Marshes on the Move

A Manager's Guide to Understanding and Using Model Results Depicting Potential Impacts of Sea Level Rise on Coastal Wetlands

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Introduction

THE SCIENTIFIC COMMUNITY IS GENERALLY IN AGREEMENT THAT global sea level is rising and coastal wetlands are changing as a result. Depending on local conditions, coastal wetlands may disappear under the rising seas, persist in their current locations, or migrate inland. In many places, these changes have important ramifications for the ecosystem and economy. Understanding where and how coastal environments could change in response to sea level rise, however, is a complex challenge dependent upon many factors—from interdependent ecological processes to data quality and availability. As a result, resource managers and other coastal decision-makers need appropriate tools that can help them to anticipate and prepare for the future effects of sea level rise on coastal wetlands.

Information in this document applies to a wide range of coastal wetlands, including

- tidal freshwater, brackish, and salt marshes, and
- coastal freshwater forested and riparian wetlands.

Many models and methods are being used for this purpose. Managers and other professionals with oversight responsibility for coastal resources are often presented with model outputs in the form of maps that illustrate projected sea level rise and potential loss or migration of coastal wetlands. These maps or visualizations may appear to provide a definitive picture, when in fact each represents a collection of assumptions, compromises, and simplifications based on the amount and quality of available data and information and on the model's purpose. As a result, it can be challenging to interpret model results and to use the information appropriately.

This document is intended for people who need to use model outputs for decision-making but who do not build models themselves. It provides a basic understanding of the parameters and uncertainties involved in modeling the future impacts of sea level rise on coastal wetlands. This is a first step toward informed use and communication of these models to support a range of sea level rise adaptation activities—from stakeholder education to habitat management to land conservation. Equipped with this conceptual understanding, managers and planners will be able to more effectively

THIS DOCUMENT IS INTENDED FOR PEOPLE WHO NEED TO USE MODEL OUTPUTS FOR DECISION-MAKING BUT WHO DO NOT BUILD MODELS THEMSELVES.

- ask the right questions of technical specialists regarding model use and results,
- evaluate the real-world implications of model results, and
- incorporate modeling results into management initiatives.

Summary of Key Messages

- Wetland migration models can help guide managers and planners in land use planning (e.g., protection, restoration, adaptation) as well as emergency management (e.g., understanding where wetlands may reduce the risk of hazards to vulnerable coastal communities).
- Wetland migration models are valuable tools in the management decision-making toolkit. Models do not make decisions or predictions.
- Key parameters in wetland migration modeling are rate of sea level rise, tides, salinity, elevation, sediment dynamics, and habitats and species. Models may include some or all of those parameters, which affects their complexity, their data requirements, and the types of information they can provide.
- The best use of a given model may be to investigate a range of possible future scenarios and to identify the key influences on the ecosystem, rather than attempting to define one "most likely" scenario. Various plausible scenarios can be explored with multiple model runs.
- Maps based on model results contain inherent uncertainties that may not be evident but may alter the effectiveness of management decisions.
- To provide appropriate information for management, outputs of a model need to be interpreted based on the assumptions, simplifications, and uncertainties included in the model.

Refer to page 18 for a list of "Good Questions to Ask About Model Results"

Why Use Models?

The future is uncertain, and yet management decisions must be made. What are the best ways to sustain coastal wetlands in the face of sea level rise? How will wetlands change, how will those changes affect people living nearby, and what steps can coastal towns take to adapt? How will changes in coastal wetlands affect fish and wildlife that depend on marshes for habitat, and how can resource managers plan? These sorts of management questions are daunting in part because so many factors are uncertain—magnitude and rate of sea level rise, effects on wetland vegetation, and amount of wetland area that will be lost, to name just a few.

Models provide a framework for understanding the possibilities, and this knowledge can feed into the management decision-making process. For example, if models indicated that a particular section of coast was especially vulnerable to loss of wetlands, or that certain marshes provided a substantial buffer between incoming storms and vulnerable coastal communities, managers could use this information when prioritizing their management activities. The modeling information would help guide managers to direct their effort to where it is most needed. Without the benefit of modeling, the managers in this example would have much less certainty about where to direct their effort.

MODELS PROVIDE A FRAMEWORK FOR UNDERSTANDING THE POSSIBILITIES, AND THIS KNOWLEDGE CAN FEED INTO THE MANAGEMENT DECISION-MAKING PROCESS.

Types of Questions that Models Can Help Answer

Models can be useful for many management purposes. They can be tools for understanding how a complicated ecosystem functions. They can provide insight into the future state of particular components of an ecosystem. They can be used to examine the sensitivity of the ecosystem to specific types of human impacts. They can be used to compare the potential outcomes of different management options. They can determine the relative vulnerability of habitats and can also indicate where human communities may benefit from the presence of these habitats. Each of these uses can help managers take actions today to avoid any negative consequences that model outputs suggest may be in store if no action is taken. However, it is important to note that the models provide guidance, not the answers.

GIVEN THE MANY POSSIBLE USES OF MODELS, MANAGERS AND PLANNERS NEED TO FOCUS ON WHAT IT IS THAT THEY SEEK TO ACCOMPLISH WITH THEM.

Given the many possible uses of models, managers and planners need to focus on what it is that they seek to accomplish with them. A clear focus on specific management questions—and the types of answers needed—is invaluable for guiding the selection of a model, deciding what information is needed, and choosing how to present the model outputs. The following are examples of management questions that models can help to address about impacts of sea level rise on coastal wetlands:

- Which wetlands in the management area are most vulnerable under different sea level rise scenarios?
- What areas of a present-day wetland may become open water, and what areas of upland may become wetland?
- Where could wetlands migrate inland without encountering natural or anthropogenic barriers?
- How would a wetland's vulnerability to sea level rise be affected by changes in factors such as river discharge, sediment inputs, and adjacent land use? Where could restoration reduce a wetland's vulnerability?
- How much economic damage from increased flooding is likely to occur because of loss of wetlands in a given geographic area? Which populated areas are most vulnerable?
- How much would it cost to implement various adaptation strategies?
- Are wetlands in the management area likely to continue protecting coastal properties from storm damage as sea level rises? What management actions could be taken to sustain and enhance the role of wetlands in coastal hazard mitigation?

Using and Communicating Model Results

STATISTICIAN GEORGE E. P. BOX SAID, "ALL MODELS ARE WRONG, but some are useful." Box's quip neatly sums up the basic truths of models, including models of sea level rise and impacts on coastal wetlands. Models, by their very nature, are simplifications of the real world. They are artificial constructs designed to help people understand what is happening within a limited set of circumstances.

ECOLOGICAL MODELS SIMPLIFY COMPLEX NATURAL PROCESSES.

Ecological models simplify complex natural processes. By being aware of modeling pitfalls and limitations, managers can make better use of these important tools. There will always be more complexity and unpredictability in natural systems than can be captured in an ecological model. For simplicity's sake, models remove some real-world processes from the equation entirely. Modelers include specific processes and interactions about which the model is intended to answer questions. For those processes that are included, models make simplifying assumptions about how the real world operates. Furthermore, the data on elevation, vegetation, and other factors that are used to create models are simplified representations of reality, and data may not exist for every desired model parameter.

All models are wrong in the sense that they cannot reproduce the real world. Nonetheless, some models provide a good approximation of the potential outcomes of particular scenarios, and they are valuable as decision support tools for management. When communicating model results publicly, it is a good idea to convey the message that models are a useful tool for helping with decisions, but they are a simplification of natural processes and although they can be used to explore various scenarios, the actual future real-world outcomes will be different.

MODELS ARE A USEFUL TOOL FOR HELPING WITH DECISIONS, BUT THEY ARE A SIMPLIFICATION OF NATURAL PROCESSES AND ALTHOUGH THEY CAN BE USED TO EXPLORE SCENARIOS, ACTUAL FUTURE REAL-WORLD OUTCOMES WILL BE DIFFERENT.

A range of model types is available for investigating the potential impacts of sea level rise on coastal wetlands. The models vary greatly in their complexity, their data requirements, and the types of information that they can provide. The simplest models show land areas that would be inundated if sea level were to increase by a specified amount. Somewhat more complex are models that indicate potential effects of sea level rise on habitats, including loss and inland migration of wetlands, through a limited set of ecological and geological processes. Very complex models are available that simulate many ecological, hydrological, and geological processes over time, such as hydrodynamics, vegetation growth, and sediment transport, as well as feedbacks among these processes, to provide a more nuanced view of changes in wetland vegetation and habitats. Other models integrate socioeconomic factors along with ecology and geology to assess vulnerability of human

DEFINING UNCERTAINTY

When addressing sea level rise and marsh migration, managers often need to communicate with non-scientists about scientific findings. One term that often leads to misunderstanding is "uncertainty". A non-scientist may interpret uncertainty as meaning that the answer is not known and that any projection is just a guess. Scientists think of uncertainty as a specific, quantifiable measure of how well something is known. Scientific uncertainty comes in many shades of gray, not just black ("we are absolutely certain this is correct") or white ("we have no idea what the answer is"). In the context of wetland migration modeling, for example, a model result could have a confidence level of 95%, meaning that for all practical purposes it can be considered correct, even though there is a small amount of uncertainty associated with it. Talking in terms of "confidence levels" instead of "uncertainty" is one way to convey the intended meaning for both scientific and non-scientific audiences.

communities to sea level rise and costs of adaptation.

The simplest models may require only topographic data and a value for projected sea level rise. To use a complex model, however, it may be necessary to obtain large quantities of detailed data on wetland plant species, vegetation growth rates, tides, sediment erosion and deposition, human demographics, land use, and other factors. Existing datasets may be available for some of these data types, while in other cases original data may need to be acquired. The best choice of model depends on the question being asked, the types of data available, the level of effort and expertise required to use the model, and the time and financial resources available.

Models Are Only One Tool

While models are valuable tools, they do not make decisions, and they provide only certain types of information. People engaged in the management process need access to a range of different models and other tools in order to make well-informed, effective decisions. Modeling can be extremely insightful, but it is only one tool in the management toolkit. Other types of data and analysis tools are usually needed to inform management decision-making. For example, decisions about where to protect uplands in order to accommodate wetland migration could not be made based solely on model-generated maps of projected paths of wetland migration. These decisions would require information about factors such as stakeholder priorities and goals, actual environmental conditions in the management area, and land prices and ownership.

WHILE MODELS ARE VALUABLE TOOLS, THEY DO NOT MAKE DECISIONS OR PREDICTIONS.

THE RIGHT TOOL FOR THE JOB

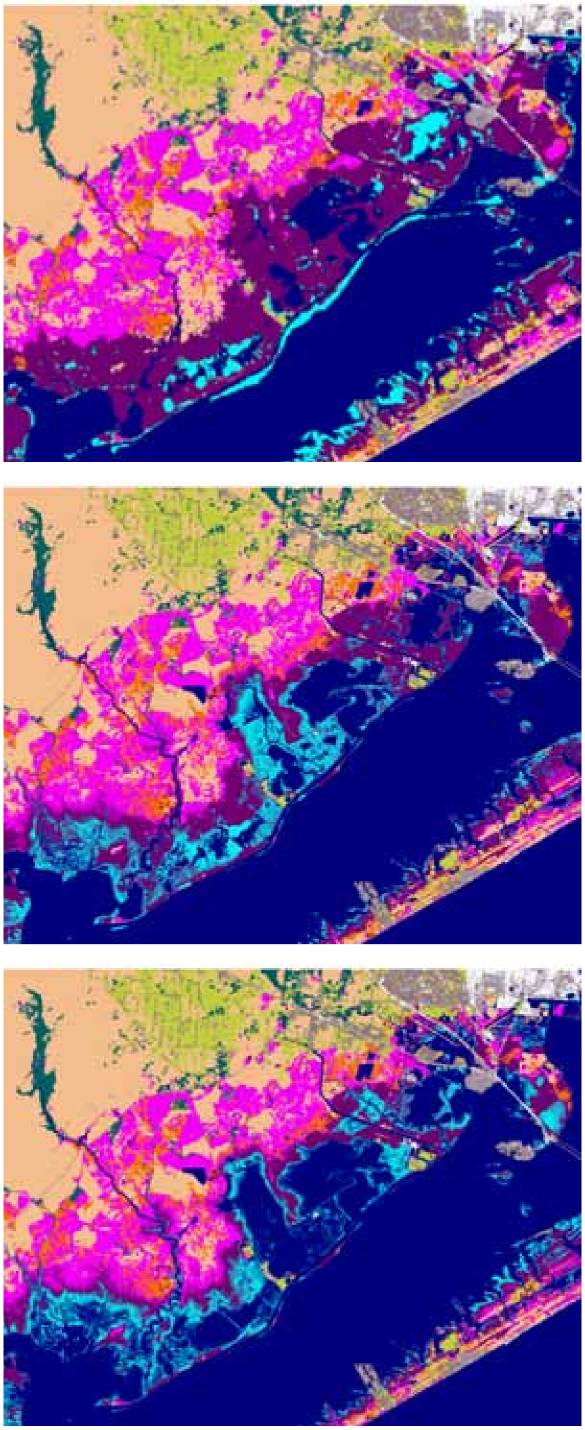
When models are used outside the scope of their design, then they can cease to be useful and become liabilities instead. It is not always easy to recognize the actual scope of a model. Consider, for example, a very simple descriptive seasonal model that states, “The air temperature is colder in winter than in summer,” a reasonable, simple description of seasonal dynamics. This simple seasonal model reduces the world down to only two seasons: summer and winter. Using this model to predict daily weather instead of seasonal cycles would be to use this model well outside its intended scope. For example, a user of the seasonal model might say, “Based on the proposed model, and given that it is past mid-winter now, but not yet summer, then tomorrow should be warmer than today.” The seasonal model, however, contains no information about daily temperature dynamics. And in reality, we know that there can be large variability on shorter time scales than a seasonal one, and temperatures can vary greatly from day to day. Models of wetland migration are far more complex than this example, but the same principle applies. Users of the model need to make sure they are not pushing beyond the model’s capabilities.

Importance of Multiple Model Scenarios

By using a variety of models or running them multiple times with different parameter values, it is possible to explore a range of plausible future scenarios. Key drivers of wetland change, such as sea level rise, accretion, and salinity intrusion, can vary in complex ways across the landscape and over time. But models greatly simplify these processes. Rather than trying to identify one scenario that represents future conditions and basing management decisions on that scenario, managers can reduce uncertainty by using multiple model runs to explore a range of possible futures. This will help reveal the most important variables affecting the long-term persistence of their wetlands. Comparing many alternative scenarios is an excellent way to improve understanding of wetland vulnerabilities and make better management decisions.

COMPARING MANY ALTERNATIVE SCENARIOS IS AN EXCELLENT WAY TO IMPROVE UNDERSTANDING OF WETLAND VULNERABILITIES AND MAKE BETTER MANAGEMENT DECISIONS.

Since the results of any single modeling scenario may contain considerable uncertainty, the patterns and trends revealed by multiple runs can be especially insightful when few data are available to configure the model. For example, good-quality data on sediment accretion is often scarce. Running multiple scenarios using different accretion rates could help a manager to better understand the conditions under which the management area is vulnerable and to target monitoring efforts.



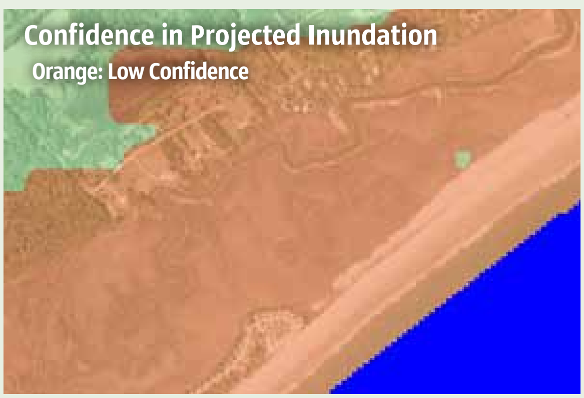
Sample outputs from a model depicting coastal wetland response to sea level rise. Wetland types are indicated in magenta, orange, and green colors. Top shows current conditions. The bottom two images show how two different accretion rates affect the outcome of a four-foot rise in sea level.

MAPS MAY LOOK MORE CERTAIN THAN THEY ARE

Managers and stakeholders often see the results of wetland migration models in the form of maps. Although these maps may be quite detailed, giving the appearance of great certainty and precision, they contain all of the uncertainties, assumptions, and limitations of the model results and the data used to produce them. Maps A and B below illustrate how maps may contain uncertainty that is not evident to the person viewing it and that leads to an incorrect understanding of sea level rise impacts. If managers and stakeholders were to see only Map A, they might reasonably conclude that not much of this marsh would be inundated by sea level rise. However, Map B, which is based on more accurate LiDAR data, shows that in fact sea level rise poses a major threat to this marsh. Awareness of the invisible uncertainties contained in maps can lead to more effective management decisions.

A. Based on National Elevation Dataset (NED)

B. Based on LiDAR data, which are more accurate



C. Large area of low confidence using NED

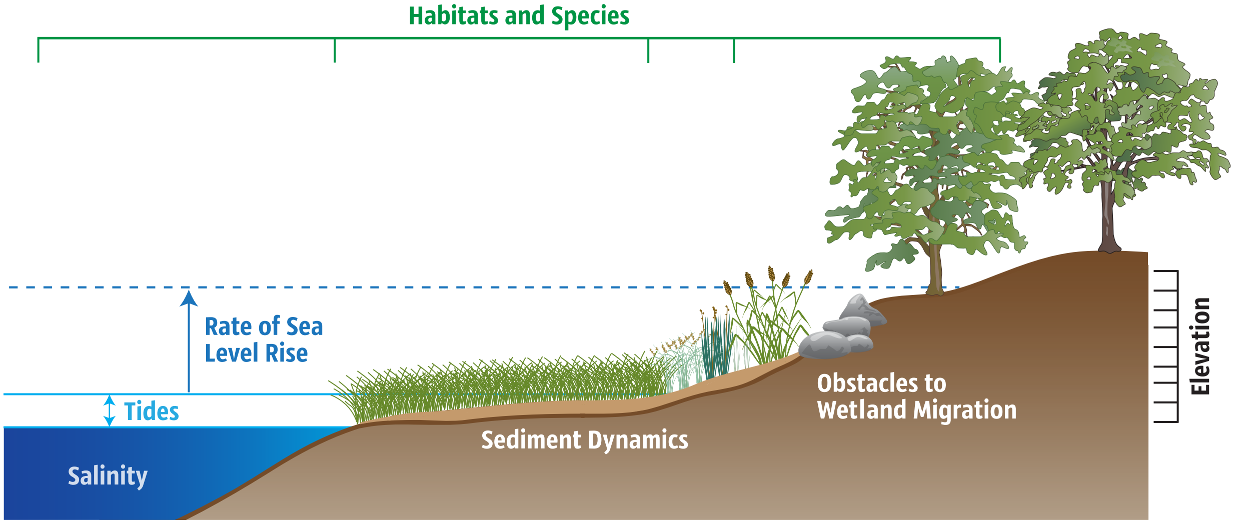
D. Smaller area of low confidence using LiDAR

These maps show an area of beach, marsh, and uplands in Edisto Beach, South Carolina. Map A shows the area in blue that would be inundated by three feet of sea-level rise based on data from National Elevation Dataset (NED), which has a vertical accuracy of ±2 meters. The NED data suggest that little of the marsh will be inundated under a three-foot rise. Map B shows the same scenario based on more accurate data collected with LiDAR, which has a vertical accuracy of ±20 centimeters. The LiDAR data suggest that nearly all of the marsh will be inundated. The difference between the maps is due solely to the difference in vertical accuracy of the elevation data. The bottom two maps show the uncertainty associated with the results depicted in Maps A and B. Green and blue indicate areas in which there is high confidence in the model's determination that the area would be land or water. Orange indicates areas in which there is less than 80% confidence in the model's determination. Map C shows that the results based on NED data had a low confidence level across the entire marsh. In contrast, Map D shows that the results based on LiDAR data had a high confidence level across most of the area. The difference in the accuracy of the elevation data makes a tremendous difference in the apparent impacts of sea level rise, but most people viewing only Map A would likely assume that it presents a reliable picture of the impacts. Any map based on modeling outputs contains some degree of uncertainty, which needs to be understood in order to interpret the map correctly.

Key Parameters and Dynamics for Modeling Sea Level Rise and Coastal Wetland Migration

THIS SECTION PRESENTS AN OVERVIEW OF KEY FACTORS THAT AFFECT the accuracy of models used to project wetland migration. It highlights considerations about data quality and inherent uncertainty in datasets that may be used to represent environmental variables and processes. Managers can use this information as a starting point for assessing the strengths and weaknesses of a modeling approach and for understanding the real-world implications of model outputs. The following discussion of parameters begins with sea level rise and other physical and chemical drivers of habitat change, and then discusses the habitats themselves. To assist with evaluating the results of a model, a number of example questions are provided at the end of the section.

Conceptual Diagram



This figure illustrates key parameters for modeling wetland migration in response to sea level rise. The parameters are discussed on the following pages.

- Rate of Sea Level Rise: Not only the amount but the rate of sea level rise is a key factor.
- Tides: Tide levels are important in determining wetland extent and persistence.
- Salinity: If the salinity regime changes, vegetation and wetland functioning may change.
- Elevation: Elevation is one of the most important data components for modeling sea level rise.
- Sediment Dynamics: If sediment accumulates, or accretes, on the wetland surface as fast as the sea level rises, then the wetland may avoid being submerged under the rising sea.
- Habitats and Species: Land cover data and habitat change rules can be used to project the effects of sea level rise on the locations of habitats and species. Obstacles to marsh migration are an important consideration when modeling these changes. Note that the locations of other intertidal and shallow subtidal habitats will shift, too, but this report does not address models that account for changes in those habitats.
- Additional Complicating Factors: Many other factors complicate the process of modeling and projecting changes in coastal wetlands into the future. These factors are difficult or impossible to address in quantitative or numerical models, so they may be best addressed in conceptual models or qualitatively in the management process.

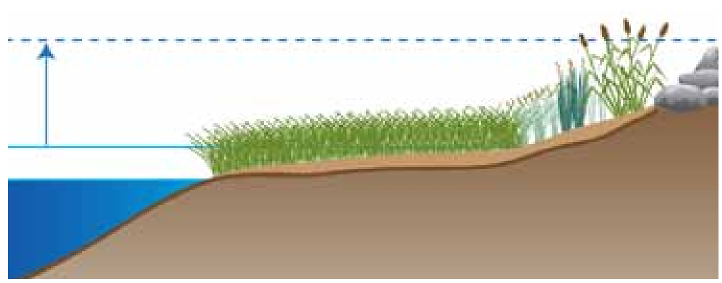
Rate of Sea Level Rise

Not just the height of sea level but the rate at which sea level rises is an important factor affecting wetland migration processes and model results. When sea level rises, tidal wetlands may migrate landward to an extent dictated by the slope of the land and rates of vertical sediment accretion and peat formation, which may enable wetlands to keep pace with sea level rise (see Sediment Dynamics). A combination of the amount and the rate of sea level rise will determine if a wetland will drown or if it will keep up with sea level rise and migrate landward. Scientific projections indicate that sea level may rise up to or more than two meters by 2100 with an increasing rate of rise over time. Wetland migration models can be used to investigate the management implications of various scenarios covering a range of projections. Because of the uncertainty associated with climate models themselves and projections of sea level rise, using multiple runs of wetland migration models is useful for exploring a range of sea level rise scenarios and for identifying a plausible range of future states of the wetland ecosystem. Another important factor for wetland migration modeling is that the local (relative) rate of sea level rise in a given area may differ from the global (eustatic) rate because of a number of factors. Modelers, managers, and planners should consult the latest science to obtain the best available projections of sea level rise in their area.

A COMBINATION OF THE AMOUNT AND THE RATE OF SEA LEVEL RISE WILL DETERMINE IF A WETLAND WILL DROWN OR IF IT WILL KEEP UP WITH SEA LEVEL RISE AND MIGRATE LANDWARD.

CALCULATING LOCAL RATES OF SEA LEVEL RISE

Wetland migration models can be tailored to a particular study area in part by using a local rate of sea level change. The rate of sea level rise is not the same everywhere. It differs from place to place because of many factors. For example, uplifting of tectonic plates in a region can reduce the local rate of sea level rise, whereas subsidence can increase the local rate. A local rate of future sea level rise can be calculated based on a scientifically determined global rate and adding or subtracting a local correction factor. Historic data from tide stations can be used to determine the local correction factor by finding the difference between the measured local trend in water level and the historic global trend from the same period. NOAA's Sea Levels Online website (tidesandcurrents.noaa.gov/sltrends) shows the historical sea level trends around the globe based on tide station records.



Tides

THE PROJECTED FUTURE ELEVATIONS OF SPRING TIDE AND MEAN TIDE MAY APPROXIMATE THE LAND AREA INTO WHICH A WETLAND MAY MIGRATE.

Because tide levels are important in determining wetland extent and persistence, and tidally influenced salinity regimes are important in determining wetland type (salt, brackish, or fresh), tidal fluctuations are a key factor to consider in models of wetland migration. For example the landward edge of a salt marsh typically lies at the elevation flooded by spring tides. The approximate seaward edge usually occurs near the elevation of mean tide. In some models, the projected future elevations of spring tide and mean tide approximate the land area into which a wetland may migrate. Depending on the size and characteristics of the study area, data from nearby tide stations may be adequate for modeling small areas. Another approach for larger areas is to use VDatum software (vdatum.noaa.gov) to produce a spatially varied model of tidal variability. The method used to include tides in a wetland migration model affects the level of confidence in model outputs.

Salinity

Potential changes in the salinity regime are a key factor to consider when modeling the future responses of a coastal wetland to climate change. If the salinity regime changes, the plant community and overall ecological functioning of the wetland may change. In river deltas, for example, tidal wetlands range from very low salinity in the higher reaches to very high salinity in more distant salt marshes. Different plant and animal species occur in the various kinds of tidal wetlands, and this is important as each wetland type provides different ecosystem services to human communities.

In the context of wetland migration models, the focus is not on short-term salinity fluctuations such as those caused on a daily basis by tides, but on long-term shifts in salinity, which may be associated with changes in precipitation patterns, watershed land use, groundwater extraction, dam construction or removal, and other factors. For example, projected changes in the seasonality and amount of precipitation could greatly affect the input of freshwater from watersheds into coastal wetlands, resulting in droughts that increase salinity or high flows that decrease it. Some models identify how each wetland type will respond to changes in both sea level and salinity. Other models do not attempt to address salinity changes at all, which could mean that important management questions are overlooked. Regardless of the model used, understanding how it addresses salinity is important when evaluating model outputs to inform management decisions.

IF THE SALINITY REGIME CHANGES, THE PLANT COMMUNITY AND ECOLOGICAL FUNCTIONING OF THE WETLAND MAY CHANGE.

Elevation

Elevation is one of the most important data components for modeling sea level rise and its impacts on coastal wetland systems. Model parameters are often compared to, calculated from, or influenced by elevation, and elevation ultimately determines which places will be wet or dry as sea level rises. Using the most accurate elevation dataset, or Digital Elevation Model (DEM), available is one of the best ways to improve results of wetland migration models.

When reviewing the outputs of wetland migration models, it is important to consider the accuracy of the elevation data. Vertical (how high is this place?) and horizontal (where is this place located?) accuracy indicate how closely a DEM resembles actual conditions on the ground. The vertical accuracy, or the correctness of the elevation value for each cell, is likely the more influential DEM aspect for sea level rise and wetland migration modeling. The resolution or size of the grid cells is also influential because all of the area within the cell is set to the same elevation, which determines the degree of detail that will be depicted. The appropriate resolution can be determined based on the size of the smallest features that must be captured in the model in order to answer the management questions. A rule of thumb is that the DEM resolution should be no more than half of the smallest dimension of the feature in question. For example, if it is necessary to resolve berms that measure six feet wide and one hundred feet long, then the DEM resolution should be no larger than three feet by three feet to reliably identify and capture these features.

USING THE MOST ACCURATE ELEVATION DATASET AVAILABLE IS ONE OF THE BEST WAYS TO IMPROVE RESULTS OF WETLAND MIGRATION MODELS.

COLLECTING HIGH-RESOLUTION ELEVATION DATA

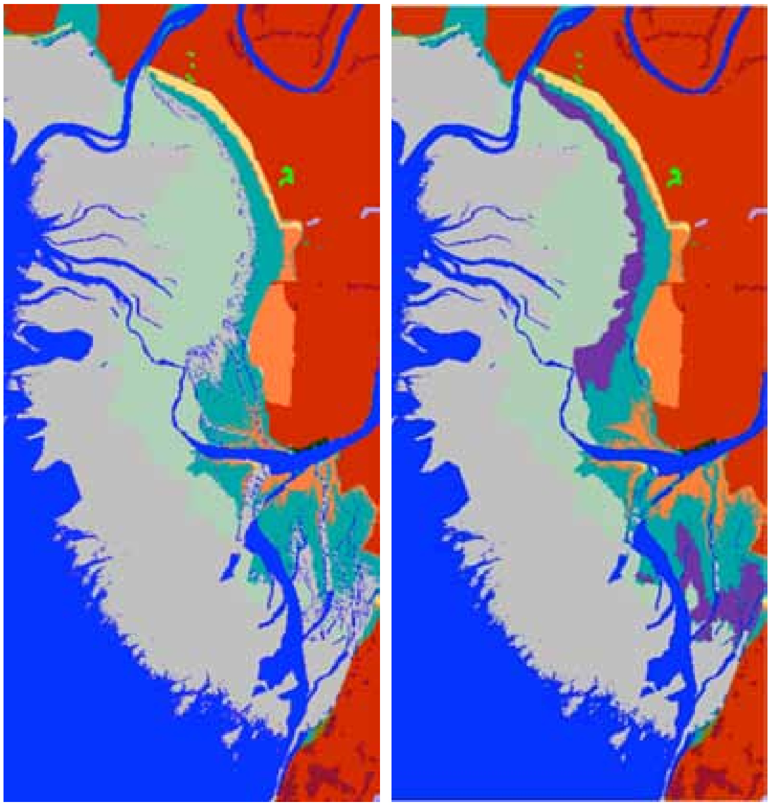
Light Detection and Ranging (LiDAR) is a remote-sensing technology that has been used to collect high-resolution, high-accuracy elevation data in coastal areas for many years. An aircraft equipped with LiDAR flies over the area and captures measurements that can be used to create detailed topographic maps typically accurate in marshes to within ±10 to 35 centimeters. While LiDAR data is a valuable tool, managers should use care when interpreting LiDAR maps, especially those of coastal wetlands. LiDAR data tend to have more uncertainty in wetlands than in uplands, where the technology has been tested more extensively. Although LiDAR can measure the surface elevations of bare earth or vegetation, it is difficult to measure ground elevations through vegetation, particularly in wetlands. It is common for less than 5% of the “ground points” to have actually hit the ground surface in wetlands. Standing water can also reduce LiDAR’s accuracy. Consequently, LiDAR measurements in wetlands may have less vertical accuracy than measurements in adjacent uplands. While LiDAR data usually are not suitable for examining centimeter-scale elevation changes in wetlands, they are far better than older, lower-accuracy types of data for modeling sea level rise and wetlands migration.

Sediment Dynamics

Areas within a tidal wetland change in elevation as sediment builds up or erodes away. The rate at which sediment accumulates, or accretes, can vary greatly over short distances, so that two spots in the same wetland may have different accretion rates. Accretion rates can also vary over time, such as when changes in land use or precipitation cause more sediment to be carried into the wetland. If sediment accumulates on the wetland surface as fast as the sea level rises, then the wetland may avoid being submerged under the rising sea.

IF SEDIMENT ACCUMULATES ON THE WETLAND SURFACE AS FAST AS THE SEA LEVEL RISES, THEN THE WETLAND MAY AVOID BEING SUBMERGED UNDER THE RISING SEA.

Therefore, accretion is an important process to consider when projecting wetland migration in response to sea level rise. Data on accretion are difficult to obtain, however, and one important issue in models that incorporate accretion is the source and quality of the accretion data. The data quality for accretion rates used in a model will affect the level of uncertainty in the model output. When possible, it is preferable to use accretion data that have been collected at many different places within the study area, using the same methods at each location, over a long time period. Frequently, such data are not available, making it necessary to use data from one or a few sites, or published accretion rates from other places. Running a model multiple times with a range of different accretion rates can provide insight into whether and under what conditions accretion may be a major concern at the study site.



Some wetland migration models incorporate sediment accretion, and the way in which accretion is represented can greatly affect the modeled habitat outcome. For example, these images both show model outputs after 100 years with 3 feet of sea level rise and the same average accretion rate. However, in the figure at left accretion occurred at a constant rate across the low marsh (aqua color), while in the figure at right the accretion rate in the low marsh varied according to elevation. That difference in model assumptions resulted in 25% more low marsh area (purple). This example illustrates the important ways that a model's assumptions can affect the results and the benefit of conducting multiple model runs in order to see a range of potential outcomes.

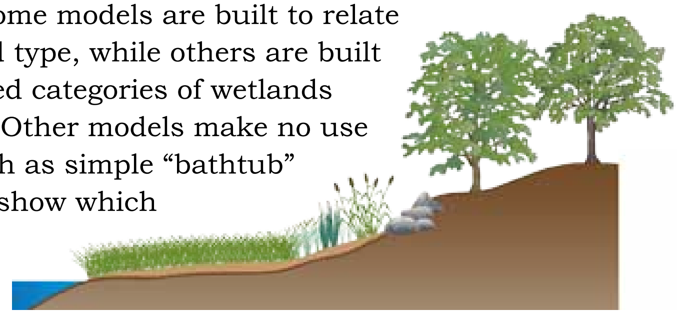
Habitats and Species

Habitat Maps and Land Cover

Data on the current presence and distribution of plant and animal species provide a baseline for modeling the potential impacts of sea level rise on coastal wetland systems. Because maps are a modeled representation of reality, there are a number of factors to consider regarding the vegetation data used in wetland migration models. Key among these are collection date (recent or potentially outdated), spatial resolution, number and types of vegetative classes identified, and stated accuracy of the dataset.

IT IS IMPORTANT TO UNDERSTAND THE SPECIFICATIONS, CHARACTERISTICS, AND POTENTIAL LIMITATIONS OF THE LAND COVER DATA SOURCE USED.

Several national land cover data products have been used in wetland migration models (see box for two examples). Local habitat maps, if available, are another possibility and may be of better quality. In general, it is important to understand the specifications, characteristics, and potential limitations of the land cover data source used. It is also important to be mindful of the types, scale, and variety of land cover classes considered by a model. Some models are built to relate to one geographic area or wetland type, while others are built to function based upon generalized categories of wetlands (freshwater, brackish, saltwater). Other models make no use of current wetland condition, such as simple “bathtub” models that are intended only to show which areas of land above the tidal range could be inundated by sea level rise.



EXAMPLES OF NATIONAL LAND COVER DATASETS

The **National Wetlands Inventory (NWI)** dataset is the national standard for mapping wetland types within the United States. While the dataset is of a detailed resolution (derived from 1:24,000-scale aerial photography) and is available in digital format for most of the country, it is important to check the date of collection. Some of the current NWI data reflect wetlands as they existed in the mid-1980s and so are not necessarily representative of current conditions or sea levels. This can be an issue in areas that have experienced a large amount of change. In addition, the NWI covers only wetlands and provides no information about the condition of uplands, which can be particularly important to determine if inland wetland migration is viable.

The **NOAA Coastal Change Analysis Program (C-CAP)** is another source of land cover and wetland information. The data include many classes of uplands and impervious surfaces, but these data are mapped at a coarser resolution (derived from 1:100,000-scale satellite imagery). The data are updated on a regular cycle, but they do not enable detailed mapping. The coarser scale and fewer wetland classes can be advantageous in that the user is not given a false sense of accuracy by viewing model outputs in greater detail than the model accommodates or data accuracy warrant.

Habitat Change Rules

Some types of wetland migration models contain a set of rules that determine which habitat occurs at any particular geographic location, or "cell" in a model. These rules are usually based on specific data ranges for one or more critical parameters affecting wetland habitat. The most common is elevation. For example, some models are set up so that cells within a certain elevation range are designated as having high marsh vegetation and cells within a slightly lower elevation range are designated as low marsh vegetation. A cell that initially was high marsh changes to low marsh if sea level increases a specific amount in the model, putting that cell into the lower elevation range. This change would be reflected in maps of habitat types based on the modeling results. Plant and animal species respond in complex ways to different physical, chemical, and biological aspects of their environment, and habitat change rules are a very simplistic way to try to determine when a species will shift its distribution as a result of changes in those parameters. Because of the many assumptions and simplifications involved, habitat change rules are a major source of uncertainty in modeling. Rules can be very simplistic (based on elevation only) or more complex (based on salinity, sediment type/chemistry, relative vegetation density, distance to a sediment source, biophysical interactions, and other factors). Both approaches have their advantages and disadvantages. For example, using a model with complex rules may be valuable for management if it provides better information, but the data requirements will be greater, demanding a higher level of effort from the project team. Interpreting model output requires an understanding of whether habitat change rules were incorporated into the model and what the rules include and ignore.

HABITAT CHANGE RULES ARE A VERY SIMPLISTIC WAY TO DETERMINE WHEN A SPECIES WILL SHIFT ITS DISTRIBUTION AS A RESULT OF CHANGES IN ENVIRONMENTAL PARAMETERS.

OBSTACLES TO WETLAND MIGRATION

Models of coastal wetland migration make assumptions about how habitats change and how plant and animal species respond by shifts in location. Over time these shifts may allow coastal wetlands to migrate inland as sea level rises. However, it is critical to recognize that natural obstacles such as rocky cliffs and anthropogenic obstacles such as buildings, roads, seawalls, berms, dikes, and other forms of shoreline armoring can block wetland migration. When one of these barriers lies along the inland edge of a wetland, it prevents the wetland vegetation from shifting farther inland. Over time, the wetland becomes narrower, until eventually it may disappear under the rising sea. Models must take these barriers into account when calculating the inland movement of wetlands. The potential for increases or decreases in barriers is a source of uncertainty when modeling wetland migration. Analysis of land development can reveal places where more shoreline armoring is likely to occur in the future, but if land-use regulations are revised—as part of a coastal adaptation effort, for example—development patterns and the rate of armoring could change.

Additional Complicating Factors

Many other factors complicate the process of modeling and projecting changes in coastal wetlands into the future. These factors are difficult or impossible to address in quantitative or numerical models, so they may be best addressed in conceptual models or qualitatively in the management process. Some examples of complicating factors are listed below. Every management area will differ with respect to which factors are important and how important they are.

- **Thresholds.** Ecological thresholds exist that, once crossed, are essentially irreversible and trigger additional changes that accelerate wetland loss.
- **Human behavior.** People will respond in many different ways to climate change and sea level rise, and their behavior could affect the persistence and migration of tidal wetlands (see box).
- **Disguised rates of change.** Some habitat changes happen rapidly over a period of one or a few years, but when averaged over many years they appear to be gradual.
- **Unexpected key players.** Species can unexpectedly take on new ecological importance and alter the wetland system. For example, wintering populations of snow geese have expanded tremendously in some places where the geese now act as ecosystem engineers by overgrazing on marsh plant rhizomes, resulting in increased erosion and reduced capacity to accrete sediment.
- **Major storms.** Storms can cause rapid, large changes in wetland habitats, such as rerouting river channels and eroding barrier beaches. By their nature, storms are difficult to predict and a storm event can significantly change conditions on the ground from those predicted by a well-executed model.

HOW WILL PEOPLE INFLUENCE WETLAND MIGRATION?

For centuries, people have impacted coastal wetlands, and they will continue to do so. When looking at model projections of wetland migration, it is important to consider the many ways that people could influence the outcome—and that are not included in the model. Land use and development patterns around wetlands may continue on their present trajectories, or they may change. Some communities may choose to pursue an increase in coastal armoring, while others retreat from the coast. Some may proactively implement adaptive management plans, while others delay action. In some watersheds, people may build more dams to store drinking water and generate electricity, while in other watersheds they may remove dams. Land-use regulations affecting wetland health may stay the same, or they may be revised to be more or less wetland friendly. These types of behaviors should be considered both as factors that add uncertainty to projections of wetland migration and as factors that could be targeted in management efforts to sustain wetlands.

- **Status of other stressors.** Nutrient and toxic pollution, invasive species, habitat fragmentation, and other stressors affect a wetland's resilience. A stressed marsh may succumb more easily to sea level rise.
- **Cyclical climate patterns.** Phenomena such as El Niño, the North Atlantic Oscillation, and the Pacific Decadal Oscillation cause cyclical effects on local sea level, wave regimes, precipitation, storm conditions, and other factors. When there is a regime shift in any of these climate patterns, local influences on habitats can likewise shift, sometimes across thresholds that reverse or accelerate key processes of change.
- **Unknowns and surprises.** Much is still unknown about the ecological functioning of tidal wetlands. Interactions among biology, physics, and chemistry can be especially difficult to understand and model in coastal wetlands. Some changes now happening in the environment may result in ecological responses that we simply cannot conceive of yet. In addition, models are often based on observations over recent decades, while future changes in ecosystem processes may extend beyond the recently observed range of values. As a result, surprises are to be expected as unanticipated changes occur.

These complicating factors can be addressed in decision-making by incorporating other data such as local development trends. In some cases, models for different factors can be explicitly linked. For example, development trends can feed into a wetland migration model through alternative scenarios for hardened shoreline. Even if quantitative data are not available on some complicating factors, they can be incorporated qualitatively into decision-making. By consulting with local experts, a manager can evaluate which factors are likely to be important in a particular area and how these factors could affect the wetland ecosystem. This information can be used in combination with model results to make management decisions.

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Wintering snow goose populations have increased their numbers unexpectedly in some areas, sometimes leading to major changes in wetland ecosystems. Models of wetland migration do not usually address this type of unanticipated change. However, if these kind of "what if" scenarios can be identified in advance, models are excellent tools to explore the potential implications.

Good Questions to Ask About Model Results

How can managers and planners evaluate modeled wetland migration results? Asking these types of questions will help.

OBJECTIVES AND AUDIENCE

- What management question was the model intended to address?
- For what audience and purpose were the model results produced?
- What are the limitations regarding appropriate use of the model results for management decision-making?

ASSUMPTIONS AND DYNAMICS

- What are the basic assumptions of the model? For example: Does the model assume a constant or an increasing rate of sea level rise over the time period modeled?
- What parameters does the model include and not include?
- Does the model adequately include ecological and/or socioeconomic factors important to the management question or specific to the type of wetland being examined?

UNDERLYING DATA AND MODEL FUNCTIONS

- Were any key datasets not available?
- What is known about the quality of the data used? For example: Are the data sufficiently recent? Were the data collected over a spatial area and/or time period appropriate to the model?
- Are the data used to drive the model appropriate for the management question being addressed and the context in which the outputs are being used? For example: What type of land cover data were used, and do they capture features of interest in the management area?

SPATIAL SCALE AND GEOGRAPHY

- Is the model appropriate for the management area? If it was developed in a different area, are the parameters included appropriate, and are any necessary parameters missing?
- Does the model cover an appropriate spatial scale?
- Is the spatial resolution of the model high enough to show the features of interest, but not higher than the available data and computing power can support?

TIME SCALE AND DURATION

- Are processes modeled through time or as if they occurred all at once?
- Are processes modeled with time increments relevant to management decision-making?

Conclusion

Modeling is a valuable tool for addressing the important management issue of coastal wetland migration, which involves complex ecological and socioeconomic processes. The purpose of this document is to assist managers and planners in using wetland migration models by being aware of the models' limitations and appropriate uses. Appropriate use of models could lead to more effective management decisions. Given all the complexities and complications, how can managers make use of models effectively? How can model results be used appropriately in decision-making? How can model results be communicated accurately and effectively to stakeholders engaged in the management processes? These general guidelines, based on the preceding sections, can help point the way:

- Think of modeling as one tool of many for management decision-making. Models do not provide the answer or make decisions. They provide additional information that managers can use in making a more-informed decision.
- Remember that models do not forecast or predict the future. They make only projections based on the rules and inputs that they are given.
- Every map generated based on modeling outputs should be viewed as one approximation of potential future conditions, which may or may not come to pass. The map does not represent "the way it will be".
- The best model to use depends on the management questions being asked and the management context, including the time and funding available for data collection and modeling. Examining how models and their outputs have been applied in other situations helps to reveal a model's strengths and limitations.
- The level of confidence needed in model outputs depends on how the information will be used. For example, more confidence is needed when purchasing property to conserve wetlands than when teaching general concepts about wetlands in an educational setting. Achieving greater confidence in modeling results usually requires a greater investment of time and funding, which needs to be weighed against the intended use of the model.
- By being aware of potential sources of uncertainty in the modeling approach, one can gauge how much confidence to place in the maps or other outputs.

- By reviewing the results of multiple model runs, different types of models, and other kinds of information, one may find consistency in some elements of future projections, suggesting that one can be reasonably confident in these elements.
- Models can offer a framework for integrating the knowledge and input of experts and stakeholders, as well as a jumping off point for discussions and decision-making at meetings and workshops.

By being aware of the complexities and areas of uncertainty in wetland migration models, managers and planners are better equipped to ask the right questions of technical experts before, during, and after modeling, and they can apply model results more effectively to decision-making. They can utilize models in raising community awareness about future impacts on wetlands, identifying where the presence or wetlands can reduce hazard-related vulnerabilities to coastal communities, setting management priorities, crafting ecosystem-based adaptation strategies, determining areas in need of further study, and numerous other management applications.

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