Planning for Sea Level Rise in the Northeast: Considerations for the Implementation of Tidal Wetland Habitat Restoration Projects

Workshop Report
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Lincoln Park wetland restoration site, Jersey City, NJ, (New Jersey Department of Environmental Protection)

NOAA Restoration Center, Northeast Region

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Executive Summary

Tidal wetlands provide many ecological and human benefits, including serving as a habitat for NOAA trust resources such as fish and shellfish. The NOAA Restoration Center has been active for many years in restoring tidal wetlands from historic degradation such as filling, diking and restriction of tidal exchange. Climate change, and sea level rise in particular, poses new threats that need to be incorporated into restoration planning. This document presents the results of a workshop held by the Northeast Region of the NOAA Restoration Center in September 2010 to develop suggested guidance for NOAA Restoration staff and partners on how to assess and incorporate sea level rise impacts into site-specific tidal wetland restoration planning and design. NOAA is currently field-testing the methods detailed in this workshop report and, based on the results of those efforts, will develop and issue guidance for use by the NOAA Restoration Center, its project partners, and other interested parties in the design and implementation of tidal wetland restoration projects in the Northeast region.

The five step process below was developed with input from workshop participants and steering committee members, and is meant to be used during the feasibility, design and monitoring phases of projects to guide impact analyses and planning.

<u>Sea Level Rise Planning Process</u>
Step 1: Predict relative sea level rise at site over 50 years
Step 2: Gather relevant information on project site
Step 3: Conduct relative sea level rise impact analysis
Step 4: Incorporate sea level rise analysis into project design
Step 5: Develop and implement plans for project maintenance and monitoring

Step 1: Predict relative sea level rise at site over 50 years
The Army Corps of Engineers sea level rise prediction methodology (USACE 2009) should be used to predict future water elevations/tidal datums at the project site. Low, medium and high sea-level rise rate scenarios should be predicted at 5-year intervals for 50 years into the future from the start of the project.

Step 2: Gather relevant information on project site
The following information should be collected or obtained for each project site. Many of these items are necessary for any project, but these data are especially important for consideration of sea level rise.

- Base map of the site, including:
    - Site elevation/ surface topography and bathymetry
    - Habitat/vegetation zones (biological benchmarks)
    - Tidal elevations and/or tide observations
    - Locations and elevations of critical infrastructure

    - Anthropogenic and natural barriers to wetland migration
- Historic conditions (geomorphic and site history)

In addition, the following items may be necessary to assess, depending on the site and scope of the project. The choice of models or method selected for the impact analysis (Step 3) will also dictate which additional baseline data need to be collected.

- Rate of wetland accretion at site
- Freshwater inflows affecting the site
- Water velocities and depths
- Suspended sediment concentrations
- Potential flooding from storm events
- Additional information as needed for site assessment and modeling

Step 3: Conduct relative sea level rise impact analysis

At a minimum, relative sea level rise impacts should be assessed for low, medium and high scenarios at year 50, but depending on the scope of the project, analysis of additional time steps may be necessary. Relative sea level rise impacts should be predicted for both the designed project and the site if no restoration action is taken to allow comparisons of benefits and drawbacks of restoration. Project managers may choose which methods of impact analysis are most appropriate for their site. The level of detail for the impact analysis should scale with the size and complexity of the project. The following impacts should be assessed:

1. Ecological impacts
    a. Habitat and vegetation zones/ biological benchmarks
    b. Tidal range
    c. Potential for inland migration
    d. Fish and shellfish communities
    e. Protected resources
    f. Coastal geomorphology
2. Infrastructure impacts
    a. Project infrastructure
    b. Adjacent property and resources
3. Storm and flooding impacts
    a. Floodplain effects

Step 4: Incorporate sea level rise analysis into project design

The project design should be created or modified based on the results of the impact analysis and/or modeling in Step 3. The selected design should maximize ecological benefits, while minimizing adverse consequences such as risks to human health and safety, over the life of the project. Project design reports should explicitly outline predicted relative sea level rise impacts and how each project is designed to address them, as well as a justification for the design choice. Specific planning guidance follows:

- *Planning Scenario:* At a minimum, projects should be planned for the predicted impacts of the current rate of local sea level rise (the "low" scenario). However, the "medium" and "high" scenarios should also be fully considered and the benefits and risks assessed for each design alternative.
- *Elevation:* Projects should consider targeting elevations at the high end of the growth range for their desired plant community to add resiliency to sea level rise. This would not apply to sites experiencing uplift or where additional inundation is a goal.
- *Migration potential:* To allow for inland/landward migration of marsh from relative sea level change, projects should consider maintaining or protecting transition/buffer zones, incorporating gradual slopes, and removing barriers where possible and compatible with the ecological goals of the project.

Step 5: Develop and implement plans for project maintenance and monitoring

In order to ensure that a project continues to function as planned into the future, NOAA recommends the development of both an operations and maintenance plan and a monitoring plan prior to the start of the project. Adaptive management is essential for projects that require long-term maintenance, since there is a great deal of uncertainty concerning sea level rise and its effects. Monitoring can help inform adaptive management as well as provide information about the success of the project. The following parameters are recommended to be monitored at least one year pre-restoration and three years post-restoration:

1. Accretion rates across the wetland site
2. Topographic and bathymetric elevations
3. Vegetation/habitat zones (biological benchmarks)
4. Hydrology/ tide elevations
5. Soils and sediment characterization

Workshop Recommendation: The results of each of the steps above should be compiled and provided to NOAA as supporting design documentation with the design plans if the project is requesting NOAA funding for construction. This five step process will ensure that tidal wetland restoration projects take into account current and future sea level rise impacts, which will increase the likelihood of long-term project success. By adopting this methodology, and continuing to adapt it as needed in the future, the NOAA Restoration Center and its project partners will be able to maximize the ecological and human benefits of tidal wetland communities for the long term.

1. Introduction

Tidal wetlands provide many valuable ecological and human benefits, including habitat for fish, shellfish, birds and other wildlife, protection from flooding and storm surges, and recreational opportunities. These wetlands have been threatened and degraded on a large scale by human activities such as filling, draining and restriction of tidal exchange, as well as by natural processes such as regional coastal subsidence. The NOAA Restoration Center and partner organizations have been active in restoring tidal wetlands from these impacts for several decades, in order to promote the health of NOAA trust resources (fish, shellfish, marine mammals, sea turtles, and their habitats). While NOAA has not yet systematically included impacts of climate change into project selection and design, there is a clear need to address this threat in concert with the others currently addressed. Climate change is causing significant impacts on ocean and coastal habitats, with effects likely to increase in the future (Hoegh-Guldberg and Bruno 2010). While these impacts are varied (e.g., ocean acidification, shifting species distributions, changes in precipitation patterns), sea level rise (SLR) has one of the most direct effects on tidal wetlands.

In May 2010 the NOAA Offices of Habitat Conservation and Ocean and Coastal Resource Management jointly released a "Programmatic Framework for Considering Climate Change Impacts in Coastal Habitat Restoration, Land Acquisition, and Facility Development Investments." This Framework addresses the need to consider climate change by calling for the development of regionally-specific technical guidance for addressing the effects of climate change. The guidance is to be based on input gathered at regional workshops of relevant science experts and project staff. In response to this Framework, the NOAA Restoration Center, Northeast Region convened a regional workshop of science and restoration experts on September 14-15, 2010 in Gloucester, Massachusetts. Workshop participants reviewed and discussed a white paper and draft technical guidance, and provided feedback on these documents. This report is the outcome of that workshop and feedback received from participants and reviewers. NOAA is field-testing the methods detailed in this workshop report and, based on the results of those efforts, will develop and issue guidance for use by the NOAA Restoration Center, its project partners, and other interested parties in the design and implementation of tidal wetland restoration projects in the Northeast region.

Guidance scope

This document provides a review of sea level rise impacts on tidal wetlands as well as draft guidance for incorporating sea level rise impacts into project planning and design. While many aspects of climate change influence tidal wetlands and their restoration, this report focuses primarily on sea level rise, leaving other climate change effects and responses for future efforts. Similarly, while there are many types of habitat restoration projects, this report will center on tidal wetland restoration projects that add or remove sediment or relieve hydrologic constrictions (also known as hydrologic reconnection or restoration projects). The geographic focus of this report is the Northeast United States (Maine through Virginia). Physical and biological conditions (e.g., tidal range, topography, vegetation) vary greatly within this region, so the recommendations made in this paper are rather broad and may need to be tailored by project managers to specific sub-regions and project sites. Likewise, this guidance covers all types of tidal wetlands, including salt marsh, brackish, and tidal fresh wetlands. While restoration in all of these wetlands shares common principles, the exact techniques used will vary. The term "wetlands" in this document refers to all types of tidal wetlands.

The focus of this guidance is incorporating sea level rise into site-specific project design, but sea level rise impacts should also be considered when prioritizing projects on a regional scale. Many of the same analyses and tools used in site-specific project design can and should be applied to project prioritization. Although prioritization frameworks may already exist for restoration within a particular state or watershed, an assessment of sea level rise resiliency can and should build upon these frameworks and serve as another decision-making factor. Much attention has focused on wetland vulnerability assessments, but on their own they do not inherently result in a priority listing of wetlands to restore. The extent of inundation, potential for inland migration, ecological value of the wetland, socioeconomic impacts and other factors may all serve as criteria to evaluate the priority of a project. The relative weight of each of the factors considered in prioritization should depend on state and/or region-wide objectives.

Use of this guidance

This document outlines a five step process for analyzing and considering sea level rise in tidal wetland restoration design. These steps should occur as part of the feasibility and design process. **Workshop Recommendation: The results of this five-step process should be a pre-requisite for construction funding from the NOAA Restoration Center in the future.**

The recommendations in this guidance are based on the best scientific information available at the time of writing, as well as the expertise and experience of numerous restoration practitioners and other professionals who provided input into this document. However, given the uncertainty with sea level rise projections and its effects on tidal wetlands, NOAA expects to regularly update this document as new data becomes available and policy dictates. At a minimum, this guidance will be re-evaluated every five years for its applicability and usefulness.

2. Background on sea level rise and wetland impacts

Sea level rise in the Northeast region

Sea level rise is attributed to two main factors: thermal expansion of ocean water due to rising global temperatures, and an increased input of water from land-based sources, such as melting glaciers and ice caps (IPCC 2007). *Global* or *eustatic sea level rise* is a result of this increase in ocean volume. *Relative* or *local sea level rise* is the combined effect of global sea level rise and local land movement. Land elevation can decrease locally due to subsidence, tectonic movement, soil compaction and fluid withdrawal, or increase due to tectonic movement and land rebound from glacial melting after the last Ice Age. Relative sea level rise is measured by local tide gauges, which record sea level relative to a fixed datum (Williams et al. 2009). In this document the focus is on relative sea level rise, since it has the most direct effect on tidal wetlands and site-specific planning.

Sea levels are rising throughout the Northeast region. Mean rates of relative sea level rise for the Northeast range from 1.76 mm/year at Seavey Island, Maine to 6.05 mm/year at the Chesapeake Bay Bridge-Tunnel, Virginia, with rates generally increasing towards the south (NOAA CO-OPS 2010). In comparison, the global sea level rise rate was 1.7 +/- 0.5 mm/year for the 20th century (IPCC 2007), which indicates that many parts of the Northeast region are subsiding and/or experiencing higher rates of sea level rise than the global average.

Projections of future sea level rise rates have been developed by several groups of scientists. Perhaps most widely cited are the estimates made by the Intergovernmental Panel on Climate Change (IPCC), most recently revised in the Fourth Assessment Report published in 2007. Based on a range of potential emissions scenarios the IPCC projects that global sea level is likely to rise 18 to 59 cm from 1990 levels by 2100 (IPCC 2007). However, a major criticism of the IPCC projections is that they do not include the potential for increased meltwater from the Greenland and Antarctic ice sheets. While there is great uncertainty regarding the precise fate of the ice sheets, losses from both ice sheets have accelerated, doubling over recent years (Velicogna 2009). The paleoclimatic record of past ice sheet melting shows that the rate of further melting and sea level rise could occur very rapidly (11-20+ mm/year, Overpeck et al. 2006), causing serious impacts to coastal areas in a short period of time. Recent observations from satellite altimeter data indicate that the current sea level rise rate exceeds the high end of the rates predicted by the IPCC (Rahmstorf et al. 2007) and is accelerating (Church and White 2006). Analysis and models proposed by Vermeer and Rahmstorf (2009) and Pfeffer et al. (2008) address potential ice sheet melt, and predict sea level rises of 0.7 to 1.9 m and 0.8 to 2.0 m by 2100, respectively.

A major challenge is translating these global estimates of sea level rise to a local and regional level. Several studies predict that sea level rise from melting ice sheets will not be globally uniform, with above average impacts to the Northeastern United States due to reduced gravitational attraction on ocean water by the West Antarctic Ice Sheet (Mitrovica et al. 2009, Bamber et al. 2009). Impacts to the Northeast are also predicted to be relatively greater than to other areas due to changes in ocean circulation driven by climate change (Yin et al. 2009).

While the exact magnitude of sea level rise is difficult to predict, it is clear that the trend of rising waters will continue for the foreseeable future, and that the Northeast region must plan for its coastal impacts.

Sea level rise impacts on tidal wetlands

Occupying the coastal fringe, tidal wetlands are among the first habitats to bear the impacts of sea level rise. Sea level rise effects on tidal wetlands are numerous and include inundation, changes in tidal flow patterns, changes in sediment transport and vertical accretion rates, shoreline erosion, landward migration of tidal waters and habitats, changes in plant and animal species composition, habitat loss, migration of estuarine salinity gradients, and changes in tidal amplitude (Cahoon et al. 2009). Although not the focus of this document, other climate change effects in addition to sea level rise can also lead to tidal wetland changes. For example, alterations in precipitation patterns can lead to changes in freshwater inflows, which in turn affect sediment delivery rates to coastal wetlands. These impacts must be considered together with sea level rise impacts. Since tidal wetlands are maintained by a complex system of processes and feedback loops, a change in any one of the inputs, if not balanced out by the others, can alter the stability of the system.

The primary concern regarding tidal wetlands from sea level rise is inundation leading to wetland plant community stress and loss. In recent geologic time, wetlands that have not been anthropogenically influenced have often kept up with sea level rise through surface sediment deposition and subsurface accumulation of organic material. In general, a rise in sea level will increase plant productivity, which in turn enhances sediment deposition by increasing the efficiency of sediment trapping (Morris et al. 2002). Furthermore, greater flooding results in greater soil waterlogging or anaerobiosis that slows belowground decomposition (Anisfeld et al. 1999). If a marsh grows too high, then its supply of sediments and nutrients will decrease, aerobic decomposition will increase, and net accretion will slow (Cahoon and Reed 1995). As accretion slows the wetland is more likely to experience greater flooding, which will in turn increases net accretion rates. In this way wetlands have historically kept pace with sea level rise.

However if a natural marsh system cannot build vertically fast enough to keep pace with rising waters it will eventually be converted to an intertidal mudflat or subtidal open water (Cahoon et al. 2009). Accretion rates vary greatly, and depend on the geomorphic setting of the wetland, the elevation of the wetland relative to the potential elevation range of plant growth, and sediment supply, among other factors. Upland land use practices in particular have major impacts on tidal wetland accretion rates and subsequent evolution, by altering sediment delivery patterns or causing erosion (Mattheus et al. 2010). Accretion rates are also likely to change as a result of restoration efforts, so accretion in a degraded wetland may not be the same as in a restored system. However, knowledge of existing accretion rates at a site is valuable in determining the potential impacts of relative sea level rise on the wetland. (A more detailed review of accretionary processes is given in Reed et al. 2008 and Cahoon et al. 2009).

Sea level rise impacts on a tidal wetland also depend on the wetland's potential for horizontal migration. Given appropriate slope, sediment supply and other factors wetlands can migrate both landward and seaward (although most marsh edges have sufficient wave energy and ice scouring to prevent seaward migration) (Redfield 1972). If a wetland can keep pace vertically with sea level rise and there are no barriers to inland migration (such as road causeways, seawalls or naturally occurring bedrock), then over time the landward wetland boundary will migrate inland as uplands are converted to wetlands (Cahoon et al. 2009). Depending on the rate of shoreline erosion/expansion, the total marsh area may increase, remain the same, or decrease as the marsh migrates inland. However, existing marshes built up and flattened steeper topography over several thousand years. Even without anthropogenic barriers, natural slopes often exist landward of marshes that will result in reduced wetland size if seaward edges erode as sea level rises.

The vast majority of the Northeast coast is privately owned or has infrastructure close to the coast that is currently blocking marsh migration. Private landowners may respond to sea level rise by building additional barriers that block landward migration. If no potential for migration exists, over time a marsh is likely to become narrower as a result of lateral erosion of the seaward edge of the marsh (even when the marsh is keeping pace with sea-level rise), until the marsh disappears altogether (Cahoon et al. 2009).

Tidal wetlands that have been altered by human influences (e.g., tidal restrictions, filling) may respond differently to sea level rise than natural systems. While responses are site-specific, in some cases a restricted or artificially elevated system may actually be restored and enhanced due to sea level rise, rather than lost. The specific impacts need to be evaluated based on each site, but it is important to be aware of the differences between natural and altered systems.

Challenges associated with tidal wetland restoration projects in the face of sea level rise

There are a number of issues currently faced by project managers when designing tidal wetland restoration projects that consider sea level rise. Several key challenges are described below.

A primary concern is to decide on the target range of elevations (or target elevation trajectory) for the wetland and desired plant community. An elevation that may support high marsh plants under current conditions may become dominated by low marsh species in 50 years with rising water levels. Predicting the amount of relative sea level rise over the project lifespan, and balancing marsh development and health for current versus future conditions are common challenges throughout the region.

Another challenge is accurately predicting future tidal ranges and water elevations to decide on placement and sizing of creek channels, culverts or bridges, and potential flow control measures. Water levels can be affected by sea level rise as well as from other impacts of climate change, such as increased precipitation and more intense storms, so these factors need to be considered collectively in designing sufficient capacity to handle these flows. However, tidal constriction projects need to balance increased water elevation with threats to nearby infrastructure such as homes and roads. Even restoring water elevation to historic levels may cause harm to neighboring properties (which may have been constructed after a wetland was altered), and increased water levels in the future may cause even more damage. While many projects include adaptive management[1] measures in their design, such as tide gates that allow adjustments to flow in the future, deciding on an optimal operations and maintenance plan can be difficult and these adaptive measures may not fully meet project goals such as water quality improvement or fish passage.

An additional issue is how to handle the scour and erosion of channels and banks caused by increased flows, which can damage vegetation and lead to bank instability. Although projects can be designed to be stable for current conditions, in some cases channels will need to become wider in the future to handle these increased flows. Based on current estimates of sea level rise, channel adjustment may occur gradually and adjust while sea level is rising. If dramatic increases in sea level rise are experienced in a short time frame, channel adjustment may occur quickly and require future restoration actions such as channel enlarging and re-grading.

Perhaps the largest challenge for restoration practitioners however is priority-setting. Recognizing that some wetlands are more vulnerable to sea level rise than others, whether due to high subsidence rates, a small growth range (range of elevations at which plants can survive) or lack of migration potential, does it make sense to focus restoration efforts on these highly vulnerable areas that may still perish in 50 years, or to instead dedicate resources to restoring or creating wetlands that have a better chance of withstanding the impacts of sea level rise? Some argue that funds are best allocated for upland land acquisition adjacent to existing tidal wetlands to enable future wetland creation and/or natural succession. Deciding how to best allocate scarce resources is a challenge for project managers throughout the region.

In the recommendations that follow we address some of these key challenges to provide restoration practitioners with advice and guidance on how best to incorporate sea level rise impacts into their project selection and design.

3. Guidance on incorporating relative sea level rise into tidal wetland restoration design

In order to address the current and future impacts of relative sea level rise on tidal wetland restoration projects, the NOAA Restoration Center offers the following guidance for project design and implementation. The purpose of this guidance is to provide steps for assessing the vulnerability or sensitivity of a project to relative sea level rise and for how to avoid, minimize, adapt to, or mitigate these impacts through the use of best management practices or recommended alternatives.

[1] Adaptive management: a system in which knowledge gained through monitoring of the project is used to inform project redesign and restoration policy (Thom 2000).

The process described below includes five major steps that should be followed to evaluate and plan for potential relative sea level rise impacts. While every project is different and will require analysis specific to its site, these steps are sufficiently broad to be applied to all projects.

Sea Level Rise Planning Process

Step 1: Predict relative sea level rise at site over 50 years

Step 2: Gather relevant information on project area

Step 3: Conduct relative sea level rise impact analysis

Step 4: Incorporate sea level rise analysis into project design

Step 5: Develop and implement plans for project maintenance and monitoring

Step 1: Predict relative sea level rise at site over 50 years

Workshop Recommendation: The NOAA Restoration Center should require an analysis of potential relative sea level rise impacts 50 years into the future. While some projects may not last 50 years and others may last in perpetuity, providing an assessment of the predicted water levels and relative sea level rise impacts at a consistent time into the future will allow project funders and managers to better anticipate likely issues and make informed decisions. It should be noted that 50 years is to be used as a planning horizon for assessing potential impacts, but this timeframe is separate from the planned life of a project or any infrastructure, which should be determined separately based on site-specific goals. However, if a project is specifically planned to last less than 50 years, then relative sea level rise projections should be made for the design life of the project.

The first step in assessing relative sea level rise impacts on a site is predicting the future water elevations and tidal datums. The most accurate site-specific predictions of relative sea level rise are based on local current rates of relative sea level rise. These rates of sea level change can be obtained from local tide gauges, such as those maintained by the NOAA Center for Operational Oceanographic Products and Services (CO-OPS). The CO-OPS website (http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml) charts historic sea level observations, as well as the mean sea level trend based on at least 30 years of data, for 35 tide stations throughout the Northeast coastal region. While the tide stations are broadly spaced and may not be adjacent to a project site, if oceanographic and geologic conditions at the nearest tide station are similar to the site, the sea level trends there can generally be used or extrapolated. Particular attention should be paid to the geomorphic setting of a tide gauge however, as tidal patterns and relative sea level rise trends are likely to be very different in open coastal sites versus semi-enclosed locations in a bay or sound. If no appropriate tide station data are available, a tidal hydrodynamics expert (such as a CO-OPS staff member, see Appendix B) should be consulted.

There are numerous estimates of future rates of global sea level rise (see part I), but downscaling these projections to a local level is challenging, and few reliable methods exist. Given the level of uncertainty that exists in predicting relative sea level rise, a multiple scenario approach (low, medium, and high) is best at assessing the range of potential impacts.

Workshop Recommendation: The NOAA Restoration Center should require the use of the Army Corps of Engineers guidance for incorporating sea level change considerations in civil works projects (USACE 2009). The Corps guidance uses current local sea level rise rates (based on local tide gauge data, as discussed above) to form projections for the "low" scenario, and a combination of these local rates with IPCC (2007) scenarios and the National Research Council's (1987) equations for the "intermediate" and "high" scenarios. This method derives locally specific estimates for sea level rise which span a broader range of scenarios than the IPCC estimates alone. As stated in the Army Corps guidance, low, intermediate and high scenarios should be predicted at 5-year intervals for 50 years into the future from the start of the project. This will produce a range of estimates for water elevations at each of these time periods that will be incorporated into the impact analyses in Step 3. The Army Corps guidance is scheduled to be reviewed and revised on a regular basis; as updates become available they should be used in place of the July 2009 document.

Step 2: Gather relevant information on project area

For any project it is essential to gather background information about the site to create an appropriate design. To assess the effects of relative sea level rise, additional information may be needed. The specific baseline information to collect depends on the project site, type of project, and method used to determine relative sea level rise impacts, as well as the project's goals. The information selected should enable a project manager to sufficiently predict impacts on both the site's ecological resources and infrastructure 50 years into the future under high, medium, and low relative sea level rise scenarios. The items listed below represent information commonly needed to make these predictions. The first group of information is required of all projects, although in most cases data on barriers to wetland migration and historic geomorphic conditions may be the only items not already collected. The second group of information may be required depending on the site and scope of a project. For small and simple projects, none of these items may need to be assessed, while for large, complex projects all of these items plus others may need to be determined. An overview of these items is below, followed by a more detailed description of what each one entails, and potential sources for this information.

Workshop Recommendation: Background data to be collected should be categorized as required or recommended as described below.

Required information

- Base map of the site, including:
    - Site elevation/ surface topography and bathymetry
    - Habitat/vegetation zones (biological benchmarks)
    - Tidal elevations and/or tide observations
    - Locations and elevations of critical infrastructure
    - Anthropogenic and natural barriers to inland migration
- Historic conditions (geomorphic and site history)

Recommended or required information (depending on the site and project)

- Rate of wetland accretion at site
- Freshwater inflows affecting the site
- Water velocities and depths
- Suspended sediment concentrations
- Potential flooding from storm events
- Additional information as needed for site assessment and modeling

Required Information

<u>Base Map of the Site</u>

The design of most projects necessitates a detailed site map including basic information, but it is especially important to include the factors listed below in light of potential relative sea level rise impacts. The site map should cover the area in which restoration will occur, and horizontally extend out to the sea level elevation projected under the "high" scenario in 50 years.

- *Site elevation/surface topography and bathymetry:* Mapping shall include all topographic and planimetric features encountered within the survey limits. This includes detailed information about the existing elevations of the marsh surface, upland slope, tidal channels or waterways, intertidal areas, ponded areas, any critical infrastructure, buildings, exposed utilities, fences, property lines, road and bridge elevations, top and bottom inverts of culverts, and any other notable features. All road names, pavement types, building types, and building addresses shall be shown on the plans. These elevation points should all be relative to the North American Vertical Datum of 1988 (NAVD 1988) and referenced in horizontal space to the North American Datum (NAD) of 1983 in project specified units of measure (e.g., feet). Survey benchmarks and spot elevations should be clearly identified on the map. The most accurate elevations are derived from on-the-ground surveys of the site, ground-truthed aerial photogrammetry or bathymetric/green LIDAR.

- *Habitat/vegetation zones:* These zones (also known as biological benchmarks) represent the current elevation of different plant communities within the wetland. They also correspond to the tolerance of flooding/inundation and growth range of vegetation in the marsh. Knowing these elevations is important because the growth range of the marsh can affect its vulnerability to relative sea level rise. Especially in cases where wetlands are not keeping pace vertically with sea level rise, wetlands with a narrow flooding and/or salinity tolerance range can be more vulnerable to relative sea level rise than those with a broader tolerance range (Cahoon and Guntenspergen 2010). Benchmarks should be determined both for the project site as well as a nearby reference (natural or desired state) marsh, since altered hydrologic conditions at the restoration site may have affected the range of each vegetation type or community, artificially raising or lowering the range depending on the nature of degradation at the site. Determining the biological benchmarks for both the affected project site as well as a nearby reference marsh for comparison will help assess target elevations. Biological benchmarks for a site can be ascertained by conducting a field survey (as described above for elevation) and using transects along a topographic gradient to identify boundaries between vegetation zones. Benchmarks should describe the range of plant community types and zones currently present (e.g., the upper and lower limits of low and high marsh), as well as the health and quality of the vegetation, so that these ranges can be compared to design elevations. Their present location should be clearly marked on the base map. These elevation points should also be relative to the North American Vertical Datum of 1988 (NAVD 1988) and referenced in horizontal space to the North American Datum (NAD) of 1983 in project specified units of measure (e.g., feet).

- *Tidal elevations or observations*: The base map should include all relevant tidal datums (also relative to NAVD 1988) to indicate the tidal range. This may include the existing high tide line (HTL), mean spring high water (MSHW), mean higher high water line (MHHW), mean high water (MHW), mean tide level (MTL), mean low water (MLW), mean lower low water (MLLW), mean spring low water (MSLW), and the low tide line (LTL). This information is valuable because the tidal range of a wetland relates to its growth range, and therefore its vulnerability to relative sea level rise. Data on tidal ranges are available from NOAA CO-OPS (http://tidesandcurrents.noaa.gov/tides10/) for many locations. The most accurate data on tidal range are usually obtained from a local tide gauge installed at or near the project site. For tidally restricted sites, actual tide observations, collected over a minimum 30-day period are essential to identify how the constriction (e.g., coastal inlet, culvert) is attenuating the tide. In these cases, site-specific tide data are required both on the upstream and downstream sides of the restriction.

- *Locations and elevations of critical infrastructure:* While ideally restoration projects restore a site to as close to natural or healthy conditions as possible, in reality projects are often constrained by neighboring private property and infrastructure that may have been constructed after the wetland was degraded. Even without sea level rise, restoring tidal flow to a site or changing water surface elevations can affect low-lying property. In planning for sea level rise it is important to know the elevations of nearby structures, property, and other features that could be affected, not just under current conditions, but over the entire lifespan of the project. This information is best obtained from property maps (available from town or city halls) and local survey data and on-site observations. It is important to include not just adjacent properties, but any properties that may be affected by the project, such as those upstream of current tidal constrictions. Special attention should be paid to sub-surface stormwater piping infrastructure in the project area, which can lead to additional flooding at outlets during storm events.

- *Anthropogenic and natural barriers to inland migration:* As sea level rises, tidal wetlands are potentially capable of migrating inland by converting existing upland into wetland. However, both manmade and natural barriers to migration may exist. In general, property maps, local survey data and site visits are recommended to identify potential barriers to migration and evaluate terrain suitability. These barriers may consist of infrastructure such as roads, seawalls and buildings; private property boundaries; or physical conditions such as steep slopes or bedrock. In some cases upland habitat may also be of critical natural importance (e.g. a regionally significant vernal pool) and may not be suitable for conversion. Several states have already undertaken wetland migration potential mapping activities (e.g., Massachusetts), or barrier assessments (e.g., New Hampshire; Bozek and Burdick 2005) so regional maps for some areas may already exist.

<u>Historic conditions (geomorphic and site history)</u>

The history of the project site, over both geologic and recent time, is also necessary to investigate in order to plan appropriately for sea level rise. Often aided by storms, rising seas have the potential to change the shape of the shoreline and create new inlets. An examination of the historical changes, underlying surficial, and in some cases bedrock, geology and the potential for large shifts in the shape and dynamic of the wetland can be very useful in anticipating possible changes. Also, for specific sites, a better understanding of the coastal processes that have shaped the site (e.g., waves, littoral transport, inlet and barrier migration, etc.) may be required to determine the potential for influences of the restored system on the beach resources, or vice versa. On a large scale, it is also important to evaluate the geologic processes governing the site. Some regions have been subsiding for the last several thousand years, while others have been experiencing uplift. These trends have major implications for the impacts of sea level rise.

An evaluation of the site's more recent land use history is also essential in order to aid in predictions of how the site will react to sea level rise. This information (often derived from aerial and ground-level photographs and soil mapping among other sources) is typically required for all restoration projects, but may be especially relevant in understanding, for example, past water levels and plant growth before a constriction was installed. Understanding whether the wetland was recently formed (for example following deforestation) and is more ephemeral or is very old (greater than 1000 years old) may also help in deciding the level of effort and techniques to use in restoration

Recommended or required information (depending on the site and project)

The design of restoration projects can vary greatly depending on the project site, so the data needed for each project differ. As mentioned above, the size, scope and location of a project dictate the necessary data to collect. Most models also have specific data requirements for local parameters. The information listed below should be considered for inclusion in project design to assess the impacts of relative sea level rise, but may not be appropriate or needed for all projects.

<u>Rate of wetland accretion at site</u>

If available, these data can provide valuable insight into the current and past rates of vertical marsh plain building, which when analyzed with predicted relative sea level rise rates can provide estimates of potential wetland sustainability. Several methods exist for quantifying wetland accretion rates. Historical rates of organic and inorganic material accumulation can be measured by taking soil cores and radionuclide dating the horizons (Rooth et al. 2003). Surficial accretion of mostly inorganic material can be measured for non-erosional sites by placing a marker horizon (MH) on the surface of the marsh at the beginning of a study period and measuring its depth over time (Cahoon and Turner 1989). Another technique for measuring contemporary accretion rates is the use of surface elevation tables (SETs), which measure the net change in marsh elevation relative to a fixed datum, often in conjunction with marker horizons (Cahoon et al. 2002). SETs are able to determine the net result of processes that increase elevation (such as surface sediment deposition and soil peat accumulation) and those that decrease elevation (such as compaction and decomposition) (Reed et al. 2008).

Accretion rates can vary over time and even within a project site, so data need to be collected at the project site itself, not simply within the same region or watershed. Since several years of data are needed to obtain results from an SET or marker horizon, it is not usually possible to obtain this type of accretion data rapidly prior to the start of a project. However, where SETs or other accretion markers are already established they can provide useful data on accretion rates pre and post restoration. Reed et al. (2008) compiled a summary of published accretion studies for the Mid-Atlantic, which can serve as a background reference for project managers in that region.

<u>Freshwater inflows affecting the site</u>

Freshwater inputs, from rivers, groundwater, and stormwater discharges, can have large impacts on wetland growth and accretion. Freshwater inflow affects the salinity and nutrient availability of wetland water, which in turn can affect plant community composition and vegetation patterns. It is also important in sediment delivery, which plays a large role in maintaining marsh elevations. Some rivers and streams have USGS stream gages installed, which provide a record of base and storm discharge over time. Additional site-specific measurements can be made to determine the influence of freshwater inputs from storm drains or sheet flow from adjacent impervious surfaces. The rate of freshwater inflow is most commonly used as an input into site-specific hydrodynamic models (described in Appendix A).

Water velocities and depths

The rate at which water travels through existing and designed channels, and the size of channels in cross-section, are necessary for calculating hydraulic equations and parameterizing site-specific models. Water velocities and water depth also has strong implications for passage of a number of fish species that live and spawn in tidal marshes (Eberhardt et al. 2010). Fish passage is essential for exporting high quality food resources to coastal fisheries through the trophic relay (Kneib 1997, 2003, Deegan and Garritt 1997).

Suspended sediment concentrations

The amount of sediment present in a wetland's water supply can provide an indication of the potential for sediment capture by wetland vegetation. It also directly influences the wetland accretion rate. Suspended sediment concentrations are measured via field sampling techniques at the project site. This information is also often used as an input to site-specific hydrodynamic models.

Potential flooding from storm events

Eustatic sea level rise will affect the base water level upon which storm surges are built. Climate change may also affect, and may already be affecting, coastal storm magnitudes and frequencies (Kirshen et al. 2008). While predicting the impacts of changing storm frequency and intensity are beyond the scope of this paper, it may be important to consider how storm surges and wave height magnitudes can impact project sites.

It is essential to consider storm events in designing culverts, tide gates and other hydrologic connection structures (the design storm frequency of storm event is determined by local permit regulations). Information on predicted storm magnitudes and frequencies can be obtained from Federal Emergency Management Agency (FEMA) flood maps[2] and the United States Army Corps of Engineers Tidal Flood Profiles (USACE, 1988). An assessment of potential flooding from storm events (as a consequence of project implementation) should be part of the due diligence process of any design and may be a regulatory requirement if your project lies in a Special Flood Hazard Area as designated by FEMA. In addition, since some coastal wetland restoration projects reintroduce either full or partial tidal flow to previously restricted wetlands,

[2] Available at:
http://www.msc.fema.gov/webapp/wcs/stores/servlet/FemaWelcomeView?storeId=10001&catalogId=10001&langId=-1

this analysis may be required as part of a USACE Section 404 permit application and/or a NEPA analysis. Federal law requires such analyses of projects that may raise FEMA base flood elevations.

FEMA is presently evaluating the impacts of climate change on the National Flood Insurance Program (NFIP), which establishes base flood elevations for coastal and riverine floodplain communities. To our knowledge this effort is not complete, but project design teams who desire to evaluate the impacts of future storm surge and wave run-up on their projects, or those that are required to (primarily hydrologic restriction projects), should apprise themselves of any updated FEMA Flood Insurance Studies (FISs) for their area and/or new analytical guidance from FEMA.

Additional information as needed for site assessment and modeling

There are other types of information and data that may be recommended or needed to design a restoration project in the face of sea level rise. While it is not possible to address every scenario here, it should be recognized that a thorough analysis of the factors influencing the site and the data required for any necessary modeling may require additional data collection. For example, wave exposure (length of fetch, presence of dredged channels, boat/shipping traffic) or potential for herbivory could be additional relevant factors to examine depending on the site.

Step 3: Conduct relative sea level rise impact analysis

Workshop Recommendation: In funding the construction of tidal wetland restoration projects in the Northeast region, the NOAA Restoration Center should require an analysis of the potential impacts of relative sea level rise on the project site over the next 50 years. At a minimum relative sea level rise impacts should be assessed for low, medium and high scenarios at year 50, but depending on the scope of the project, analysis of additional time steps may be necessary. Predictions should be made of sea level rise impacts on the site both with the project constructed as designed, and if left in its current state, to allow comparisons of benefits and drawbacks of restoration. The impact analysis should include the project area and extend out to the predicted sea level elevation under the "high" scenario in 50 years.

The impacts listed below are recommended for assessment, building on the baseline data collected for each site, but others may also need to be considered, depending on the site. The level of detail necessary for these impact analyses will scale with the size and complexity of the project. While the analysis should address each of the categories and questions below, it does not need to be exhaustive. Rather, this analysis should reflect the best professional judgment of the project manager and indicate that he or she has done due diligence to assess potential relative sea level rise impacts. The information collected in Steps 1 and 2 should be used as the basis for these impact analyses. The manner in which these data will be used depends on the analysis method used (examples are described below), but in all cases they should serve as a baseline from which to measure future impacts, and as a guide for what levels of sea level rise should be considered. An overview of the impacts to assess is below, followed by more detailed descriptions.

1. Ecological impacts
    a. Habitat and vegetation zones/ biological benchmarks
    b. Tidal range
    c. Potential for inland migration
    d. Fish and shellfish communities
    e. Protected resources
    f. Coastal geomorphology
2. Infrastructure impacts
    a. Project infrastructure
    b. Adjacent property and resources
3. Storm and flooding impacts
    a. Floodplain effects

<u>Ecological impacts</u>

Habitat and vegetation zones/ biological benchmarks

Project managers should determine the predicted elevation of vegetation types and transition zones under each scenario (e.g., for a salt marsh in 50 years, where are the low marsh and high marsh boundaries likely to be?). A summary of the changes in vegetative cover that are expected over the 50 year planning horizon, and whether the wetland is likely to survive and maintain its elevation into the future, should also be included.

Tidal range

For each scenario, the predicted elevations of the site's tidal datums in 50 years should be calculated. This should include the datums most relevant for the project and site, such as HTL, MHW, MTL, MLW, and LTL.

Potential for inland migration

A wetland's potential to migrate inland should be evaluated, based on the presence of manmade or natural barriers, as well as the accretion rate. The relationship between accretion and migration potential is described in Section 2.

Fish and shellfish communities

For each scenario, the predicted impacts on fish and shellfish communities and other resources and their habitats should be estimated. While there are many factors that influence the health and abundance of these resources and habitats, this analysis should focus on large-scale changes to the quality and quantity of habitat available. For example, will intertidal habitat convert to subtidal habitat? Will future water velocities prevent fish passage through culverts or other tidal control structures?

Protected resources
While most projects already require an analysis of potential impacts on threatened or endangered species, or other species of concern, this analysis is to examine impacts beyond the current restoration site. Increased water levels 50 years in the future may affect these species and their habitats, for example, by flooding a vernal pool currently located in an adjacent upland with salt water. The presence of a species of concern in the upland fringe would not have to prevent project construction, but could allow for design modifications if desired, or at a minimum, the evaluation of ecological benefit trade-offs.

Coastal geomorphology
Coastal habitats are shaped by their geomorphology, which can change over time, especially when areas are subjected to strong physical forces such as increased sea level and storms. An evaluation of whether inlets, barrier beaches protecting wetlands, or other coastal landforms at the site are predicted to change or be inundated due to sea level rise can be valuable to determine potential impacts on the project and whether it is likely to succeed. Geologic records can often give clues as to how an area has responded to sea level rise in the past.

<u>Infrastructure impacts</u>
Project infrastructure
With the water levels predicted under each scenario, project managers should evaluate whether the project infrastructure (culverts, tide gates, bridges, channels, etc.) will be sustainable 50 years in the future. For example, will the culvert openings be set high enough to accommodate higher water levels? Can the tide gate be adjusted to ensure desired flow if the high tide level becomes 20 cm higher? If project infrastructure is designed to last less than 50 years, then its effectiveness out to its design life should be evaluated, and noted in the design report.

Adjacent property and resources
Project managers should also determine whether increased water levels are likely to inundate adjacent or upstream properties or infrastructure, under each scenario. This infrastructure includes but is not limited to buildings, public utilities, roads, and wells. Managers should also evaluate whether increased water levels might threaten any historic, cultural or recreational resources, and whether any predicted losses might be offset by potential gains (e.g., flooding could increase waterfowl habitat in some areas along with birdwatching opportunities). The future of existing infrastructure and resources over the next 50 years should also be considered. For example, a tidal reconnection project that combined with sea level rise may increase water levels sufficiently to threaten a bridge in 50 years might not be problematic if the bridge is slated for replacement in 30 years.

Storm and flooding impacts

Floodplain effects

While it is difficult to predict exactly how sea level rise may influence storm surge impacts, in many cases it will lead to increased flood elevations because the base elevations upon which storm surges are built are increased. If a project entails removal of tidal restrictions and may change flood elevations, and it is located in a Special Flood Hazard Area under the National Flood Insurance Program (NFIP), then project managers will be required to determine how this may affect FEMA 100-year flood maps for the area (see the "Potential flooding from storm events" section under Step 2 for more details) irrespective of sea level rise. In these circumstances, we recommend that project teams analyze project-induced changes in flood elevations both for conditions at the time of construction, and for 50 years into the future considering sea level rise. For projects that are not in NFIP-regulated areas, but have nearby low-lying infrastructure of community importance, these analyses are recommended as well.

Impact Assessment Methods

There are many methods for estimating these potential relative sea level rise impacts, ranging from relatively simple estimates of inundation and vegetation growth ranges based on elevations, to site-specific ecological, hydrodynamic and numerical models. There is no “best” technique or model to use for all situations, since sites and the factors governing their processes vary greatly. Below is an overview of several techniques and models that can be used to evaluate marsh processes and predict the effects of relative sea level rise upon them. This is not a comprehensive list of potential approaches, and other viable methodologies may exist. The decision as to which technique or combination of techniques to use should be made by a wetland restoration expert in the context of each site individually. The technique chosen should be documented in a design or feasibility report.

Analysis of future water level elevations

The most basic method for predicting relative sea level rise impacts on a site is to calculate the projected water level increases under each scenario and simply add them on to an existing tidal datum on a topographic map. For example, using the Army Corps methodology, if the current local rate of relative sea level rise at a site is 3 mm/year, then in an unrestricted marsh not undergoing uplift or subsidence under the “low” scenario in 50 years the mean high water level will be 150 mm higher vertically than its current level. The predicted water levels can be plotted on a topographic map. For hydrologic restriction projects, basic hydrodynamic equations can be used to estimate future water levels if tidal ranges are known inside and outside the restriction.

Future plant community zones and infrastructure impacts can then be estimated based on these predicted tidal datums. This type of inundation or “bathtub” method can be useful for getting a rough sense of where on the site water levels may be in the future, and may be appropriate for small projects without sensitive adjacent infrastructure. However, this technique does not give any weight to how the marsh itself will respond to increased water levels. Depending on the rates of accretion and subsidence the marsh may be able to keep pace with relative sea level rise, maintaining its horizontal position, rather than retreating inland as would be predicted with this method. This method also does not account for the changing height of the tidal prism with increased water levels, which could alter the tidal range significantly. There are a host of other factors, such as sediment transport, flow dynamics, and ecological responses, which are not included in this technique as well. However, if there are insufficient resources to support site-specific modeling, this method can give a preliminary estimate of relative sea level rise impacts.

Elevation capital technique

This method of determining the vulnerability of a tidal wetland to relative sea level rise starts with an assessment of existing tidal datums and marsh vegetation elevations, as above, but incorporates how wetland processes may respond to sea level rise. It was developed by Cahoon and Guntenspergen (2010), and is a four-part process, building off an assessment of a wetland's elevation capital. Part one is to determine the elevation capital, which is the position of a wetland relative to its growth range: the lowest and highest elevations at which plants have a tolerance to flooding frequency and duration. In other words, the first step is to determine where the wetland system lies within the local tidal range. In general, wetlands with large tidal ranges have large growth ranges, and subsequently more potential to accumulate minerals and organic matter (elevation capital). Wetlands with small tidal ranges have small growth ranges, and subsequently less potential to accumulate elevation capital. Wetlands considered to have large elevation capital are generally more resilient to the effects of relative sea level rise.

The second part in this process is to determine elevation trends relative to sea level rise to evaluate whether the wetland is keeping pace or developing an elevation deficit. This requires some knowledge or observations of local sea level rise rates, as well as rates of sediment deposition and biomass accumulation in the wetland system. As discussed previously, one method for determining accretion rates is the use of SET-MH data (if available); other sediment measurement techniques, or sediment transport modeling for the site can also be helpful.

Part three consists of determining, at least on a preliminary level, the environmental processes and factors controlling elevation response to sea level rise. This involves an assessment of the surface and sub-surface processes controlling elevation change such as sedimentation and decomposition. While historically impacts of sea level rise on wetlands have focused on physical processes, it is equally important to consider biotic processes that affect vertical soil building and plant growth. It can be challenging to isolate impacts of relative sea level rise since the effects of sea level rise interact with other wetland processes, but it is important to consider which processes may be affected.

The final part is to use the data generated in the first three steps, as well as estimates of future sea level rise rates (generated using the Army Corps method) to calibrate and validate models for predicting future wetland response to relative sea level rise. While there are a range of potential models to use (as described below and in Appendix A), this technique recommends the use and development of numerical coastal wetland models that predict the response of wetlands to relative sea level rise through non-linear feedback mechanisms. The final output is an assessment of the size of the wetland over time and how long it will persist into the future.

This technique benefits from its focus on wetland processes, and from its fairly straightforward assessment of a wetland's vulnerability based on its elevation capital. The elevation capital concept is one that can be easily applied to many wetlands. However the complete technique relies on site-specific models to derive more focused predictions of how a wetland will react to relative sea level rise, and so is constrained by the costs and current limitations of those models.

Site-specific ecological models

Whether used in conjunction with the elevation capital technique above, or independently, these models provide a mechanistic, process-based prediction of how wetlands may react to relative sea level rise. Site-specific models (e.g. Morris et al. 2002) incorporate both biological and physical processes, and can provide detailed predictions of a wetland's fate in the face of relative sea level rise. For example, Mudd et al. (2009), built upon the work of Morris et al. 2002, and developed two models that analyze the site-specific feedbacks between biomass production, sedimentation and relative sea level rise, and also incorporate sediment compaction and belowground biomass production. The accuracy of site-specific ecological models can be improved by using input provided by the hydrodynamic models described below, which provide details on the changes in the physical water dynamics of a wetland system. These models generally allow the user to specify future rates of sea level rise (that would be derived from the Army Corps methodology) to use in determining the impacts at various times in the future.

The benefit of these models is that they can be quite effective at predicting site-specific sea level rise impacts and they incorporate marsh ecological processes. Their drawback is that in order to produce localized outputs many models require a large amount of localized inputs, which can be costly. However, if measures of plant biomass/productivity, rates of sediment loading, and efficiency of vegetation at trapping sediment are known, or sufficient funding exists to collect this information, then these models can be valuable tools. Examples of this type of ecological model include MARSH MD (Konisky et al. 2003), MEM (Morris et al. 2002, Morris 2010), and SLAMM (Warren Pinnacle 2010).

Hydraulic and hydrodynamic numerical models

These models can predict physical processes, such as water surface elevations, velocity, flow, salinity levels, and sediment transport within a system, based on empirical relationships and physical laws. They can also be used to provide improved physical processes input into the elevation capital technique and ecological models. The models are typically calibrated and validated to existing conditions, and then applied to predict the impacts on the system caused by proposed restoration designs, relative sea level rise, and storm events. They range in what quantified information they can provide, complexity, cost, and degree of expertise required, but are intended to simulate the impacts of a range of different relative sea level rise scenarios given appropriate inputs. Application of these types of models is most useful in cases where a modification to the current system is being proposed (e.g., a tidal constriction is being reconstructed, opened, or modified) and future relative sea level rise impacts on both the existing and proposed system need to be assessed. For these models, rates of future sea level rise (as calculated in Step 1 using the Army Corps methodology) would be an input.

Restoration of a wetland, and specifically the alteration of the system hydraulics, often will result in a wide range of potential impacts. In addition to assessing relative sea level rise, this type of modeling can provide information about the potential for upland flooding and salt water intrusion, the change or loss of certain habitat types or plant communities, modification to the tidal exchange, alteration of surface and ground water quality and salinity levels, and/or potential impacts on the barrier beach/inlet system. Hydraulic and hydrodynamic modeling of these systems provides the ability to assess potential changes, evaluate a range of potential restoration alternatives, and optimize designs to ensure a successful project.

Modeling of the hydrodynamics of a tidally-forced wetland system is not straightforward. There are a wide variety of hydraulic, hydrologic, and hydrodynamic models available, ranging from simple to complex, and from proprietary to public domain, but not all are applicable for tidally-forced, marsh restoration projects. The correct model selection, which includes consideration of the dominant physical processes and driving factors within the wetland system, is a key component of the numerical modeling process. For example, depending on the physical system, the model selection process should evaluate the need for the model to appropriately simulate wetting and drying of a marsh surface, salinity levels, potential stratification, control structures (e.g., culverts, dikes, weirs), flow resistance due to various vegetation types, upland flooding, sea-level rise integration, and/or storm impacts. Ultimately, the model user must understand the abilities and utility of each model prior to selecting the appropriate model for the restoration project. An overview of some commonly used classes of models that have been applied to assess the hydrodynamics of estuarine marsh systems is presented in Appendix A of this document.

While there are many benefits to these numerical models, they also have some significant drawbacks. In general, they do not incorporate ecological processes and so do not account for how a wetland itself may respond to sea level rise and hydrologic changes. In addition, many of these models require specialized computers, large amounts of time, and experienced professionals to run and interpret the results, and thus can be quite costly. However, for large-scale or complex projects these models are valuable tools.

Step 4: Incorporate sea level rise analysis into project design

The results of the data analysis and/or modeling in Step 3 should inform the creation or modification of project design with relative sea level rise in mind. In selecting a design, it is essential to first clearly indicate the intended project goals. Specific guidance regarding the planning scenario, elevation, and migration potential follows.

Planning Scenario

Workshop Recommendation: At a minimum, projects should plan for the predicted impacts of the current rate of relative sea level rise (the "low" scenario). However, the "medium" and "high" scenarios should also be fully considered and the risks assessed for each design alternative. The selected design should maximize ecological services while minimizing adverse consequences such as risks to human health and safety over the design life of the project. For example, if water levels predicted from the "high" scenario pose a catastrophic risk to nearby infrastructure such as flooding of an adjacent hospital, then it may be advisable to plan for that "high" scenario in order to address that risk, even if the hospital would not be affected under the "low" and "medium" scenarios. In some cases addressing risk might mean modifying the project design (e.g., installing tide gates to limit upstream water levels), while in others it could potentially mean not constructing the project at all. The choice of scenario to plan for also depends on how much increased risk is due to the project itself versus impacts that would occur even without the project being constructed. Project design reports should explicitly outline predicted relative sea level rise impacts and how their project is designed to address them, as well as a justification for the design choice.

Elevation

Workshop Recommendation: Project proponents should target the design elevation of their wetland based on the current biological benchmarks (i.e., growth range of wetland plant communities) and predicted future tidal levels in order to meet the ecological goals of the project. For many sites, NOAA should recommend targeting elevations for the high end of the desired wetland community in order to add resiliency to potential accelerating sea level rise impacts. However, higher elevations are generally not advisable for sites that are experiencing tectonic uplift or have ecological goals that require additional inundation, such as immediate gain of low marsh acreage or avoidance of invasive species like *Phragmites*.

Migration potential

Workshop Recommendation: To allow for inland/landward migration of marsh from relative sea level change, projects should consider maintaining or protecting transition/buffer zones, incorporating gradual slopes where appropriate, and removing barriers where possible. Again, the ecological goals and risks of the project should be the primary consideration, and in areas with high-value uplands or where invasive species such as *Phragmites* are likely to dominate an upland buffer or sloped transition zone, trade-offs between short and longer-term benefits will have to be evaluated.

Step 5: Develop and implement plans for project maintenance and monitoring

To ensure that a project continues to function as planned into the future it is important to develop and implement both an adaptive management plan and a monitoring plan prior to the start of the project. These plans may vary greatly depending on project goals and the expected project life. Some projects are planned to be self-sustaining and will require little, if any, maintenance. For projects that are expected to entail active management in the future, an adaptive management plan accounting for climate change should facilitate adjustments over time as sea level rises. This may involve altering the settings of a tide gate, adding additional sediment if a wetland is losing elevation, or other measures as conditions warrant. This adaptive management is an essential component of a maintenance plan, since it is difficult to predict the exact consequences of sea level rise. Expected funding sources for maintenance should also be included in the plan.

A closely related issue is the development of a monitoring plan. While most projects require post-restoration monitoring for 2-5 years, it is unlikely that the effects of relative sea level rise will be fully realized over that timeframe. Since funding for long-term monitoring is improbable for most projects and project partners, we recommend at a minimum the collection of baseline data that would facilitate the evaluation of sea level rise impacts at a later time. This recommended monitoring includes one year of pre-restoration conditions and three years of post-restoration monitoring (ideally years 1, 3, and 5 post-restoration) to show as-built conditions as well as relatively short-term ecological responses to restoration actions. Monitoring should be conducted concurrently at the restoration marsh and a local reference marsh. **Workshop Recommendation: the following parameters are recommended for inclusion in monitoring plans:**

1. Accretion rates across the wetland site
2. Topographic and bathymetric elevations across the site (from on-the-ground local surveys using laser level and rod; total station, etc.)
3. Vegetation/habitat zones (elevation, composition, and density of plant community types)
4. Hydrology (tide elevation using automatic water level data loggers, ideally recording every 10 minutes over 30 days to capture consecutive spring and neap cycles)
5. Soils and sediment characterization (pore-water salinity and sulfides, soil mineral content and organic matter content)

4. Research needs/Areas for future study

While our understanding of sea level rise and our ability to predict its impacts have grown rapidly over the last several decades, there is still much we do not know. Our recommendations are based on the best available science and knowledge, but further research into many of these areas, especially long-term studies, would greatly benefit restoration efforts in consideration of sea level rise. Although there are many issues that deserve additional attention, the areas of greatest need are outlined below.

Local-scale sea level rise projections

Most sea level rise projections are global, and do not take into account local factors that influence relative sea level rise, such as subsidence, uplift, geomorphic setting, and anthropogenic activity. To date, methods of down-scaling these global models have not been very successful so local projections are largely derived from models based on the current rate of relative sea level rise at a site. In addition, current rates are based on the past 50+ years of data, not just the past 10 years, so they do not directly reflect the recent acceleration of sea level rise rates. Furthermore, local sea level rise data can be difficult to obtain since NOAA CO-OPS tide gauges are widely distributed throughout the region and the nearest gauge may not accurately represent conditions at a project site. An expanded network of tide gauges, in conjunction with increased local-scale sea level rise projections, would greatly aid restoration planning.

In addition, site-specific information about geologic history and past rates of sea level rise would provide valuable context for predicting future change with the least uncertainty. This information could be gathered from analyses of cores to decipher rates of sea level change over the last 5000 or so years.

Current elevation data

Inundation mapping and assessments of wetland vulnerability to sea level rise on regional scales depend on accurate coastal elevation data. The National Elevation Dataset (NED), maintained by the USGS, contains the most accurate available raster elevation data for the United States. However, for much of the Northeast coast the highest resolution data is Digital Elevation Maps (DEMs) derived from 5 or 10-foot contour interval USGS topographic maps. Given the level of accuracy associated with these maps, the minimum relative sea level rise increment that can appropriately be used for inundation mapping is 1.82 or 3.64 meters respectively (Gesch et al. 2009), far greater than the amounts of relative sea level rise expected over the next century. While many states have gathered LIDAR data for their coastlines, which has greatly increased accuracy, LIDAR still suffers from problems with estimating elevation in the presence of dense vegetation and often requires ground-truthing. LIDAR is typically not used for in-water depths due to the turbidity within the water column. Project-specific elevation data can be gathered by ground surveys with a high degree of accuracy, but higher accuracy regional elevation data would greatly help in assessing wetland vulnerability and in regional prioritization.

Wetland elevation and accretion trend data

Because wetland response to sea level rise depends on complex relationships that affect the rates at which wetlands build vertically, it is extremely valuable to be able to measure wetland elevation and accretion and subsidence rates over time. The SET-MH and other methods such as coring and geochronology are quite useful, but currently these data are collected only in scattered locations. A greatly expanded and strategic network of SETs throughout the Northeast region would aid in assessing accretion and elevation trends across the area, and allow for better planning on both a site-specific and regional level.

Increased modeling capability and ease of use

While wetland models have grown increasingly sophisticated and are able to incorporate a range of biological and physical processes, there is still a need for improved accountability of all of the input variables involved. In addition, the wide range of models in existence and the degree of parameterization involved pose a challenge for a general project manager who would like to derive estimates of sea level rise impacts, but may not have the expertise or financial or staff resources to engage in complex numerical models. There also remains a need for accurate assessments of sea level rise vulnerability on a regional level to assist in prioritization. While SLAMM has widely been used for this purpose and has continued to improve through updated versions, further model refinement is needed to address several flaws (Kirwan and Guntenspergen 2009). Developing user-friendly, cost-effective models for both site-specific and regional modeling, and training for project managers on how to use these models appropriately, would be of great benefit.

Ecological impacts of sea level rise

Last, but perhaps most important of all, additional research needs to be done on the impacts of sea level rise on the ecology of tidal wetlands. As tidal wetlands change in size and geomorphic location, and potentially become fewer in number and acreage, we need a better understanding of what the implications are for estuarine fish habitat and populations, connectivity, and broader food webs. Nearshore recreational and commercial fisheries are likely to be affected, but it is unclear to what degree. Further study and predictions of the effects of sea level rise on tidal wetland communities would be valuable both for ecological and related socioeconomic reasons.

5. Conclusion

It is clear that sea level is currently rising in the Northeast region and will continue to do so for the foreseeable future, potentially at accelerating rates. Tidal wetland restoration, protection and creation efforts are essential for maintaining the many ecological services of coastal habitats, but these efforts must adapt to climate change. While sea level rise impacts are uncertain, the recommendations presented here are based on the best scientific information available, and provide a methodology for addressing a key issue that has previously not been consistently considered. Sea level rise is not a reason to stop doing restoration. The analysis described here is in part to avoid future potential infrastructure and socioeconomic problems caused by sea level rise at tidal wetland restoration sites while maximizing the ecological benefits of these projects.

By accurately assessing future risks and benefits, and utilizing adaptive management practices, tidal wetland restoration projects can yield ecological and human benefits well into the future.

In the context of restoration, it is important to remember that sea level rise is just one threat to tidal wetlands. It is essential to consider not only other climate change impacts, but also other impacts (such as sediment supply, anthropogenic modification of water flow and nutrient loads, human-induced wave action causing erosion, etc.). These threats will vary geographically depending on tidal ranges, geomorphic setting, local bathymetry and substrate type. Although this guidance focuses on one potential threat, project managers must be sure to consider the range of factors that influence their site. Designing and implementing successful restoration projects may not be straightforward, but the benefits to human and natural communities can be both valuable and long-lasting.

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Appendix A: Surface water models used to predict sea level rise impacts on tidal wetlands

This appendix provides a brief discussion of the model classes available for modeling surface water dynamics in marsh restoration projects. There are a wide variety of hydrologic, hydraulic, and hydrodynamic models in use today, but not all are applicable for tidally-forced marsh restoration projects. Selecting the correct model for your application requires consideration of the dominant physical processes and driving forces in the wetland system, the overall complexity of the system, and the results desired from the model. This appendix does not provide a comprehensive list of the modeling tools and programs that are available, which are too numerous to describe and are constantly evolving. Instead we present a discussion of model classes and the types of physical conditions and processes best suited for each class. Also included for each class is a brief list of example models. With this information, a project manager should be better equipped to have an informed discussion with a hydrodynamic modeling expert who is proposing models for project use.

Analytical models

In some cases, simple analytical models that utilize standard governing equations of hydraulics, coupled with site-specific topography, bathymetry, and tide data, can be used to assess potential restoration projects. These types of models provide a simple procedure that calculates the exchange of water between the marsh system and the ocean, bay, or sound. They usually treat the marsh as an over simplified basin (defined by the hypsometry) that is filled or drained by the flooding and ebbing tide through the inlet, culvert, or flow structure. This approach is best applied in tidal wetland systems where the marsh is relatively simple. For example, for marsh systems that are not surrounded by critical upland infrastructure or where the system is comprised of a single relatively evenly distributed wetland area (e.g., coastal pond), the analytical modeling approach may be sufficient. These models are limited in their ability and function and should not be used in more complicated systems. For example, in wetlands where it is critical to accurately define the spatial distribution of the water within the marsh, wetting and drying processes are important, or the frictional impacts of the wetland itself may result in tidal attenuation throughout the system, these models are inadequate. Analytical models are typically developed in house by modelers and engineers and are just based on standard hydraulic equations, so there are no named examples.

Hydrodynamic models

Surface water flow in marsh environments varies over time and three dimensional space with changes in forcing mechanisms (e.g., tides, fresh water inputs, winds), topography, resisting forces (e.g., frictional effects), temporary storage, and other factors. To most effectively model this complexity, dynamic hydraulic models—those that accommodate time-varying inputs and are able to simulate other time-varying phenomena (e.g., wetting and drying)—are needed. Hydrodynamic models are typically distinguished by their geometric complexity; that is, whether they can simulate dynamic flow in 1, 2, or 3 dimensions (1-D, 2-D, and 3-D). For tidal wetland applications, 2-D and 3-D models are frequently needed, but in certain situations a 1-D model may suffice.

1-D Hydrodynamic Models

There are certain situations where a 1-D dynamic representation of the marsh setting may be adequate for the project purposes. These may include tidal wetland systems that are more riverine in form, consisting of a primary channel with a relatively consistent cross-section and minimal variation in marsh plains. They are useful in restoration projects that do not have significant infrastructure concerns, do not require engineering design considerations, or do not require accurate water surface, salinity, or habitat projections. These models typically include the ability to simulate bi-directional flow, produce accurate velocities, and can be used to determine potential scour at constriction within the system (e.g., bridge crossings). They lack the details of the estuary and wetland, do not accurately assess upland flooding and habitat loss/swapping, and most lack water quality and salinity processes. These models should not be applied in situations where the spatial distribution of the water within the marsh is important, in cases where there may be significant frictional effects of the marsh plains, or in systems that experience significant or complex wetting and drying processes. Example 1-D models include HEC-RAS (UNET) and DYNLET.

2-D and 3-D Hydrodynamic Models

Surface water flow is inherently a 3-D phenomenon, but for many marsh applications it can be adequately represented in 2-D. To do so, one dimension (frequently the depth dimension) is represented as an average (depth-averaged). For example, although velocity actually varies in the x, y, and z (depth) direction, 2-D models assume that velocity in the z direction is essentially uniform in depth. This assumption is usually reasonable for most system and does not significantly influence the hydrodynamics. 3-D models simulate the full range of physical processes, but can also be complex and costly. Yet in some more complex systems, 3-D processes can be important and may not be ignored. For example, in tidal estuaries and wetlands where significant salinity or temperature stratification exists, density driven circulation and vertical mixing can produce variations in the current fields that cannot be evaluated using a 2-D model. In these situations, a 3-D model is recommended.

2-D and 3-D models are applicable in most restoration cases that include alternative assessments, engineering design, and habitat and impact analysis. These models were developed to evaluate dynamic and multi-direction flows, specifically in estuarine and tidally-forced environments.

Most of the these models also have the capability to handle full wetting and drying for marsh plains, engineered flow structures, impacts of freshwater input and wind forcing, salinity and water quality parameter mixing, and sediment transport.

There are a number of potential models that are available for simulation of the tidal hydrodynamics; however, it is important to evaluate the applicability of a specific model for a project based on key considerations, including, but not limited to:

- Can the model adequately handle wetting and drying and shallow water flow?
- Is the model capable of simulating salinity processes and stratification?
- Can the model accurately simulate the engineering control structures and constrictions that are present or are being proposed for the restoration site?
- How does the model simulate flow resistance to vegetation and other wetland friction?
- Is the model capable of simulation storm impacts (both freshwater and storm surge), as well as sea level rise scenarios?

Example 2-D and 3-D models include the RMA family of models, FESWMS, EFDC,, FVCOM, Delft 2D/3D, and MIKE 21 and MIKE 3.

1-Dimensional hydraulic models

These models, founded in river hydraulics, have limited applicability in many marsh restoration projects. They were originally intended to simulate riverine processes, which are dominated by uni-directional, gravity flow as opposed to multi-directional, tidally-forced flow. In many cases, these models are inappropriate for simulating estuarine systems. However they can be useful in modeling flows in tidal rivers and channels as long as their limitations are recognized. They are limited in their ability for restoration applications since they typically only simulate uni-directional flow and lack wetting and drying capabilities. Example 1-D hydraulic models include the original HEC-RAS, DAFLOW and MIKE 11.

Hydrologic and watershed models

There are a number of terrestrial hydrologic models that users have attempted to apply to tidally-based estuarine restoration projects. However, these models, developed for simulating surface water runoff in watersheds, have limited capability for simulating marsh wetland systems. They were not developed to simulate dynamic, tidally-forced systems and are generally inappropriate for this purpose. These models are useful for providing input conditions (e.g., freshwater surface runoff during rainfall events) for the hydrodynamic estuarine models. Examples include Pondpack, TR-20, and HSPF.

Appendix B: Annotated bibliography of relevant documents, tools and workshops

I. Relevant Documents

These documents provide useful background on sea level rise, tidal wetland processes, and climate change adaptation strategies.

- United States Army Corps of Engineers (USACE). 2009. *Water Resource Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs.* Circular No. 1165-2-211. July 1, 2009. http://140.194.76.129/publications/eng-circulars/ec1165-2-211/entire.pdf

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II. Relevant tools and resources

- *Climate Change Information Resources for the Mid-Atlantic*: http://collaborate.csc.noaa.gov/climateadaptation/pages/chc.aspx?PageView=Shared&DisplayMode=Design. This website includes a resource guide and a wide range of documents and tools for the Mid-Atlantic and beyond compiled for a June 2010 workshop.
- *EcoAdapt Climate Adaptation Knowledge Exchange (CAKE):* http://www.CAKEX.org. The Climate Adaptation Knowledge Exchange (CAKE) is an innovative community website initiated by EcoAdapt and Island Press. This is a free online resource of data, tools, and best practices for adaptation. CAKE provides access to: case studies; a virtual library to support adaptation planning; adaptation community expertise, discussion, and opportunities; a directory of individuals and organizations working on adaptation; and tools for adaptation planning.
- *The Nature Conservancy Coastal Resiliency Project:* http://www.coastalresilience.org. This interactive mapping tool displays wetland vulnerability and coastal community threats associated with different inundation levels. It is currently focused on the south shore of Long Island, NY, but there are plans to expand its geographic focus in the future.

III. Relevant workshop resources and proceedings

- *Coastal Habitat Conservation in a Changing Climate - Strategies and Tools in the Mid-Atlantic Workshop*. June 21-23, 2010. Wilmington, DE. Sponsored by the NOAA Fisheries Office of Habitat Conservation and the NOAA Climate Program Office. http://collaborate.csc.noaa.gov/climateadaptation/pages/chc.aspx?PageView=Shared&DisplayMode=Design)
- *Adapting to Climate Change in the Mid-Atlantic.* March 23-25, 2010. Cambridge, MD. Sponsored by the Department of the Interior, the USDA Forest Service and NOAA. http://www.fws.gov/northeast/climatechange/conference/conferences.html)
- *AFWA Climate Change Committee Northeast Regional Climate Change Workshop.* June 15-16, 2010. Hadley, MA. Sponsored by the Association of Fish and Wildlife Agencies. http://www.fishwildlife.org/agency_science_NEClimateChangeWorkshop.html)

- *Climate Change in the Northeast: Preparing for the Future.* June 3-5, 2008. Amherst, MA. Sponsored by the U.S. Fish and Wildlife Service, U.S. Geological Survey, National Park Service, Minerals Management Service, National Oceanic and Atmospheric Administration, U.S. Forest Service, State of Massachusetts and the George Wright Society. http://www.fws.gov/northeast/climatechange/conference/ccintro.html

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