topics: Sea Level Rise, Confidence, Marsh, Vulnerability, and Flood Frequency.

- In the **basic Marsh mode**, the Viewer displays results from a Category 3A elevation-based (or “bathtub”) model, and the user can select from 0 to 6 feet of sea level rise in 1-foot increments without any specified time period.

- When **Advanced Options** are selected in the Marsh mode, the Viewer shows results from a Category 3B elevation-and-time-based model. The Advanced Options menu makes it possible to choose from 4 rates of soil buildup or accretion (0, 2, 4, or 6 millimeters per year) and 5 time periods (0, 25, 50, 75, or 100 years).

The Viewer uses nationally consistent land cover data from the Coastal Change Analysis Program (C-CAP). Because the land cover data are based on 30-by-30-meter pixels with 1-acre mapping units, small-wetlands may be omitted. The marsh migration analysis is based on the same rules regarding vegetation and elevation that are used in the Sea Level Affecting Marshes Model (SLAMM, p. 35). However, the Viewer does not include land-cover transition rules, such as those in SLAMM that restrict beach from turning into marsh. The Viewer uses shaded colors to indicate uncertainty in the model results for projected land cover.

**OUTPUTS**
- Online interactive maps

**FOR MORE INFORMATION**
- coast.noaa.gov/slr
- coast.noaa.gov/digitalcoast/tools/slr
Coastal Resilience

The CoastalResilience.org website provides information about ecosystem-based adaptation to climate change. An interactive map shows modeled projections of marsh migration, along with other geospatial data on coastal ecosystems, socioeconomics, community vulnerability, and coastal hazards. The interactive mapping platform is intended to meet a variety of needs, including as decision support for local and regional planning, and as an educational tool for stakeholders. In the northeastern United States, Coastal Resilience has marsh migration model results for Connecticut and New York. The custom-built model of marsh migration incorporates down-scaled sea level rise projections and estimates of soil buildup or accretion rates, which are based on extrapolations of field data. Users can select from three dates (2020, 2050, 2080) and see highlighted areas that the model identifies as potential marsh migration pathways. The model delineates areas of tidal wetland and other types of land cover based on a standard cover class analysis. The model incorporates hydrologic linkages between tidal waters and low-lying areas of land that may be inundated as sea level rises, but those linkages are not always correct and may require groundtruthing.

For all 24 communities along the Connecticut coast, The Nature Conservancy produced downloadable maps showing the Coastal Resilience marsh migration data at the level of individual parcels of land. A report for each community provides statistics on how much marsh migration may occur onto protected open space such as parks and preserves or onto undeveloped but currently unprotected parcels. The maps also show potential tidal inundation of roads, airports, schools, neighborhoods, and businesses.

Outputs

- Online interactive maps
- Downloadable maps and reports for coastal communities in Connecticut

For More Information

- www.coastalresilience.org

Examples of Coastal Resilience results for Old Saybrook, Connecticut
**Sea Level Affecting Marshes Model (SLAMM)**

The Sea Level Affecting Marshes Model (SLAMM) simulates the dominant processes involved in wetland and shoreline change during long-term sea level rise. SLAMM offers a more complex simulation than other models and allows for a high degree of user modifications to adjust many spatial variables. For example, the model includes geomorphic and landscape processes such as sediment transport, freshwater flows, groundwater changes, erosion, and overwash. There are options to import additional data on ground uplift and subsidence, specific soil buildup (accretion) variables, and other ecosystem processes, and to incorporate blockages in tidal flooding associated with dikes and other hard structures.

The model uses a complex decision tree, incorporating geometric and qualitative relationships among the data types, to determine changes in land cover across the study area in 5-year increments as sea level rises. The model generates results as geographic information systems (GIS) data, and uncertainty mapping and sensitivity analysis are available. Using SLAMM requires specialized training or related expertise. A Web-browser version, SLAMM-View, which does not require special skills, presently covers the entire coastlines of 5 states and partial coastlines of 15 states.

**Outputs**
- GIS data
- Downloadable and printed maps

**For More Information**
- warrenpinnacle.com/prof/SLAMM
- www.slammview.org

Credit: Rhode Island Coastal Resources Management Council and partners
Investing in high-quality data is one of the most effective ways to improve modeling results.

Land cover data for portions of Newbury, Rowley, and Ipswich, Massachusetts. Credit: Massachusetts Office of Coastal Zone Management
Three types of data lie at the heart of marsh migration modeling—elevation, land cover, and tide levels. Data are available in various levels of spatial resolution and accuracy, and one of the most effective ways to improve modeling results is to invest in high-quality data. For long-range projections of several decades or more, assumptions about the rate or amount of sea level rise have perhaps the greatest influence on model outputs, as well as being one of the largest sources of uncertainty. Because all data contain inherent uncertainty, it is important to understand the limits of the data being used in the model.

**INITIAL CONDITIONS:** Setting the Stage for Modeling
- Elevation
- Land Cover
- Tide Levels

Present-day elevation, land cover, and tide levels provide the foundation for modeling of marsh migration. They represent the initial conditions and set the stage for a model to play out future scenarios. As such, they are sometimes called “time-zero” data. Because elevation, land cover, and tide levels can be measured before being entered into a model, people usually think of them as known conditions. Yet measurements of time-zero data are never perfectly accurate and represent a simplification of the real world. The quality of data fed into a model affects the model results. Following good practices for obtaining and using time-zero data can increase confidence levels of model results.

**FUTURE CONDITIONS:** Parameters that Change Over Time
- Sea Level Rise
- Barriers to Marsh Migration
- Soil Buildup

Sea level rise, barriers to marsh migration, and soil buildup are key influences on marsh persistence and migration over time. They are referred to as “time-X” data. Sometimes these parameters can be approximated reasonably well based on present values, but often they are essentially unknowns. Other types of time-X data, such as erosion or storm overwash, are included in some models in an effort to make the model reflect more of the real-world complexities. Scientists are working to incorporate additional factors such as projected changes in storm surge and wave heights. Understanding the limitations of time-X data is important for proper interpretation of model results.
ELEVATION

High-accuracy elevation data play an important role in modeling of marsh migration because changes in sea level are measured in fractions of an inch and slight differences in elevation strongly influence plant communities in and near tidal marshes. Elevation data are used to create a digital elevation model (DEM) of the marsh and surrounding land surfaces. Data from light detection and ranging (LiDAR) technology are typically used for marsh migration modeling. LiDAR is comparable to sonar, except it uses light instead of sound. Lasers mounted on aircraft emit rapid pulses of light downward, and sensors record the time for the light to bounce back from the ground, which is translated into elevation. LiDAR makes it possible to collect data with horizontal resolution of 12 to 20 inches (30 to 50 cm) and vertical accuracy of 2 to 12 inches (5 to 30 cm).

NOTES AND TIPS

- Accurately measuring elevation in marshes is difficult even with LiDAR. The dense cover of marsh vegetation often throws off the LiDAR measurements by a few inches. However, this issue is less problematic when modeling marsh migration, which focuses on the upland edge where data are often much better. Based on the most-cited potential trends in sea level rise, measurement errors in LiDAR elevation data may cause projections of land cover within marshes to have an accuracy of 20 to 50 years, whereas projections of marsh migration into the uplands may be accurate within 10 to 20 years.

- Depending on the management purpose of the modeling, it may be preferable to collect elevation data using RTK-GPS (real-time kinematic global positioning system). RTK-GPS can provide vertical accuracy of 0.8 to 1.6 inches (2 to 4 cm) but requires labor-intensive fieldwork. Another emerging technology is waveform LiDAR, which provides greater accuracy than standard LiDAR but is extremely data intensive.

- Using elevation data to depict water flow in the marsh (hydraulic modeling) can be difficult and costly. Data on culverts and underground drainage infrastructure may not be readily available.
OBTAINING AND WORKING WITH DATA

The amount of error in an elevation dataset can greatly affect precision of inundation projections. In each of these figures, there is a 60 percent chance that the height of daily tidal inundation will lie in the area between the white and blue lines. That area is much narrower for higher-accuracy elevation dataset, indicating greater precision. Credit: K. Schmid

WHERE TO GET DATA
LiDAR data are readily available from:
- Digital Coast: www.coast.noaa.gov/dataviewer
- National Map: nationalmap.gov/viewer.html
- USGS: cmgds.marine.usgs.gov

FOR MORE INFORMATION
Download LiDAR 101: An Introduction to LiDAR Technology, Data, and Applications from NOAA coast.noaa.gov/digitalcoast/_/pdf/LiDAR101.pdf

PROCESSING OF LI DAR DATASETS
Several techniques can be used to correct and enhance LiDAR data after they are collected.

Hydro Correction
- Hydro-flattening: Making waterbodies “water”
- Hydro-enforcement: Making sure waterbodies flow downhill
- Hydro-conditioning: Making sure surface waters flow downhill

Marsh Correction
- By re-sampling: Removing data points that hit plants instead of ground
- By vegetation: Correcting elevation bias by plant type
- By surveys: Correcting elevation bias by location
LAND COVER

Land cover datasets provide information on where wetlands, developed areas, forests, agricultural lands, and other types of land cover are located. Simple elevation-based, or bathtub, models do not use land cover data, but these data play a key role in elevation-and-time-based and geomorphic models. Starting from the time-zero land cover data, models project how land cover in the study area will change over time. Once sea level rises a threshold amount, for example, areas of low marsh change to intertidal flats in the model, and high marsh to low marsh. Studies of marsh migration focus on when and where land cover changes from upland to marsh in the model.

WHERE TO GET DATA

The National Wetlands Inventory and Coastal Change Analysis Program are the most widely used sources of land cover data for marsh migration modeling.

National Wetlands Inventory (NWI)  www.fws.gov/wetlands
- Covers wetlands only, not uplands where marsh migration occurs
- Has detailed categories, such as different wetland types
- Not updated regularly and some data are decades old
- Produced with less-structured methods
- Resolutions and accuracies not well documented

Coastal Change Analysis Program (C-CAP)  www.coast.noaa.gov/digitalcoast/data/ccapregional
- Covers wetland and upland areas
- Wetland land cover classes based on NWI but less detailed
- Comes in two formats:
  - Moderate-resolution (30 meter) with national coverage, updated every five years
  - High-resolution (1 to 5 meter) covers selected areas, updated as needed
- Produced with a standardized, structured methodology

Land Cover Categories

<table>
<thead>
<tr>
<th>Developed</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed, High Intensity*</td>
<td>Open Water</td>
</tr>
<tr>
<td>Developed, Medium Intensity*</td>
<td>Palustrine Aquatic Bed</td>
</tr>
<tr>
<td>Developed, Low Intensity*</td>
<td>Estuarine Aquatic Bed</td>
</tr>
<tr>
<td>Impervious**</td>
<td>Wetlands</td>
</tr>
<tr>
<td>Developed, Open Space</td>
<td>Woody Wetlands</td>
</tr>
<tr>
<td>Agricultural</td>
<td>Palustrine Forested</td>
</tr>
<tr>
<td>Cultivated Crops</td>
<td>Palustrine Scrub/Shrub</td>
</tr>
<tr>
<td>Pasture/Hay</td>
<td>Estuarine Forested</td>
</tr>
<tr>
<td>Rangeland</td>
<td>Estuarine Scrub/Shrub</td>
</tr>
<tr>
<td>Grassland and Herbaceous</td>
<td>Herbaceous Wetlands</td>
</tr>
<tr>
<td>Scrub/Shrub</td>
<td>Palustrine Emergent</td>
</tr>
<tr>
<td>Forest Land</td>
<td>Estuarine Emergent</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>Perennial Ice/Snow</td>
</tr>
<tr>
<td>Evergreen Forest</td>
<td></td>
</tr>
<tr>
<td>Barren Land</td>
<td></td>
</tr>
<tr>
<td>Barren Land</td>
<td></td>
</tr>
<tr>
<td>Unconsolidated Shore</td>
<td></td>
</tr>
</tbody>
</table>

* Moderate-resolution C-CAP only
** High-resolution C-CAP only
These images illustrate how the same geographic area is represented in 3 different land cover datasets. The aerial photograph (upper left) shows actual land cover in Wells, Maine. Colors in the other images represent categories of land cover in the dataset. Each dataset has its own strengths and limitations for modeling.
Real-World Land Cover Represented in Datasets

Just as with other types of data used in marsh migration modeling, land cover data are never completely accurate and introduce uncertainty to the model results. These images show examples of how two datasets can differ in how they represent specific areas on the ground. These examples help to illustrate why model results should not be considered as highly accurate projections.

**A**
- Actual: UPLAND*
- NWI Classification: Wetland
- C-CCAP Classification: Upland
- *11.5 ft (3.5 m) above sea level

**B**
- Actual: WETLAND**
- NWI Classification: Non-wetland
- C-CCAP Classification: Non-wetland
- **Wetland next to channel

**C**
- Actual: WETLAND
- NWI Classification: Non-wetland
- C-CCAP Classification: Upland

**D**
- Actual: WETLAND
- NWI Classification: Wetland and Non-wetland
- C-CCAP Classification: Upland

**NOTES AND TIPS**

- All land cover datasets contain error; some types of error are more important than others. For modeling of marsh migration, accurately delineating the marsh-upland boundary is generally more important than mapping subtypes of marshes.
- Converting actual land cover to the categories used in a model or crosswalking among different land cover datasets can introduce error.
- Using a recently updated land cover dataset can help reduce modeling error by capturing changes in land cover that could affect marsh migration.
- Patches of suburban and urban development may be smaller than the pixels or mapping units in the dataset. As a result, the data may not include features that would impede or block marsh migration.
- Some modelers draw on several different land cover datasets to build the best possible dataset for a study area.
TIDE LEVELS

In models of marsh migration, tidal heights are often used as proxies for boundaries between ecological zones or habitats along the shoreline. For example, the transition from marsh to upland often lies at approximately the same elevation as the average elevation of astronomical high tides (mean high water spring, MHWS) or as the highest annual tide (HAT). Although in the real world the correspondence between tidal heights and ecological boundaries is not exact, defining ecological zones based on tidal height is a practical way to model the changes that occur with changes in sea level. As tidal elevations increase over time, an area that was previously classified as upland may eventually be lower than MHWS or HAT, and the model would reclassify it as marsh.

Accurate data on tidal ranges and heights are critical for marsh migration modeling, but obtaining these data can be challenging. In the Northeast, tidal ranges vary greatly. Some places in the region have a tidal range of 4 feet, while others have a tidal range of 20 feet. Even over short distances, tides can vary markedly because of basin geometry and river influx, along with other factors. Relatively few permanent tidal-data collection stations exist in the region, which means that tides must either be estimated or measured through special data collection efforts.

NOAA has developed a tool called VDatum that takes on this challenge and makes it feasible to obtain tidal data for marsh migration modeling. VDatum uses models of tidal dynamics along with in situ measurements of tides to model tidal elevations in the United States.

Tidal heights used to define habitat zones in the Sea Level Affecting Marshes Model (SLAMM). As sea level rises in the model, the tidal heights and habitats zones shift upward.
Examples of geographic variation in tidal range (above) and high tide line (right). As shown here for Buzzards Bay, Massachusetts, these tidal characteristics can vary over a relatively small geographic area.

Credit: Buzzards Bay National Estuary Program
NOTES AND TIPS

While VDatum is a valuable tool, it does have important limitations:

- Many marsh areas are not covered by the VDatum model.
- The VDatum model does not cover dry land areas that are potential marsh migration zones in the future. Tide information for those areas must be interpolated or extrapolated.
- VDatum does not account for future variations in tidal dynamics, such as differences in tidal exchange as estuaries change shape and geometry.
- For marshes located above tidal restrictions such as undersized culverts, it may be necessary to record water levels over several weeks to months using a pressure gauge to get accurate tidal data.

SOIL BUILDUP

Soil buildup is a key parameter in elevation-and-time based and geomorphic models of tidal marshes because it can offset low to moderate increases in sea level. If soil buildup occurs at least as quickly as the sea rises, the marsh maintains its elevation in relation to the tides. However, sea level may rise faster than soil accumulates, eventually drowning the marsh. In general, typical rates of soil buildup in tidal marshes range from 0.04 to 0.20 inches (1 to 5 mm) per year.

Many factors affect soil buildup. Since decomposing plant matter makes up most of the soil, or peat, in tidal marshes, the rates of plant growth, deposition, and decay strongly influence the amount of soil buildup. When inorganic sediment is carried into tidal marshes by rivers, streams, seawater, and other sources, the sediment may be deposited onto the marsh surface. Rates of soil buildup can vary greatly among marshes and even over short distances within a marsh, depending on the area’s elevation, amount of time covered with water, and distance from creeks and other sediment sources. Rates also vary over time, such as when storms cause brief but important pulses of sediment accumulation. Over a period of years, sea level rise may cause a marsh to be flooded for longer periods of time, which can increase sediment accumulation and peat building.
Scientists refer to soil buildup as accretion or sediment accumulation. The term accretion covers all of the factors that contribute to soil buildup. Sediment accumulation refers only to deposition of mineral sediment.

While soil buildup is important in tidal marsh ecosystems, it is less relevant in studies that focus exclusively on migration of marshes into uplands. Little buildup of soil occurs along the marsh-upland edge, where other factors such as groundwater and soil type more strongly influence establishment of marsh on former uplands.

Collecting data on soil buildup is challenging and time consuming, and site-specific data are not available for most marshes. Specialized devices called surface elevation tables (SETs) must be deployed and monitored for many years. Some models are now using sediment concentrations in water as another way to estimate soil buildup.

Soil buildup data from different places are not necessarily accurate to use in models of a specific marsh. Modelers often need to use soil buildup rates from other locations and may use a range of estimates. Models can be tested for sensitivity to potential error in soil buildup estimates.
REGIONALLY SPECIFIC CONSIDERATIONS FOR THE NORTHEAST

The following regionally specific factors should be considered when modeling tidal marshes in New England.

Sea Level Rise
- In the Northeast, the earth’s crust is generally stable or moving slightly upward, unlike other parts of the East Coast where the crust is moving downward. As a result, the Northeast tends to experience less relative sea level rise (RSLR).
- The rate of RSLR can vary dramatically from year to year. In a 2-year period during 2009 to 2010, the sea level north of New York City shot up 5 inches because of changes in ocean circulation. It was the biggest increase in the history of tide gauge records.

Tides
- Tidal ranges vary tremendously across the region. Areas north of Cape Cod have large tidal ranges (macrotidal), while areas to the south have small tidal ranges (microtidal). Sea level rise has a greater impact on microtidal marshes in that the amount of time that the marsh is covered with water (hydroperiod) increases proportionately more than in macrotidal marshes. For example, a 6-inch increase in sea level would greatly increase the hydroperiod in marshes with 2-foot tides, whereas the change would be less drastic in marshes with 8-foot tides.
- In the northern parts of the region, tidal range is greater and duration of tidal flooding on the marsh surface is shorter than in most other regions of the United States. This has implications for sediment transport and deposition, which are important components of marsh models. Models developed with data from other regions may need to be adjusted for the Northeast.

Wetland Size
- The prevalence of small pocket marshes and fringing marshes in the region means higher-resolution land cover data are needed in many areas to map wetland migration.

Hydrology
- Human-made drainage ditches in marshes are small features that are not captured in most digital elevation models (DEMs) and marsh migration models, but they can greatly affect water flow and sediment transport.

Soil Buildup
- Because of the region’s glacial history, there is a general lack of sediment in water runoff from land, especially north of Cape Cod, which could affect sediment accumulation rates in marshes. Accretion of organic matter plays a larger role than in other areas along the East Coast.
- Rates of erosion vary greatly on a localized scale in the Northeast because of the region’s complex geology, compared to other regions where erosion rates are more consistent among sites.
- Ice formation and movement could have important effects on sediment transport within marshes in the Northeast.

Geomorphology/Geology
- Hilly terrain in the region constrains the amount of new marsh that can form, compared to the flat terrain of the coastal plain to the south.
- Soil development in the Northeast is scant compared to non-glaciated areas south of Long Island, where a thick layer of sediment is present and soil development is extensive. Depending on the timing and speed of sea level rise, this could influence erosion rates and other factors that are not addressed in typical models. For example:
  - In areas with lodgement till and moraines, some sites may lack the soil moisture conditions to form a marsh.
  - Existence of bedrock can lead to marsh erosion in some areas rather than marsh development.
- Urbanization can affect marsh migration. Some human activities may have modified the geological (e.g., lawns) and hydrodynamic (e.g., jetties) setting in ways that promote marsh development compared to the natural conditions.
These images show model projections of tidal marsh in 2020 and 2050. Colors indicate a range from nearly certain to be tidal marsh (purple, 99 percent likelihood) to extremely unlikely (light green, 1 percent likelihood). This method of displaying model results makes it possible to show the most likely scenario while also accounting for the uncertainties that exist in any model of marsh migration. One source of uncertainty or error not addressed in these model results is the potential for roads, buildings, and other features of developed land to block marsh migration. Credit: K. Schmid

Sea level rise is by far the biggest cause of uncertainty in model results. Projections of sea level rise vary tremendously and dramatically affect projections of marsh migration.
People make all kinds of decisions—such as financial, medical, and social decisions—on a daily basis that involve varying degrees of uncertainty. When multiple sources of information, each carrying its own uncertainties, point in the same direction, they can give us confidence to make very big decisions. In the same way, the uncertainty in marsh migration modeling results should not be viewed as a roadblock, but as something that needs to be understood and considered when making decisions.

Uncertainty is inherent in the marsh migration modeling process for two overarching reasons. First, models are simplifications of the real world, and the assumptions made in creating the model may not accurately reflect the actual conditions and processes in the ecosystem. Second, data used in the models are never perfectly accurate or complete. In turn, the model results, which depend on the assumptions and data, incorporate the uncertainties associated with both the assumptions and the data.

Despite the uncertainties, models of marsh migration can provide meaningful and useful information. The amount of uncertainty can be reduced by using valid datasets and by using models that are appropriate for the available data and based on sound assumptions. After the model results are produced, they can be analyzed, interpreted, and communicated in ways that minimize the negative impacts of the inherent uncertainties.

**WHAT DO SCIENTISTS MEAN BY UNCERTAINTY?**

In everyday conversation, when someone says she is uncertain about something, it typically means she has little or no confidence that she is correct. Scientists, however, use the term uncertainty somewhat differently. To scientists, uncertainty is a quantifiable measure of accuracy, and it can range from low (likely correct) to high (quite likely incorrect). A level of uncertainty is common in natural resource decision-making because of imperfect data and incomplete knowledge of the workings of the ecosystem. This is true for marsh migration modeling results, which have inherent uncertainties. However, there are ways to minimize the uncertainties and to account for the remaining uncertainty so that model results can be used for decision-making.

**TRANSLATING UNCERTAINTY FOR BROADER AUDIENCES**

When scientists communicate with other scientists, they usually use the term “uncertainty” to describe the level of confidence in a study’s data or results. When communicating more broadly beyond the scientific community, however, it is often preferable to talk in terms of confidence levels—such as low, moderate, and high confidence—rather than uncertainty. This is a different way of expressing the same concept, and it is more familiar to most people. Confidence levels convey the intended meaning better to people unaccustomed to scientific jargon.
Probability of Marsh Migration

Because of the many uncertainties involved in modeling marsh migration, it is not possible to determine the exact changes that will occur in the future. Models sometimes seem to provide “the answer” about what will happen, but in fact they can only provide, at best, a glimpse of different conceivable scenarios. For that reason, it is usually not appropriate to run a model a single time and to look at the output as if it showed definitively the amounts and locations of marsh migration.

Instead, models should be run many times with different combinations of parameters to understand the likelihood that particular areas will become marsh migration corridors. Comparing and contrasting results from different models, instead of relying on a single model, is another valuable way to investigate how events might unfold. The probabilities of different scenarios are important to convey when reporting the model results.

**UNCERTAINTY ANALYSIS IN THE SEA LEVEL AFFECTING MARSHES MODEL (SLAMM)**

This flowchart outlines the process of uncertainty analysis in SLAMM. Some other models provide similar analyses. SLAMM displays uncertainty analysis results on a map ranging from highly likely (red) to unlikely (blue) to be tidal marsh.

Example of SLAMM uncertainty analysis:

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For this map, the Coastal Resilience model was run seven times with different parameters. The colors indicate the number of times (from 1 to 7) that an area was projected to be tidal marsh. *Credit: University of Connecticut and The Nature Conservancy*

This map shows the projected marsh-upland boundary (red line) after 23.6 inches (60 cm) of sea level rise. Taking uncertainty into account, there is a 95 percent chance that the boundary will lie between the blue and pink lines. *Credit: Acadia National Park/National Park Service*

Models of marsh migration tend to be unreliable near barrier beaches because of sporadic and unpredictable storm overwash and erosion. To alert people to this important uncertainty, the Rhode Island CRMC put warnings on its maps near barrier beaches. *Credit: Rhode Island CRMC*
Sensitivity Analysis

A sensitivity analysis examines how much the model results differ in response to changes in the model inputs. For example, does the acreage of marsh migration change substantially when the level of sea level rise in the model varies from low to high, within a realistic projected range? Changes in the frequency or magnitude of storm surge and waves could add uncertainty to rates of migration that would sustain marshes. Sensitivity analysis helps to test the robustness of the results and to evaluate the relative importance of various inputs and their errors on the model outputs. When models are used as tools to support management and policy decision-making, the sensitivity analysis should generally focus on whether changes in parameters or other assumptions in the model affect the potential outcomes in a way that would change the optimal choice. This type of analysis must take into account the way that the information will be used. For example, decisions related to marsh migration at the upland edge may not be particularly sensitive to changes or errors in soil buildup rate, compared to decisions involving habitat zones within the marsh.

EXAMPLE OF SENSITIVITY ANALYSIS PARAMETERS

This table shows the range of values that the Massachusetts Office of Coastal Zone Management used in a sensitivity analysis for a marsh migration study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of Values Tested</th>
<th>Land Types Affected*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic Trend (mm/yr)</td>
<td>0 - 4</td>
<td>9</td>
</tr>
<tr>
<td>Great Diurnal Tide Range (% State Max Range)**</td>
<td>10 - 100</td>
<td>12</td>
</tr>
<tr>
<td>Salt Elevation (% Tide Range)***</td>
<td>40 - 60</td>
<td>9</td>
</tr>
<tr>
<td>Marsh Erosion (m/yr)</td>
<td>0 – 2</td>
<td>0</td>
</tr>
<tr>
<td>Swamp Erosion (m/yr)</td>
<td>0 – 2</td>
<td>0</td>
</tr>
<tr>
<td>Tidal Flat Erosion (m/yr)</td>
<td>0 – 2</td>
<td>5</td>
</tr>
<tr>
<td>Regularly Flood Marsh Accretion (mm/yr)</td>
<td>0 – 4</td>
<td>2</td>
</tr>
<tr>
<td>Irregularly Flooded Marsh Accretion (mm/yr)</td>
<td>0 – 4</td>
<td>3</td>
</tr>
<tr>
<td>Tidal/Inland Fresh Marsh Accretion (mm/yr)</td>
<td>0 – 40</td>
<td>5</td>
</tr>
<tr>
<td>Tidal/Inland Fresh Swamp Accretion (mm/yr)</td>
<td>0 – 10</td>
<td>6</td>
</tr>
<tr>
<td>Beach Sedimentation Rate (mm/yr)</td>
<td>0 – 10</td>
<td>1</td>
</tr>
<tr>
<td>Frequency of Overwash (yrs)</td>
<td>0 – 100</td>
<td>9</td>
</tr>
</tbody>
</table>

*Land Types Affected: A total of 14 different Land Types are present in the pilot study area. The Land Types Affected are land types that have a larger than 1% difference between the change in percent increase/decrease of that land type over the range of typical values.
**% State Max Range: The maximum tidal range observed on the MA coast is 10.7 ft.
***% Tide Range: The salt elevation is the height above mean tide which was related to the tidal range as opposed to being evaluated independently.

MANY FACTORS CONTRIBUTE TO UNCERTAINTY

One of the challenges of marsh migration modeling is that it pushes the limits of what is possible with existing data. As an example, this image shows C-CAP land cover data (colored squares) overlaid on high-resolution LiDAR elevation data from 2011 for an area near Rye, New Hampshire. While C-CAP data are among the best available, the coarse size of the mapping units means that the marsh/upland boundary—as indicated in the land cover data—does not match the marsh/upland boundary indicated by the LiDAR data (— — —). Higher-resolution land cover data would be important to reduce uncertainty in marsh migration modeling at this spatial scale. Credit: K. Schmid

LEARN MORE

Expert Guidance and Implementation

As with many other aspects of natural resource management and policy, special expertise is needed to develop a reliable and credible foundation of information for decision-making about marsh migration. Technical and scientific experts such as those in a project advisory group can determine the best technical approaches to achieve the modeling effort’s goals, implement best practices for data processing and analysis, and help with proper interpretation of results. They can assist with understanding which datasets are available, the resolution and scale of datasets and the implications for the usefulness of results, and the influence of time-zero conditions and parameter sensitivity on interpretation of results.

NOTES AND TIPS

• One of the biggest sources of uncertainty is the future rate of sea level rise. Since sea level rise is the driving force in marsh migration, uncertainty in its rate strongly affects the model results.

• Choosing the right model for the job is the first step in managing uncertainty. The choice of model should consider the desired and feasible levels of accuracy, soundness of model assumptions for the study area, and availability of robust data.

• Uncertainty tends to increase as the modeled time period increases. This is true in part because of the large uncertainty in long-term changes in sea level.

• It is usually advisable to look at the probability of different scenarios, instead of trying to predict the specific outcome. The goal of modeling should be to understand a range of potential outcomes so that the appropriate risk-reduction management actions can be taken.

LEARN MORE


BETTER DATASETS NEEDED TO REDUCE UNCERTAINTY

Researchers in the Northeast who conduct modeling of marsh migration have identified near-term data needs to lessen uncertainty:

• Extremely high-accuracy elevation data at the site level
• More accurate delineation of marsh habitat zones
• Complete inventories of coastal and riverine barriers to marsh movement
COMMUNICATING FINDINGS

PLANNING FOR COASTAL WETLAND CONSERVATION

Better understanding how dynamic-wetland ecosystems may respond to climate change and how coastal communities can prepare is critical to the future of these salt marshes. A number of research and outreach activities are planned to address these issues.

- **Mapping and Modeling**
  - Building upon a pilot project in South Kingstown, the Sea Level Scenarios Model (SLAM) is being used to simulate coastal wetland transition and implementation of adaptive strategies to protect and sustain coastal wetlands.

- **Analyzing Options for Habitat Migration**
  - The long-term sustainability of these habitats relies on the ability to identify and protect areas where marshes can move inland as upland areas that provide the best opportunity for salt marsh migration that might otherwise be threatened by rising seas.

- **Engaging Communities**
  - Focus will be held with coastal communities to review the policies, regulations, and procedures that shape coastal wetland management. The meeting will examine strategies to share flood risk information.

- **Adapting Policies and Standards**
  - Recommendations will be developed for policies to help maintain the future viability of coastal wetlands at risk from the accelerating sea level rise.

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**Sea Level Rise and the Cons of Coastal Wetlands**

Rhode Island’s coastal wetlands provide critical ecosystem services that would otherwise pay for fisheries and tourism. In addition, wetlands offer protection from coastal flooding. These wetlands protect from storm surge and erosion, mitigate further impacts under future climate conditions, and being continuously submerged.
Strategic Communication to Support Decision-Making

When marsh migration modeling is conducted to inform management and policy, results must eventually be communicated—in one form or another—to a broad range of people who are not necessarily wetland or modeling experts. Who needs to receive and understand the findings? What decisions will be made related to marsh migration? What are the most important pieces of information needed in the decision-making process? What methods and formats of communication will be best for the people involved?

Those questions should be asked at the beginning of a modeling initiative. The answers are valuable for streamlining the modeling process and for ensuring that the modeling information has the greatest possible impact. Communications efforts have the greatest chance of success when they are integrated with the research process, rather than serving as an “add-on” at the end of the research. Early strategic planning for communications and ongoing discussions among research and communications personnel can improve both the research and the communications components of a modeling project.

The Rhode Island Coastal Resources Management Council (CRMC) and its partners developed Sea Level Affecting Marshes Model maps for all 21 Rhode Island coastal communities. The maps are intended to support state and local community planning efforts and to help decision makers prepare for future conditions. The maps show current conditions and sea level rise scenarios of 1, 3, and 5 feet. To disseminate the information, the CRMC set up a web page and posted downloadable maps (right), GIS data, a technical report, and a fact sheet (previous page).
COMMUNICATING FINDINGS

EXAMPLES OF COMMUNICATING FINDINGS

In its study of marsh migration, the Casco Bay Estuary Partnership (CBEP) placed an emphasis on communication of the findings to people who live and work around the Bay. The final project report described the communications process:

One overall goal of the project was to develop methods to make the results of these investigations accessible to local officials, town planners, land trusts and local citizens. While the technical analyses going on in Parts 2 and 3 of this [CBEP] report were underway, a parallel effort was underway to craft materials to communicate major findings to local communities.

Here along Casco Bay, with our relatively steep shorelines, the most important information to convey to local communities revolves around the landward migration of wetlands, the future location of the intertidal zone, and identification of areas where marsh migration is likely to conflict with existing infrastructure. More subtle distinctions, such as specifics of whether wetland will increase or decrease overall, or how wetland change will depend on sedimentation rates are of secondary importance. The communications package we developed reflects those priorities.

CBEP produced reports for individual municipalities. Each contained local maps and a brief summary of findings.

Two examples of maps created by CBEP for 3 feet of sea level rise. Orange areas are potential marsh migration pathways.

Fourteen municipalities touch the shoreline of Casco Bay. We prepared draft communications packages for each municipality. We prepared a series of maps for each town at a 1:9,000 scale. The maps focus on areas where significant wetland change or landward migration of the intertidal zone are anticipated under significant (3 ft.) sea level rise. The maps show both areas of significant wetland change (based on the wetland change data described in Part 1 of this report), and also areas where present or future areas of wetland may conflict with existing infrastructure.

CBEP produced a communications package for each town that included a general introduction to the project, a brief discussion of sea level rise in the Casco Bay region, an overview map for the town, and detailed maps for specific locations in the town.
In 2014, the Town of Guilford, Connecticut, developed a community resilience plan as a toolbox to resist, absorb, recover from, and adapt to coastal hazards—such as daily inundation caused by sea level rise, increased flooding, and more frequent and intense storm surges. The Nature Conservancy contributed an analysis of potential marsh migration by land parcel. The results make it possible to see which parcels of currently unprotected open space are likely to host the most acreage of new marshes, such as parcel 019015 (top left). As options for improving resilience, the final plan proposed potential marsh migration zones (above) and culverts to permit marsh migration (left).
Three-dimensional visualizations of inundation and marsh migration are useful for helping people to see how their communities may be affected. This image shows inundation around a sewage treatment plant in Hull, Massachusetts, in a sea level rise scenario. *Image courtesy of Massachusetts Office of Coastal Zone Management*
NOTES AND TIPS

- **Develop communication products that are tailored to people who will be receiving the information.** Concise, high-level summaries are often the most useful communication products for non-experts. At the same time, detailed information needs to be available to those who want it. To meet a range of needs, it is often a good strategy to produce a suite of communication products that together provide a hierarchy of information—from broad overviews to in-depth technical details—in a range of formats from one-page, graphics-rich handouts to interactive maps and databases. By offering multiple entry points to the information, this approach is inviting to people with many different levels of familiarity with the topic and makes it easy for them to delve into it.

- **Translate model results both verbally and visually to have an impact.** Text and graphics that work well for scientific and technical audiences may be indecipherable to many other people involved in decision-making processes. A third-party individual or organization with both scientific and communications expertise may be the most effective bridge between the technical team and the target audiences.

- **Frame marsh migration as part of the broader issues of sea level rise, coastal hazards, and community preparedness.** To many people, the issue of marsh migration may not be especially compelling on its own. For example, some government officials may be interested in marsh migration mainly as it relates to transportation infrastructure or land-use zoning.

- **Discussing results in terms of confidence levels (low, moderate, high), rather than uncertainty, is more likely to resonate with non-expert audiences.** As discussed in the Handling Uncertainty section, the word uncertainty has a different connotation in everyday language than in the scientific realm. Avoiding scientific jargon can make information more accessible without decreasing its accuracy.

- **Use a less-is-more approach when communicating about research to non-experts.** One easy-to-understand and visually pleasing graphic with minimal text may convey more information than a dense tome—if people quickly absorb the graphic but never read the tome.

TIPS FOR MAPPING

- **Maps are indispensable tools for communicating about marsh migration, but often the standard maps produced during modeling are difficult for non-experts to decipher.** The colors and symbols may not be intuitive, for example, or the important information may not stand out. Good cartographic design can make all the difference.

This image shows the default color scheme for maps generated in the Sea Level Affecting Marshes Model (SLAMM). The colors—such as orange for marsh and red for developed upland—are not intuitive and generally should be changed if the map is intended to be used in reports or other communication products. For example, green could be used for marsh and gray for the developed uplands.

- **In presentations and meetings, it is worth taking time to explain scale, orientation, legend, colors, and key messages of maps.** Try to have large printouts of maps to display and discuss. In presentations and on the web, animated sequences of maps can be more effective than single static maps.

- **For interactive maps, ease of use should be a priority.** Many interactive maps are too difficult to use, and potential users quickly leave the web page.
CONCLUSION

State, federal, and municipal government agencies and non-government organizations are working together in the northeastern United States to develop resilience to climate change. Finding solutions to sustain the region’s valuable tidal marshes in the face of sea level rise is an important focus and an opportunity for collaboration among many individuals and entities. Modeling of marsh migration is a key component of those efforts, and while considerable progress has been made to date, much remains to be done. Further advances in modeling and associated activities are necessary to build a strong base of information for decision-making and to put that knowledge into action.
RECOMMENDATIONS

Through collaborative efforts facilitated by the Northeast Regional Ocean Council, including a workshop in December 2014 and the development of this guidance document in 2014 and 2015, more than 50 experts in the science, management, and policy of tidal marshes and sea level rise developed the following recommendations to set the course on this important issue.

A. **Further develop conceptual models of marsh migration in the Northeast.** Region-specific conceptual models are needed to capture and communicate the current scientific understanding of factors that influence marsh migration and important differences in these factors within the region.

B. **Facilitate ongoing interaction among people engaged in marsh migration-related efforts in the Northeast.** Meetings, workshops, webinars, and other interactions are needed to share knowledge and develop collaborations on modeling, management, policy, engagement, and communications.

C. **Launch a regional data initiative in support of marsh migration management.** The data initiative should focus on consolidating and disseminating existing data and results; implementing next-generation methods to obtain higher-resolution coastline elevation data; conducting detailed mapping of marshes and adjacent land cover; building a network of surface elevation table (SET) stations for accretion data; and supporting on-the-ground monitoring of marsh migration in New England.

D. **Develop a web-based information resource about marsh migration in the region.** Agencies and organizations need a place to find and share data, information, and products. The website should provide easy access to relevant datasets (physical, ecological, economic), decision support tools, and scientific and technical literature.

E. **Promote research, analysis, and planning to maximize the long-term benefits of tidal marsh restoration in an era of sea level rise.** Habitat restoration is an ongoing priority, and more information and tools are needed for decision-making to ensure a future return on investment in restoration projects.

F. **Provide data products and processes for marsh migration planning and management suitable for use at the municipal level.** The products should be suitable for technical and non-technical audiences, and should be disseminated to coastal municipalities and state regulatory programs.

G. **Develop a toolkit of policy, management, and regulatory approaches—with information on feasibility and costs—to facilitate marsh migration.** Citizens and organizations need this information to take actions that build on the information generated through modeling.
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