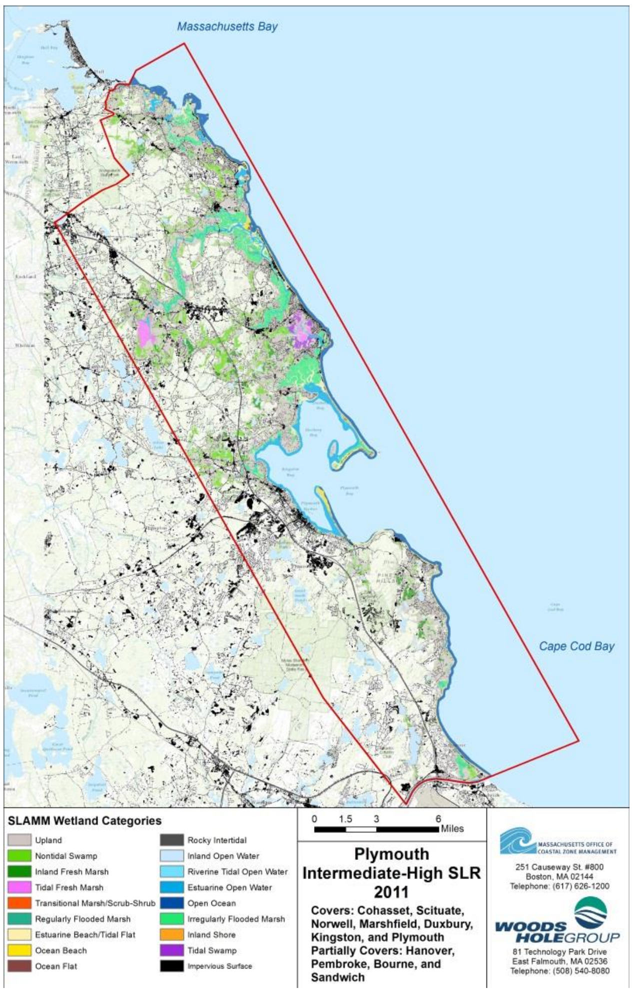
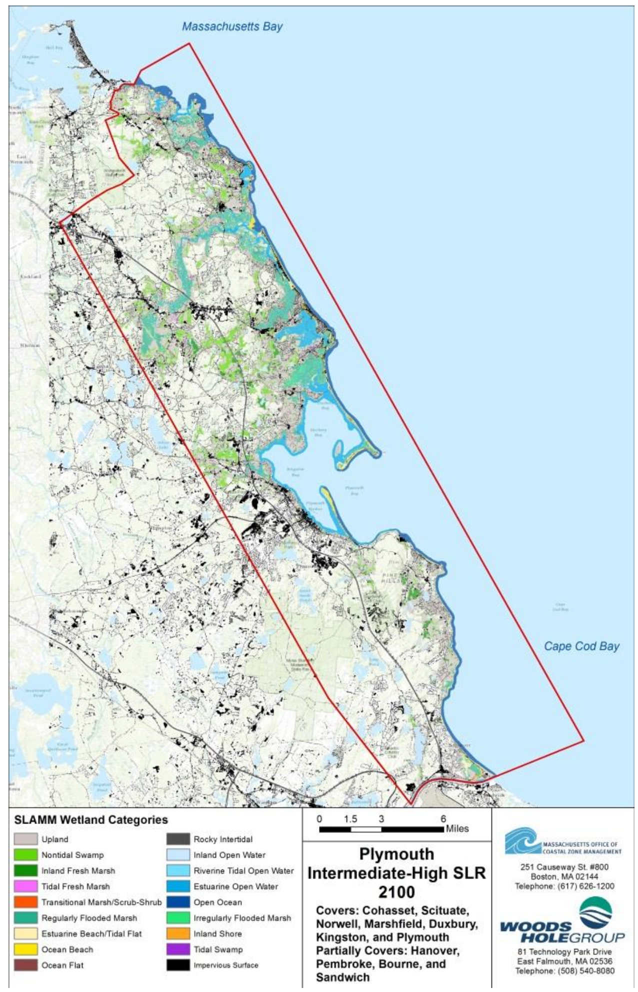
Modeling the Effects of Sea-Level Rise on Coastal Wetlands





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November 2016

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1.0 INTRODUCTION

The Massachusetts Office of Coastal Zone Management (CZM) has long been concerned with the impacts of storm damage, flooding, and erosion on coastal communities and vital natural resources and ecosystems. Climate change, with increased storm intensity, changes in precipitation patterns, and global sea-level rise will exacerbate already difficult coastal management issues faced by CZM on both infrastructure and natural resources (Bosma et al. 2015). Recent studies have identified sea-level rise as one of the most certain and potentially destructive impacts of climate change (Meehl et al., 2007). This document summarizes the methods utilized to evaluate the additional impacts on coastal wetlands that can be expected from projected sea-level rise scenarios across the coastal region of the Commonwealth of Massachusetts. The results of the assessment and modeling can be used to answer a number of important questions regarding the fate of coastal marsh systems throughout coastal Massachusetts. For example, results from the analysis and modeling can be used to assess if specific marsh systems have adequate space to migrate landward in response to the changing climate or if their migration may be hampered by topographic features or infrastructure and developed areas. The results of the modeling can also be used to determine the timeframe that a marsh's accretion rate can no longer be expected to keep up with the rate of sea-level rise, or over what timeframe specific resource areas within a marsh are expected to transition (e.g., high marsh to low marsh, or low marsh to tidal flats, etc.) due to climate change. By identifying a likely timeframe for these changes, coastal managers can plan their monitoring and conservation effects to be most effective. For example, targeted monitoring could be conducted at resource areas in transition to evaluate the need for restoration or best management practices (BMPs) for land use management. It is these types of questions that the proposed modeling effort presented herein attempts to target.

1.1 SEA-LEVEL RISE

Global mean sea level (MSL) has been rising since the end of the last ice age thousands of years ago. However, sea-level rise (SLR) rates have accelerated in recent times, with unprecedented rates along the northeastern U.S. since the late 19th century (Kemp et al., 2011). Global sea-level rise is driven by a number of factors, including thermal expansion of ocean water and freshwater inputs from melting glaciers and ice caps. As discussed in more detail below, global increases by 2100 may range from 0.2 m (0.7 ft) to 2.0 m (6.6 ft). At a local level, relative sea-level rise is a function of both global and regional changes. Local variations in sea-level rise result from factors such as vertical land movement (uplift or subsidence), changing gravitational attraction in some sections of the oceans due to ice masses, and changes in regional ocean circulation (Nicholls et al., 2014).

A consortium of government agencies has completed a National Climate Assessment (Parris et al., 2012) that provides guidance on the appropriate selection of Sea-Level Rise (SLR) scenarios. Under this guidance, four (4) projected rates of sea-level rise (highest, intermediate-high, intermediate-low, and low) are presented. Given the range of uncertainty in future global SLR, using multiple scenarios encourages experts and decision makers to consider a range of future conditions and to develop multiple response options. The highest scenario in Parris et al. (2012) surpasses the maximum of 1.2 m recently presented in the IPCC Fifth Assessment Report (AR5) WG1 material (shown in Figure 1-2). The highest scenario from Parris et al. (2012), combines thermal expansion estimates from IPCC SLR projections with the maximum possible glacier and ice sheet loss by the end of the century, and is therefore useful to consider "in situations where there is little tolerance for risk". A recent article by Bamber and Aspinall (2013) supports using a high sea-level rise projection based on the likely impact of glacier ice sheet melting. CZM also relies on the projections produced by Parris et al. (2012) in their sea-level rise guidance document (CZM 2013), as well as other state agencies, such as MassDOT and Massport. For these reasons, we recommend using the SLR scenarios presented by Parris et al. (2012) for the U.S. National Climate Assessment (Figure 1-1) as a basis for the distribution of potential increases in sea level by 2100. Additionally, the global sea level rise projections provided by Parris et al. (2012) must be adjusted to local, relative sea-level rise (RSLR) conditions (e.g., the difference in elevations between the sea surface and the land surface at a specific place and time) for this study. These adjustments are based on more recent work by Kopp et al. (2014) and use of Representative Concentration Pathways (RCPs) similar to the distribution of projections presented by Parris et al. (2012). These details are described in section 2.2.9 to arrive at the final RSLR values used in this analysis.

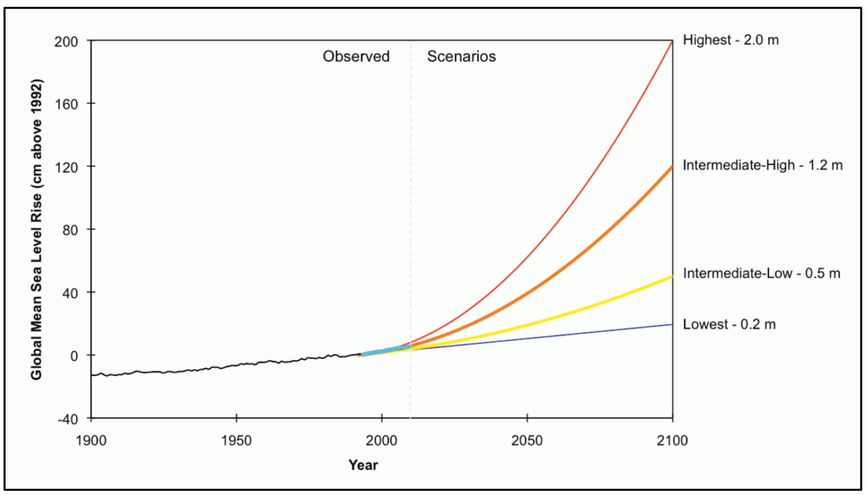

Figure 1-1. Projections of global future sea-level rise recommended in Parris et al. (2012).

The low-SLR scenario presented in Parris et al. (2012) is based on observed historical SLR trends, which can vary from region to region. For example, the long-term mean sea-level trend for Boston is increasing 2.80 millimeters/year with a 95% confidence interval of +/- 0.17 mm/yr based on monthly mean sea level data from 1921 to 2013. By comparison, the long-term mean sea level trend for Nantucket is increasing 3.55 millimeters/year with a 95% confidence interval of +/- 0.40 mm/yr based on monthly mean sea-level data from 1965 to 2013 (Figure 1-3). While these observed differences are compared over different total time periods, they do represent the data presented by NOAA (2014a) and are measures of the observed relative sea level rise that has occurred at each location since data observations were started. Additional comparisons could be made to compare the actual relative sea-level rise that occurred over the same time period, which would demonstrate the more near term trends in spatial changes of relative sea-level rise. However, using these published numbers as an example, Boston would therefore experience a relative SLR of 10.36 cm by 2050 from 2013 if current rates continued in a linear fashion (equivalent to low-SLR estimates), while Nantucket would experience 13.14 cm of relative SLR from 2013 in the same time period. These differences are primarily due to local variations in subsidence (the sinking or lowering of the Earth's surface owing to subsurface movement of earth materials). Subsidence can be caused by ground water withdrawals, underground mining, drainage of organic soils, and natural compaction (Galloway et al., 1999). Therefore, given the same rate of mean sea-level rise, an area with higher subsidence will experience a higher relative sea-level rise than an area with lower subsidence.

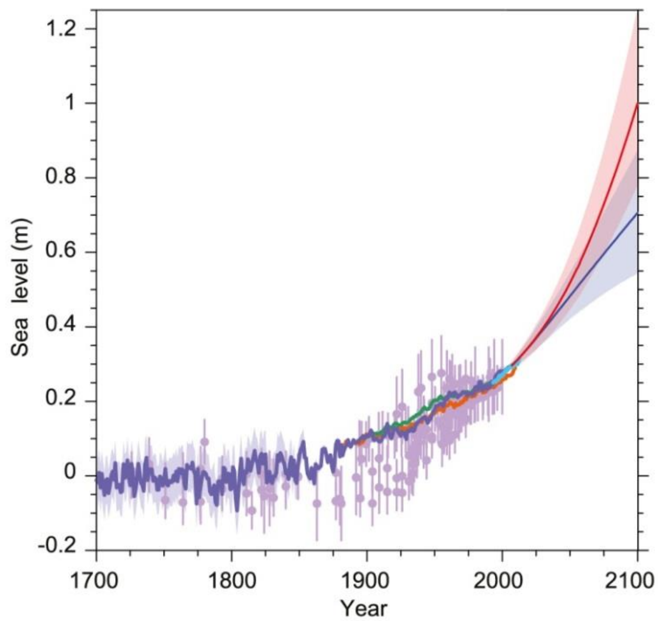

Figure 1-2. Sea-level rise projections in IPCC AR5 WG1. (Compilation of paleo sea level data, tide gauge data, and central estimates and likely ranges for projections of global-mean sea-level rise for RCP2.6 (blue) and RCP8.5 (red) scenarios, all relative to pre-industrial values.)

In this study, all four projected rates of global sea-level rise are used as presented in the United States National Climate Assessment (Parris et al., 2012) to investigate the impacts of sea-level rise on wetland distribution and marsh migration across Massachusetts. This includes the low, intermediate-low, intermediate-high, and high global sea-level rise projections. These global sea-level rise projections are adjusted to relative sea-level rise conditions using more recent studies by Kopp et al. (2014). Model results are evaluated for specific out years for each sea-level rise scenario (2030, 2050, 2070, and 2100). Additional details on the application of the projected sea-level rise and the model input parameters related to sea-level rise conditions are presented in Section 2.2.9.

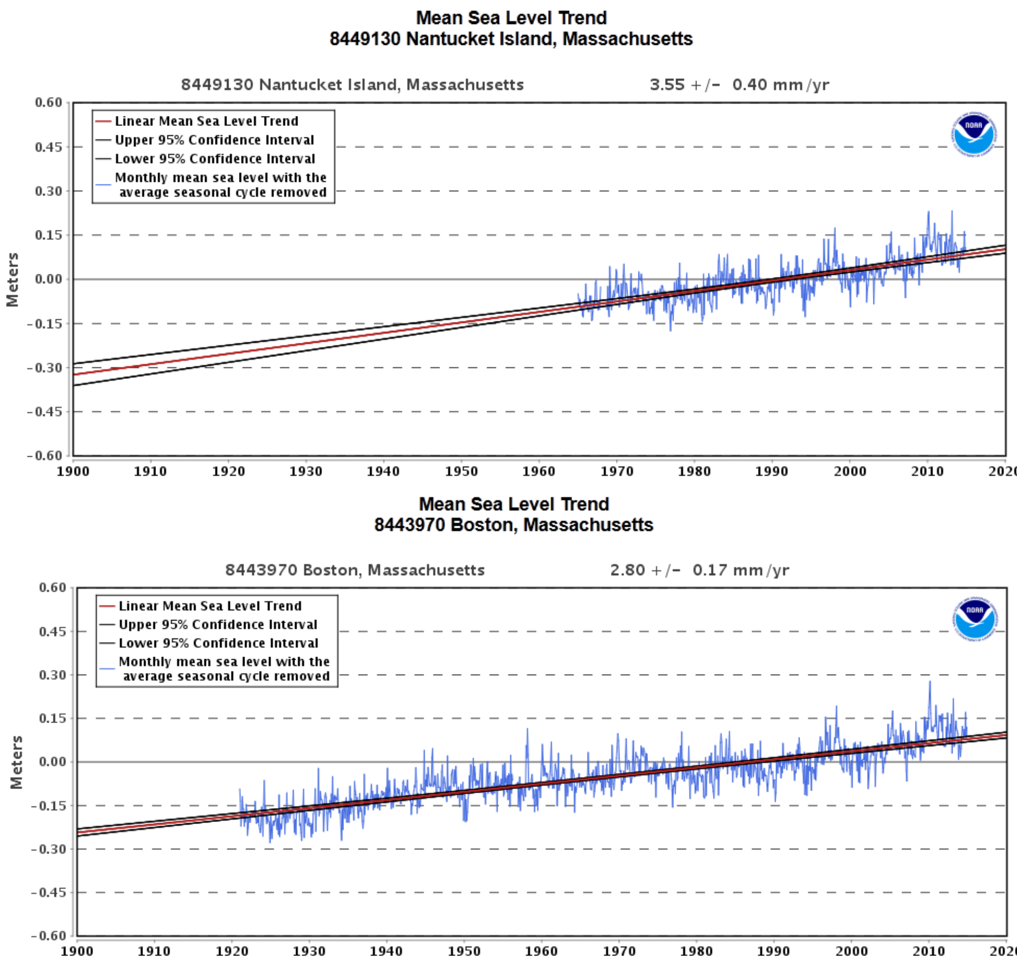

Figure 1-3. Comparison of mean sea-level rise trend at different locations in Massachusetts (NOAA, 2013). The upper panel shows Nantucket Island, while the lower panel shows Boston.

1.2 WETLAND CHANGE AS A RESULT OF SEA-LEVEL RISE

Coastal wetlands are among the most susceptible ecosystems to climate change, especially accelerated sea-level rise. Nicholls et al. (2009) points out that coastal wetlands, including salt marshes and intertidal areas, could experience substantial area losses due to sea-level rise. Because coastal wetlands are extremely productive ecosystems, and provide a variety of ecosystem services, such as flood protection, waste assimilation, nursery areas for fisheries, and conservation and recreation benefits, such loss would have a high human cost.

The vulnerability of tidal wetlands to accelerated sea-level rise depends greatly upon tide range, as well as local geologic conditions, such as subsidence and uplift. When considering the influence of tide range, macro- (> 4 m) and meso-tidal (2 – 4 m) marshes are less susceptible to sea-level rise than are micro-tidal (< 2 m) marshes (Craft et al. 2009). While, when local geologic conditions are taken into account, the Atlantic coast of North America is projected to have one of the highest losses of wetlands globally due to sea-level rise (Nicholls et al. 2009). This loss could result from tidal marsh submergence, as well as habitat migration, as salt marsh habitats transition landward, replacing existing tidal freshwater and brackish marshes in the process.

1.3 PROJECT OBJECTIVES

The Massachusetts coastal zone encompasses dozens of vital habitats, including, but not limited to, open water, salt marsh, barrier beaches and coastal dunes. These areas not only provide crucial habitat for numerous plants and animals, but also provide important ecosystem services for people, from providing recreational and economic resources to filtering pollutants and reducing the effects of storm damage along the coast. These resources also may provide resiliency to storm events under changing climate conditions. While the Commonwealth of Massachusetts has only approximately 200 miles of general coastline, due to the numerous bays and estuaries, the state actually has over 1,500 miles of tidal shoreline.

Recognizing the threats posed by climate change and sea-level rise, the Massachusetts office of Coastal Zone Management (CZM) has contracted the Woods Hole Group to assess and analyze the effects of sea-level rise on coastal wetlands for the Commonwealth of Massachusetts. To this end, Woods Hole Group worked collaboratively with CZM and other project partners, including the Marine Biological Laboratory's (MBL) Plum Island Ecosystems Long Term Ecological Research Program, to choose a suitable model, compile the most accurate data and determine the potential results of various sea-level rise scenarios on the area, extent, and resource types of the state's coastal wetlands. The project's intent was to simulate the effects of sea-level rise using an ecological model and implement the model at its highest level of complexity.

The results from this project are intended to be used for future coastal planning in a number of ways. For instance, model results from this project can be used to identify areas with barriers to landward migration of salt marshes. These results can therefore serve as a guide for development and implementation of adaptation strategies for coastal managers and policymakers to proactively address potential impacts from long-term sea-level rise.

2.0 METHODOLOGY

2.1 COMPARISON OF MODEL OPTIONS

The first task was the selection of an appropriate ecological model to assess the effects of sea-level rise on Massachusetts' coastal wetlands, including impacts, at least at a first-order level, on various resource types that exist within the Commonwealth. While not extensive, there are currently a number of open source ecological models available for evaluating the effects of sea-level rise on coastal wetlands. Each model option consists of its own strengths and weaknesses, as presented in the sections below. As such, the models were compared prior to selection of the most appropriate model to be used in the CZM study.

2.1.1 Model Comparisons

With a variety of models available, a short list of the most applicable models was developed that best met the goals of the project. This short list of models was compared and contrasted in an effort to ensure the selected model would provide the desired outcomes, while also maximizing the use of applicable and available input data. The final short list of models included the following four (4) ecologically based models:

1. SMART – Salt Marsh Assessment and Restoration Tool
2. ELM - Estuarine Loading Model
3. MEM – Marsh Equilibrium Model
4. SLAMM – Sea Level Affecting Marshes Model

While there are additional models potentially available that evaluate transitioning marshes and/or coastal wetlands ecology in differing fashions, the models listed here were most directly applicable for assessing potential impacts of sea-level rise on the natural system. Each model has a slightly different purpose for which it was designed (e.g., MEM focuses on the sedimentation rates as a function of time, SMART focuses on transitions between specific flora species in a wetland) and also model mechanics (e.g., time step or simulation period, spatial resolution, type of parameters simulated, required input data, etc.). A brief description of each of these four models, with respect to the attributes listed here, is provided below and summarized in Table 2-1.

Table 2-1. Comparison of model parameters.

Model	Time Step/ Simulation Period	Spatial Resolution/ Model Domain	Parameters Simulated/Output	Input Data Requirements	Typical Scenarios
SMART	Yearly; decadal time scale	Applied to system or regional scale; flood plain	Habitat: low/high/invasives by salinity category	Potential flood level (MHW, 4th largest, max); SLR; accretion/subroutine; salinity; plant composition; LiDAR	Predict habitat changes in marsh based on restoration alternatives; influence of sea level rise
ELM	Yearly; long-term	Watershed scale	Limited to transformations, availability, and export of nitrogen (inorganic and organic species)	Watershed nitrogen loads; water residence time; areas of open water; salt marsh and eelgrass meadows; average depth and tidal range	Predicting labile and refractory nitrogen in marsh/estuarine systems; understanding production rates of organic matter
MEM	Yearly; long-term (e.g., 100 years)	Regional/marsh scale units	Plant growth; sediment trapping; marsh plain elevation change	Plant biomass as a function of elevation; root:shoot quotient; turnover rate of BG biomass; refractory BG biomass; relative marsh elevation; tidal range; rate of sea-level rise; suspended sediment concentration and trapping coefficients	Long-term forecasts of marsh productivity and relative elevation
SLAMM	Yearly; long-term (e.g., 100 years)	Tens of meters or finer topography; wetland scale; upland edge/flood plain	Habitat: saline to fresh marshes	Existing habitats; tide range; sea-level rise; accretion by habitat; erosion rates	Predict habitat changes for sea-level rise or restoration alternatives

The objective of the Salt Marsh Assessment and Restoration (SMART) model is to predict habitat response to changes in hydrology associated with tidal restriction and/or restoration. Specifically, SMART focuses on the transition between marsh plant species (e.g., *Spartina alterniflora*, *Phragmities australis*, etc.) caused by a restoration project, or in this case, by sea-level rise. SMART was compiled as an ArcMap extension, so although it is free to download, it does require ArcMap software to operate. This model requires vegetation type, tidal elevations, projected sea-level rise, flow data, and LiDAR elevations as inputs, and outputs various resulting habitat classifications. Because SMART focuses on decadal simulation periods, it was not an ideal choice when trying to model potential long term impacts (out to 2100) of sea-level rise. In addition, SMART is ideally applied at a site-specific location where a high level of detail in the plant species is known. In this project, the entire Commonwealth of Massachusetts was being investigated at a high spatial resolution, and the specific plant species data were not readily available at the detail required to accurately simulate SMART for the entire State.

The focus of the Estuarine Loading Model (ELM) was developed to model nitrogen transformations and processes in estuarine systems. ELM requires information about nitrogen loads, depth, tidal range, and the extent of open water, salt marsh and submerged aquatic vegetation as inputs for calibration. Although ELM is a relatively simple, easy to apply model that accurately predicts nitrogen processes in Cape Cod estuaries, it was not suitable for the purposes of this project since it does not account for sea-level rise, is not a spatial model, and cannot predict changes in wetland type and extent over time.

The objective of the Marsh Equilibrium Model (MEM) is to forecast changes in marsh elevation. Required inputs include physical parameters, such as LiDAR elevations, sea-level rise rates, and suspended sediment concentrations, as well as biological parameters, such as aboveground to belowground biomass ratios, maximum, minimum, and optimal elevations for plant production, and organic matter decay rate. Some of the benefits of the MEM approach are that it can be run quickly using a spreadsheet-based model interface and can produce long-term predictions. Additionally, it can produce time-variable accretion rates, which would allow the model to adjust for changing conditions over time. However, this model's functionality is limited to specific habitat types, is more focused on its vertical elevation than changes in its horizontal extent, and is only accurate when location-specific accretion and suspended sediment data are available. However, as described herein, the MEMs utility to predict time-variable accretion rates was implemented concurrently with the overall modeling approach at specific pilot sites where data were available. This allowed for comparison of model simulations with and without a time-variable accretion rate integrated into the analysis.

The final model considered for this project was the Sea Level Affecting Marsh Migration (SLAMM) model. The objective of the SLAMM model is to predict resource area responses to physical changes, such as sea-level rise. While the model allows for a significant amount of inputs, the most influential and important parameters are LiDAR elevations, wetland classifications, sea-level rise, tide range, and accretion and erosion rates for various habitat types. SLAMM incorporates all major processes into one model, can be run for long time periods, and can accommodate both large areas and relatively fine resolution. Ultimately, the SLAMM model was the most applicable ecological model for utilization on a project of this magnitude, which consisted of conducting a high spatial resolution assessment over a large spatial area (the coastal areas of the Commonwealth of Massachusetts). SLAMM also was developed explicitly to address the potential impacts that sea-level rise may induce on marsh systems, as such, SLAMM was selected for application on this project.

2.1.2 Recommended Modeling Approach

The Sea Level Affecting Marshes Model (SLAMM) was originally developed with EPA funding in the 1980s. Since then it has gone through a number of updates and iterations. The most recent update to the model, SLAMM 6.2, contains added capabilities and increased model flexibility than previous versions. Most notably, SLAMM 6.2 was developed as both a 32- and 64-bit version; the 64-bit software essentially has no limit to the amount of memory it utilizes (as opposed to the 4GB memory limitation on the 32-bit version). The 64-bit version therefore allows each individual simulation to analyze a larger area with a greater resolution than was previously possible.

The SLAMM model is best suited to the goals of this project because it attempts to capture the major coastal processes, at least at a rudimentary level, involved in wetland conversions and shoreline modifications expected to occur over a long term. The model functions by utilizing a flexible decision tree to evaluate changes between one type of coastal resource class and others. Each model domain is divided into cells of equal area; land cover class changes are simulated within each cell separately. The developers intended the cell size to range from 5 to 30 meters, depending on the size of the site and the scale of the input data available. Once the simulation has been processed, the model results are summarized in both tabular, as well as graphical (map) form.

SLAMM has the ability to incorporate a number of different input parameters, providing relatively detailed and comprehensive results compared to other ecological models. The

SLAMM model computes relative sea level change for each cell in each time step. In addition to the effects of inundation, second-order effects occur due to changes in the spatial relationship to various coastal processes, such as wave action. For example, if the fetch for wind-driven waves is greater than 9 km, the model assumes moderate erosion. However, if the cell is exposed to the open ocean, severe erosion of wetlands is assumed. Where abundant freshwater wetlands are present, their changes are more often linked to salinity penetration rather than solely to inundation levels.

Although SLAMM was selected as the primary model, MEM results can be incorporated into SLAMM as time-variable accretion rate input parameters, and the models can used in tandem. SLAMM allows accretion rates to be entered as an average or site-specific value for each wetland category, or as a time-varying function of cell elevation, wetland type, salinity, and distance to channel. Therefore, at pilot locations where MEM results existed, site-specific marsh accretion rate curves, showing how accretion rate varies over time, could be generated to provide the necessary SLAMM input values to provide an increased level of analysis related to the projected marsh accretion rates. This was assumed to provide a more detailed level of analysis, with potentially improved accuracy at these locations. However, accretion data required for MEM simulations were not available throughout the State, therefore, in order to provide consistency in results for the entire Commonwealth, simulations were conducted without using MEM input for all project sub-regions (see Section 2.4). In the pilot locations, simulations were conducted both using MEM results and without using MEM results.

2.2 INPUT DATA (SOURCES, SELECTION, AND FORMATTING)

2.2.1 Elevation (and Slope)

High resolution elevation data may be the most important SLAMM data requirement, since the elevation data demarcate not only where salt penetration is expected, but also the frequency of inundation for wetlands and marshes when combined with tidal range data. Input elevation data also helps define the lower elevation range for beaches, wetlands and tidal flats, which dictates when they should be converted to a different land-cover type or open water due to an increased frequency of inundation.

For the most accurate results, bare-earth LiDAR should be utilized to run the SLAMM model. For this project, LiDAR data were acquired from MassGIS, which publically serves up multiple sets of LiDAR data that cover most of eastern Massachusetts, including all of the Massachusetts coastline and the islands. However, because each LiDAR dataset originates from a separate survey the various datasets are not always consistent in regards to horizontal coordinate system, vertical datum, vertical and horizontal units, and date. As such, all files were converted to a consistent set of units prior to utilization: Massachusetts State Plane Coordinate System (2001) as the horizontal coordinate system, the North American Vertical Datum (NAVD) (1988) as the vertical datum, both in units of meters (see Section 2.2.10).

The majority of the state was observed under the 2011 USGS Northeast LiDAR project, but to achieve full state coverage, additional LiDAR datasets were also utilized. Notable exceptions to the 2011 USGS Northeast LiDAR data set are the western shore of

Buzzards Bay, the Elizabeth Islands, Martha's Vineyard and Nantucket. These areas were covered by the 2013/2014 USGS Sandy LiDAR flight. Finally, no single LiDAR dataset covered the entire Boston model area, so a LiDAR mosaic was created for this region by combining various datasets including the 2009 City of Boston LiDAR, the 2010 Quincy LiDAR acquired by FEMA, the 2011 LiDAR for the Northeast acquired by USGS, and the 2002 Boston Area LiDAR. These were utilized, in order of most recent date. Table 2-2 summarizes the year of LiDAR data utilized for each region analyzed.

Table 2-2. LiDAR datasets utilized for regional panels.

Region	LiDAR Date		Region	LiDAR Date
Great Marsh	2011†		Buzzards Bay East	2011
North Shore	2011		Buzzards Bay West	2014
Boston	2010*		Taunton River	2011**
Plymouth	2011		Elizabeth Islands	2010
Cape Cod Bay	2011		Martha's Vineyard NE	2013
Cape Cod – Provincetown	2011		Martha's Vineyard South	2013
Cape Cod – Monomoy	2011		Martha's Vineyard NW	2013
Cape Cod – Vineyard Sound E	2011***		Nantucket North	2013
Cape Cod – Vineyard Sound W	2011***		Nantucket South	2013

†The Great Marsh panel also incorporated edited LiDAR acquired from CZM.
***Combined 2009, 2010, 2011, and 2002 LiDAR datasets to acquire full coverage for the Boston panel.**
****Also included portions of the 2010 Narragansett River LiDAR.**
*****Also incorporated some portions of the 2010 Dukes County LiDAR.**

These LiDAR datasets were not only used as a direct input into the SLAMM model, but were also required to develop the slope input data file. The slope for each raster cell was calculated based on the LiDAR data using ESRI ArcMap tools, and output as percent values consistent with the SLAMM technical documentation.

In order to reduce processing time within the SLAMM model, areas of higher elevation within each regional panel that are well above the elevations that would be affected by coastal processes, such as sea-level rise, wave run-up, and wave overtopping, were excluded prior to processing. Therefore, all areas above an elevation of 60 feet (NAVD88) were clipped from the input files. Since SLAMM calculations are carried out on a fixed grid basis (e.g., 5 meters x 5 meters), this approach significantly reduces the computational requirement, and allows increased overall resolution considering the complex shorelines that make up the Massachusetts coast. Figure 2-1 shows an example of how this approach reduces the calculation requirements, as well as output size, in the SLAMM model. The red box in Figure 2-1 shows the SLAMM model extents for this particular Massachusetts panel (Essex County). The white areas within the red box have been eliminated from the calculation. SLAMM can be set to not process cells containing "No Data" in the elevation input file. By excluding high elevation areas, each model simulation can include much larger regions in a single model panel, ultimately reducing the total amount of model runs needed to complete the SLAMM analysis for the entire Massachusetts coastline. This also allows for increased resolution within each model panel.

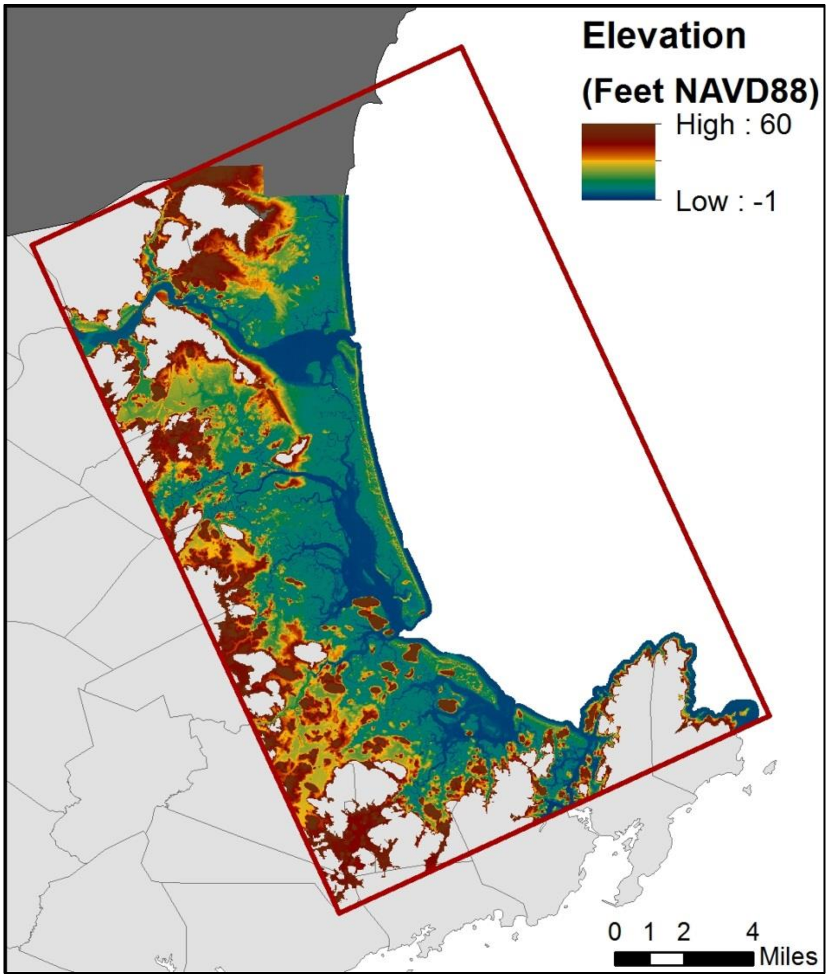

Figure 2-1. Elevation input example. Elevations above 60 feet (NAVD88) have been clipped prior to processing.

Finally, since SLAMM processes all elevations referenced to Mean Tide Level (MTL), one additional input parameter is needed to ensure SLAMM interprets the elevation input file correctly. All LiDAR data utilized in this study have a vertical datum of NAVD88 in meters. Therefore, a correction factor was necessary to adjust the LiDAR data to a MTL datum. The SLAMM model contains a solution to this problem through one of its input parameters: a vertical datum conversion. The value allows the user to specify the conversion between MTL and NAVD88. Different NAVD88 to MTL conversion values were utilized for each of the 18 model runs because the relationship between MTL and NAVD88 varies regionally. The conversion was determined using a vertical datum transformation tool (VDatum) developed by the National Oceanic and Atmospheric Administration (NOAA). Although there may be slight differences in the conversion factor between the extreme north and south edges of an individual panel, given the SLAMM model input limitations, a single conversion factor was utilized for each panel. The conversion values used for each model run are listed in Table A-3 in Appendix A in the column titled "NAVD to MTL." Additionally, the input data files included with the companion hard drive to this report contain all the associated datum conversions for each model panel.

2.2.2 Wetland Classifications

Consideration was initially given to the publically available MassDEP polygon wetlands layer, created through photointerpretation of stereo color-infrared (CIR) photography captured between 1990 and 1993. However, given that this layer represents wetland classifications and boundaries from more than 20 years ago, a more recent source of wetland data was desired. While MassDEP was currently in the process of updating this layer, it was still not publically available. After careful consideration, the 2011 wetland layer developed by the National Wetlands Inventory (NWI) was ultimately chosen as the source for the wetlands input file for the SLAMM modeling project presented herein. This 2011 NWI dataset was created by using the 1990s MassDEP wetland layer as a starting dataset, and then updating it with more recent photointerpretation from 2008 and 2011 imagery.

Utilizing the NWI data had two key benefits over the MassDEP wetland layer. First, the NWI data not only provided a more recently updated dataset, but also one that closely matched the time of the LiDAR data. Although slightly different LiDAR data sets were used (See Section 2.2.1), a vast majority of the LiDAR data used was collected in or around 2011. This allows the date of the NWI wetland input to be the same as the initial conditions date for a SLAMM simulation: 2011.

The second benefit to utilizing the NWI data is that it streamlined the conversion between source wetland categories and SLAMM wetland codes. First, NWI distinguishes regularly-flooded and irregularly-flooded salt marsh, facilitating the transition to the required SLAMM wetland breakdowns. The MassDEP wetland layer, on the other hand, has only a single "salt marsh" category for these areas, which would have been difficult to automate the conversion to SLAMM wetland classifications. The documentation provided with the SLAMM software contains a key to convert each NWI classification to the wetland classification system used by SLAMM; there was no such guide for the conversion of MassDEP wetland classifications to SLAMM wetland codes. A summary of the entire conversion key is present in Table 2-3. Although there were a few illogical codes in the NWI dataset, these aberrant codes were the exception rather than the norm. For example, the "1" in "R1UBH" indicates it is a tidal riverine system, but the "H" is a nontidal modifier; R1UBH should therefore not actually exist as an NWI classification. Despite a handful of small coding errors such as this, the conversion key provided with the SLAMM documentation allowed for a relatively streamlined reclassification process.

2.2.3 Accretion

SLAMM allows for vertical accretion values (mm/yr) to be entered for numerous wetland types, including regularly-and irregularly-flooded marsh, tidal flat, tidal fresh marsh, tidal swamp, and swamp. However, there is little site-specific accretion data available for Massachusetts marshes and coastal wetlands. Therefore, in order to create a consistent set of panels across the entire Commonwealth, it was assumed that salt marsh accretion in Massachusetts has generally kept pace with sea-level rise to date. In other words, the rate of marsh accretion is approximately equivalent to the historical rate of sea-level rise. With this assumption in mind, we utilized the historical sea-level rise data from three different gage stations (Boston, Woods Hole and Nantucket) to arrive at an input value for vertical accretion rate for both regularly- and irregularly-flooded marsh. This doesn't mean that the accretion rates specified are expected to keep up with sea-level rise in the future (e.g., under expected sea-level rise acceleration scenarios), only that the accretion rates are similar to the historical rate of sea-level rise. Using this approach, results across the Commonwealth of Massachusetts can be compared and contrasted without the unknown factor of unmeasured accretion rates in most areas and measured accretion rates in others.

However, in some areas, measured accretion rates were available. For example, a series of surface elevation table (SET) platforms are being used to collect marsh accretion data in the Great Marsh area (Essex County). As such, as an example of how observed accretion rates, and specifically time-variable accretion rates, may impact the results produced by SLAMM, the Great Marsh panel was simulated both with an accretion rate equivalent to the historic sea-level rise rate, as well as with a time-variable accretion rate obtained from implementation of the MEM model. For more detail on how MEM results were utilized as accretion inputs, see Section 2.3.3.2.

Additionally, SLAMM has an input parameter for the rate of beach sedimentation, which is also entered as a vertical measurement of mm/yr. However, the process of beach erosion is more adequately handled directly in the horizontal erosion inputs to SLAMM, as described in Section 2.4, rather than in the vertical accretion inputs. There are shoreline change rates available for the entire coastline of Massachusetts based on historical aerial analysis readily available, and therefore, the beach erosion process seemed to be better represented by horizontal changes (erosion/accretion) than by an estimated vertical value.

2.2.4 Erosion

While SLAMM allows for vertical accretion to be accounted for in the regularly- and irregularly-flooded marsh, tidal flat, tidal fresh marsh, tidal swamp, and swamp resource types, erosion is generally handled through a horizontal-based rate in SLAMM. The horizontal erosion rates can be specified for marsh, swamp and tidal flat resource types. However, these erosion rates are triggered for marsh and swamp only when a 9 kilometer fetch length is met (to an open ocean or open inland water resource); while tidal flat erosion is assumed to occur at the open-water interface regardless of fetch length. In addition, when assigning an erosion rate to the tidal flat resource, that rate also applies to the estuarine beaches (conditioned by fetch length), as well as ocean beaches (conditioned by the Bruun rule implementation). So the erosion of tidal flats is also implanted at the beach locations (as long as a 9 kilometer fetch length exists adjacent to an estuarine beach resource) and at ocean beach locations (if the Bruun rule is not utilized). The maximum fetch length at each cell is determined by evaluating sixteen points around a compass for every cell that borders water, thus identifying the maximum fetch length on a cell-by-cell basis at the beginning of each model time-step.

Given the geography and geometry of much of the Massachusetts coastline, estuaries, and marsh systems, these limitations mean that the SLAMM processer will almost never utilize any specified erosion rate for marsh or swamp (due to the 9km fetch requirement). Based on the irreplaceable SLAMM fetch requirement, the lack of viable marsh erosion data, and the relative unimportance of these parameters as determined through a sensitivity analysis (Section 2.3), specification of the marsh and swamp horizontal erosion rates were not a focus of the data collection effort and were not assigned.

As mentioned, the horizontal erosion or accretion of a beach can be specified by utilizing the Bruun rule for shoreline change. However, this general approximation does not take into account the actual erosion and accretion rates that are observed along a dynamic coastline. Implementation of the Bruun rule would only result in a horizontal erosion rate in proportion to the sea-level rise rate, and not take into account the other important coastal processes that produce changes along the Massachusetts coastline. In addition, since there are relatively detailed data available that quantify the historic shoreline changes in the State of Massachusetts, utilization of the Bruun rule was an oversimplification of the actual horizontal beach erosion occurring along the coastline. As such, since the tidal flat erosion rate value can be used as a proxy for the erosion occurring on open ocean beaches (and since SLAMM does not have a specific parameter where the user can directly input the horizontal erosion rate of ocean beaches), the tidal flat erosion rate was utilized to specify the shoreline change on the Massachusetts shorelines within SLAMM. Since the rate of erosion of ocean beaches was considered important, erosion rates for tidal flats, and therefore ocean beaches, were derived from Massachusetts Coastal Zone Management (CZM) Shoreline Change Project data.

When shoreline change rates were generally uniform throughout a model panel, the average rate of change from all CZM shoreline change transects was used to calculate the ocean beach erosion rate. However, there were often areas, such as the one outlined in red in Figure 2-2, where much higher or lower rates of ocean beach erosion were observed. In these cases, a subset area was defined in SLAMM, and a separate erosion rate was specified for each subset (subset areas are further explained in Section 2.4.2.1). The erosion rate for a given subset area was calculated using the average of all the shoreline change rates within the subset boundary. In such a way, the subset approach allowed capturing areas of particularly high or low erosion, while still maintaining a level of data resolution appropriate for a statewide analysis. The erosion rate for the remainder of the panel area, outside the subset boundaries, was then calculated by averaging the rate of change from all the CZM shoreline change transects outside the subset area. These overall erosion rates for each panel are listed in Table A-3 in the "Tidal Flat Eros" column. Additionally, the subset boundaries are delineated by a shapefile included in the hard drive accompanying this report, and the erosion values utilized for each subset are listed in Table A-4 in Appendix A.

Table 2-3. NWI Category to SLAMM code conversion table.

		NWI Code Characters					
SLAMM Code	SLAMM Name	System	Subsystem	Class	Subclass	Water Regime	Notes
1	Developed Dryland	U					Upland
2	Undeveloped Dryland	U					Upland
3	Nontidal Swamp	P	NA	FO, SS	1, 3 to 7, None	A,B,C,E,F,G,H,J,K, None or U	Palustrine Forested and Scrub-Shrub
4	Cypress Swamp	P	NA	FO, SS	2	A,B,C,E,F,G,H,J,K, None or U	Needle-leaved Deciduous Forest and Scrub-Shrub
5	Inland Fresh Marsh	P	NA	EM, f**	All, None	A,B,C,E,F,G,H,J,K, None or U	Palustrine Emergents; Lacustrine and Riverine Nonpersistent Emergents
		L	2	EM	2, None	E,F,G,H,K, None or U	
		R	2, 3	EM	2, None	E,F,G,H,K, None or U	
6	Tidal Fresh Marsh	R	1	EM	2, None	Fresh Tidal N, T	Riverine and Palustrine Freshwater Tidal Emergen
		P	NA	EM	All, None	Fresh Tidal S, R, T	
7	Transitional Marsh / Scrub Shrub	E	2	FO, SS	1, 2, 4 to 7, None	Tidal M, N, P, None or U	Estuarine Intertidal, Scrub-shrub and Forested (ALL except 3 subclass)
8	Regularly Flooded Marsh	E	2	EM	1, None	Tidal N, None or U	Only regularly flooded tidal marsh; No intermittently flooded "P" water regime
9	Mangrove	E	2	FO, SS	3	Tidal M, N, P, None or U	Estuarine Intertidal Forested and Scrub-shrub, Broad-leaved Evergreen
10	Estuarine Beach	E	2	US	1,2	Tidal N,P	Estuarine Intertidal Unconsolidated Shores
		E	2	US	None	Tidal N,P	Only when shores
11	Tidal Flat	E	2	US	3,4, None	Tidal M, N, None or U	Estuarine Intertidal Unconsolidated Shore (mud
		E	2	AB	All, Except 1	Tidal M, N, None or U	or organic) and Aquatic Bed; Marine Intertidal Aquatic Bed
		E	2	AB	1	P	Specifically for wind-driven tides on the south coast of TX
		M	2	AB	1, 3, None	Tidal M, N, None or U	
12	Ocean Beach	M	2	US	1, 2	Tidal N, P	Marine Intertidal Unconsolidated Shore, cobble-gravel, sand
		M	2	US	None	Tidal P	
13	Ocean Flat	M	2	US	3, 4, None	Tidal M, N, None or U	Marine Intertidal Unconsolidated Shore, mud or organic, (low energy coastline)
14	Rocky Intertidal	M	2	RS	All, None	Tidal M, N, P, None or U	Marine and Estuarine Intertidal Rocky Shore and Reef
		E	2	RS	All, None	Tidal M, N, P, None or U	
		E	2	RF	2, 3, None	Tidal M, N, P, None or U	
		E	2	AB	1	Tidal M, N, None or U	
15	Inland Open Water	R	2	UB, AB	All, None	All, None	Riverine, Lacustrine, and Palustrine Unconsolidated Bottom, and Aquatic Beds
		R	3	UB, AB, RB	All, None	All, None	
		L	1, 2	UB, AB, RB	All, None	All, None	
		P	NA	UB, AB, RB	All, None	All, None	
		R	5	UB	All	Only U	
16	Riverine Tidal Open Water	R	1	All, Except EM	All, None, Except 2	Fresh Tidal S, R, T, V	Riverine Tidal Open Water
17	Estuarine Open Water	E	1	All	All, None	Tidal L, M, N, P	Estuarine subtidal
18	Tidal Creek	E	2	SB	All, None	Tidal M, N, P; Fresh Tidal R, S	Estuarine intertidal streambed
19	Open Ocean	M	1	All	All	Tidal L, M, N, P	Marine Subtidal and Marine Intertidal Aquatic Bed and Reef
		M	2	RF	1, 3, None	Tidal M, N, P, None or U	
20	Irregularly Flooded Marsh	E	2	EM	1, 5, None	P	Irregularly Flooded Estuarine Intertidal Emergent marsh
		E	2	US	2, 3, 4, None	P	Only when these salt pans are associated with E2EMN or P
21	NotUsed						
22	Inland Shore	L	2	US, RS	All	All Nontidal	Shoreline not pre-processed using tidal range elevations
		P	NA	US	All, None	All Nontidal, None or U	
		R	2, 3	US, RS	All, None	All Nontidal, None or U	
		R	4	SB	All, None	All Nontidal, None or U	
23	Tidal Swamp	P	NA	FO, SS	All, None	Fresh Tidal R, S, T	Tidally influenced swamp

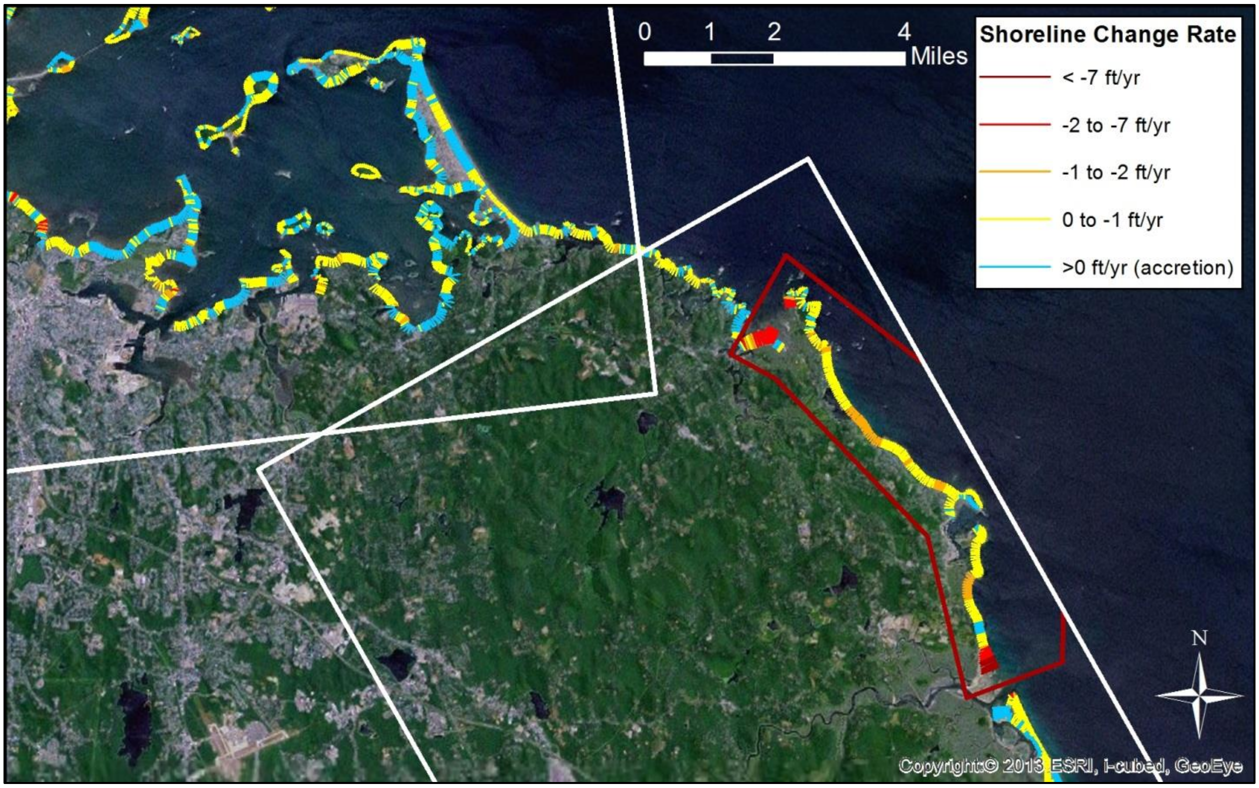

Figure 2-2. Example of CZM Shoreline Change Project data in the vicinity of the Boston and Plymouth map panels.

2.2.5 Tidal Range and Attenuation

As expected, tidal range is one of the most influential input parameters to the SLAMM model. Tidal range information is entered in meters as the "great diurnal tide range", which is equivalent to the difference between Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW).

Tidal range data for the open coastline were acquired from NOAA tide gage stations along the Massachusetts coastline. In many cases, there were multiple tide gages within the area for a single panel. In these cases, the average was calculated from all available tidal ranges within the panel's boundaries. A summary table of specific NOAA gages used to determine the tidal range input value for each panel is presented in Appendix A (Table A-1). These data, however, only accurately represent the tidal range along the open coast and do not account for any attenuation to the tidal range that may occur as the tide propagates into the coastal estuaries, marshes, and rivers throughout the Commonwealth. At its basic level, SLAMM applies a singular tidal range for the entire model area (or panel). WHG and CZM wanted to improve the predictive nature of SLAMM, and as such, applied tidal attenuation throughout the SLAMM panels by sub-setting the model into areas of reduced tidal range. In addition, this reduction in tidal range, while existing in the present day, may not continue into the future as barrier beaches, roads, culverts, etc. become unrestricted due to future sea-level rise water levels or ongoing erosion. Therefore, these tidal restrictions were also adjusted as a function of time. In other words, tidal attenuation was removed if a road was overtopped, etc. due to the rising water levels.

Based on the tidal range information collected, 191 water bodies with potentially restricted tidal ranges based on the state Atlases of Tidal Restriction were identified. This included sites identified as potential barriers by project partners. In many cases, these restrictions are caused by manmade structures. For example, many culverts attenuate the tidal range significantly, and some estuarine systems contain more than one of these restrictions. From this initial list, we identified 35 locations (Figure 2-3) where tidal data were available and the restricted waterbody was sufficiently large to incorporate this information into the model. Including every small tidal restriction throughout the state was outside the scope of this project. However, additional smaller restrictions could be added for more locally focused projects in the future.

Through the incorporation of tidally restricted subsets, the hydraulics within the SLAMM model can be vastly improved, so as not to overestimate the tidal range in restricted waterbodies, while still maintaining a full tide range along the open coast within the same model simulation. Data for the tidal ranges within these restricted sites was acquired from a variety of sources, including regional Atlases of Tidal Restrictions produced for the Massachusetts Wetlands Restoration Program, Massachusetts Estuaries Project Reports, as well as site and project specific data collected by Cape Cod National Seashore, Division of Ecological Restoration, and Woods Hole Group; for a detailed list of sources used for the 35 selected sites, see Table A-2 in Appendix A.

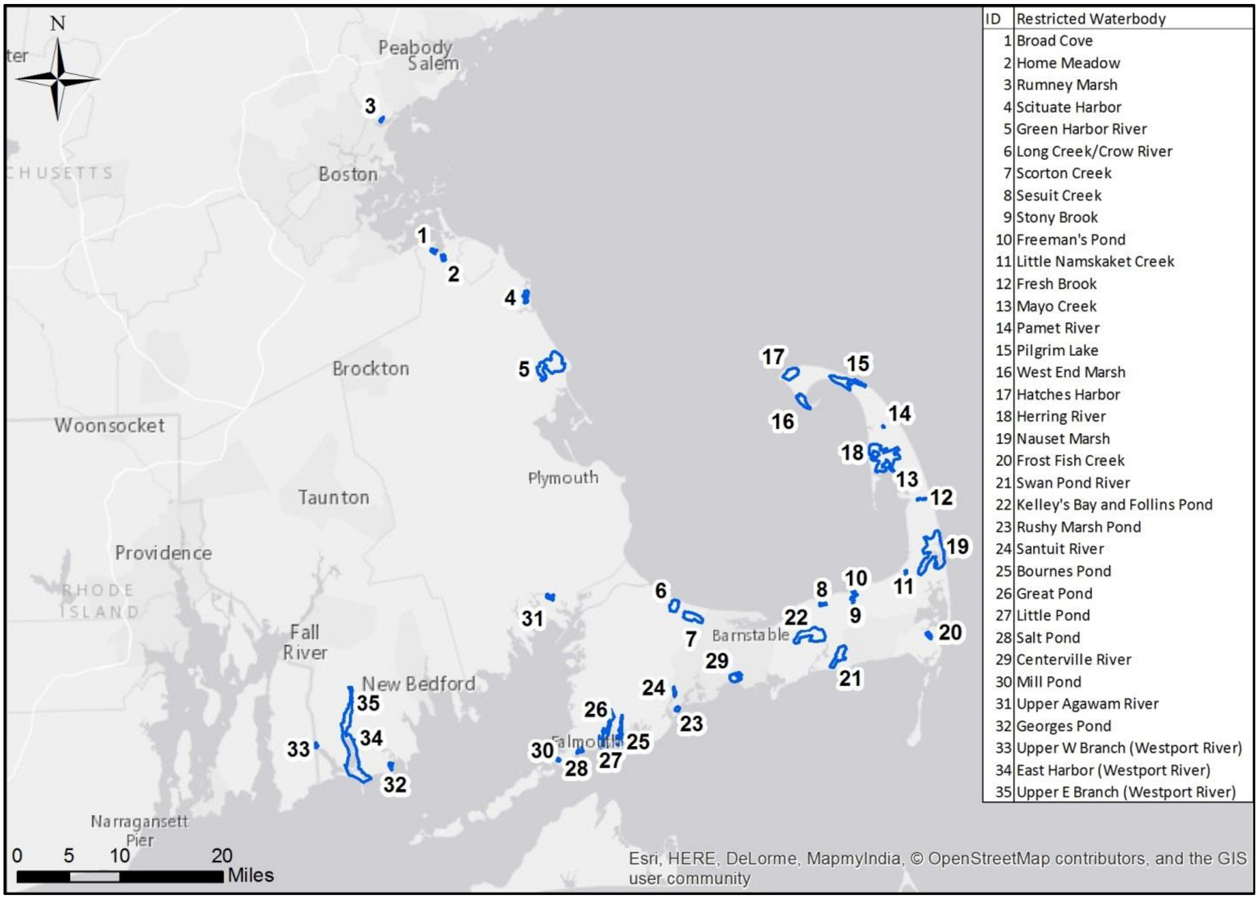

Figure 2-3. Tidally restricted waterbodies included as subsets in SLAMM simulations.

The 35 sites depicted in Figure 2-3 have a restriction in tidal range given present day conditions and sea level. However, as conditions change in the future, these restrictions may be removed, either through human intervention in the form of wetland restoration and culvert removal, natural or anthropogenic widening, erosion, or through change in water levels as sea level rises. Therefore, not all existing tidal restrictions are likely to persist until 2100. Based on the elevations of each location and the sea-level rise projection utilized for this project, as well as knowledge about planned restoration projects, if it was determined that a water body would most likely become unrestricted before 2050 given a particular sea-level rise scenario, we did not include that restriction location in that model simulation. However, if the waterbody did not become unrestricted until after 2050, or showed no indication of becoming unrestricted at all within the time frame of this project, a subset with a restricted tidal range for that location was included. Table 2-4 presents a summary of the major tidally restricted water bodies that were used in the SLAMM modeling. An ‘X’ indicates that the tidal restriction is expected to exist past 2050 for that sea-level rise scenario, and was therefore applied to that particular SLAMM simulation. In some cases, like Freeman’s Pond, there is currently a restoration project planned for that near future that would remove the tidal restriction in that system, so that site was not included as having a tidal restriction for any of the SLAMM scenarios.

2.2.6 Freshwater Parameters

SLAMM also allows users to specify major sources of freshwater flow, and to characterize that source through parameters such as river flow and salinity. Flow information was gathered from the United States Geological Survey (USGS) river gages (Table 2-5). The most recent ten years of flow data were averaged to develop a mean flow for each station; for sites with less than ten years of data available, all available data were used. In some cases, such as the Taunton River and the Merrimack River, multiple USGS gages were present along various tributaries of the same main river system. For these multi-gage river systems, mean flow (m^3/s) from each tributary was summed to calculate a total flow for each river. For example, the total flow for the Taunton River was calculated by summing the mean flow from the five (5) tributary sections listed in Table 2-5 arriving at a total flow of 27.9 m^3/s.

The other two main freshwater parameters that can be set for each freshwater source are salinity and slope of salt wedge. For all freshwater subsets created, the salinity of the upstream fresh water input was entered as 0 ppt, while the salinity of salt water input (at the mouth of the river at the ocean or bay) was entered as 30 ppt. The slope of salt wedge (m/m) parameter was set at 0.1 for all runs, which is the default value recommended in the SLAMM user manual. A sensitivity assessment of this value was also conducted to see if the slope of the salt wedge had a significant influence on the results produced by SLAMM. Even wildly changing this value had an insignificant to minimal impact on the results of the SLAMM simulation.

Table 2-4. Tidally restricted waterbodies for each sea-level rise scenario.

ID	Waterbody Name	Tidally Restricted at Various SLR Scenarios			
		Low	Intermediate Low	Intermediate High	High
1	Broad Cove				
2	Home Meadow	X	X	X	X
3	Rumney Marsh	X	X	X	X
4	Scituate Harbor	X	X	X	X
5	Green Harbor River	X	X	X	X
6	Long Creek/Crow River	X	X	X	
7	Scorton Creek	X	X	X	X
8	Sesuit Creek	X			
9	Stony Brook	X	X		
10	Freeman's Pond				
11	Little Namskaket Creek	X	X	X	X
12	Fresh Brook	X	X	X	X
13	Mayo Creek	X			
14	Pamet River	X	X	X	X
15	Pilgrim Lake	X	X	X	X
16	West End Marsh	X			
17	Hatches Harbor	X	X	X	X
18	Herring River				
19	Nauset Marsh	X			
20	Frost Fish Creek	X	X		
21	Swan Pond River	X	X	X	
22	Kelley's Bay and Follins Pond	X	X	X	X
23	Rushy Marsh Pond	X			
24	Santuit River	X	X	X	X
25	Bournes Pond	X	X	X	X
26	Great Pond	X	X	X	X
27	Little Pond	X	X	X	
28	Salt Pond	X	X	X	X
29	Centerville River	X	X		
30	Mill Pond	X			
31	Upper Agawam River	X	X	X	X
32	Georges Pond				
33	Upper West Branch (Westport River)	X	X	X	X
34	Westport River East Harbor	X	X	X	X
35	Upper East Branch (Westport River)				

Table 2-5. USGS gages used to develop freshwater input parameters for SLAMM.

River	Tributary/Section	Town	USGS Gage #	Mean Flow m3/s
Paskamanset River		South Dartmouth	01105933	1.7
Mattapoisett River		Mattapoisett	01105917	2.7
Quashnet River		Falmouth	011058837	0.6
Herring River		North Harwich	01105880	0.3
Jones River		Kingston	01105870	1.2
Taunton River	Segreganset River	Dighton	01109070	0.7
	Three Mile River	Dighton	01109060	5.2
	Mill River	Taunton	01108410	2.7
	Wading River	Norton	01109000	2.4
	Taunton River	Bridgewater	01108000	16.9
Indian Head River		Hanover	01105730	2.0
Whitmans Pond		East Weymouth	01105608	0.2
Monatiquot River		East Braintree	01105583	1.4
Town Brook		Quincy	01105585	0.1
Neponset River		Milton	011055566	9.0
Charles River	Charles River	Waltham	01104500	10.7
	Beaver Brook	Waltham	01104501	0.6
Mystic River	Aberjona River	Winchester	01102500	1.2
	Alewife Brook	Arlington	01103025	0.3
Saugus River		Saugus	01102345	1.0
Ipswich River	Ipswich River	Middleton	01101500	2.5
	Ipswich River	Ipswich	01102000	7.0
Parker River		Byfield	01101000	1.3
Merrimack River	Merrimack River	Lowell	01100000	286.1
	Shawsheen River	Andover	01100627	4.1
	Beaver Brook	North Pelham, NH	010965852	2.6
	Spicket River	Methuen	01100561	3.4

2.2.7 Dikes/Dams

SLAMM allows for dikes and dams to be entered as an additional input raster to the model. The elevation of these structures can be entered on a cell by cell basis, where structure elevations are provided in the same vertical datum and units as the input elevation raster. Only structure locations need to be specified, rather than identifying areas that are protected or unprotected by the dam as required in previous versions of SLAMM. During the simulation, SLAMM evaluates potential inundation path using an internal connectivity algorithm.

The recent SLAMM version allows the more realistic input of dam elevations, to more appropriately model water flows as function of sea level. Dams are effectively treated as a barrier with a specific elevation, which prohibits tidal exchange or sedimentation upstream until the water levels exceed that elevation downstream. Once that elevation is reached, then the estuary is no longer restricted by the dam.

Massachusetts contains almost 3,000 dams, of course not all of them are along the shoreline or influence tidally driven waters. Figure 2-4 shows the geographic distribution and density of these structures across the state. Unfortunately, there is minimal available data on the crest elevations of these structures, and it was outside the scope of this project to research and collect such information. However, in the opinion of the project team and stakeholders, this is unlikely to significantly affect the project results. Most dams in Massachusetts are relatively small and are at the end of their designed life. With a high number of structures likely to fail in the coming decades, coupled with the recent trend in Massachusetts of dam removal, most of the structures along the coastal regions either will no longer be present, or at the very least, no longer be functional by 2100. In addition, many of the coastal dams or flow control structures along the coastline are designed for storm protection; to inhibit storm surge from propagating upstream. In many cases, these dams and other flow control structures are designed to allow normal tidal exchange and thus would not inhibit a relatively small (compared to storm surge) increase in mean water surface elevation that would be caused by a sea-level rise scenario. Many of the other coastal structures are relatively small and have minimal impact on the overall marsh migration results. Similar to the tidal attenuation adjustments, including every small tidal control structure was outside the scope of this project; however these features could be extended using the base panels presented herein for more locally focused projects.

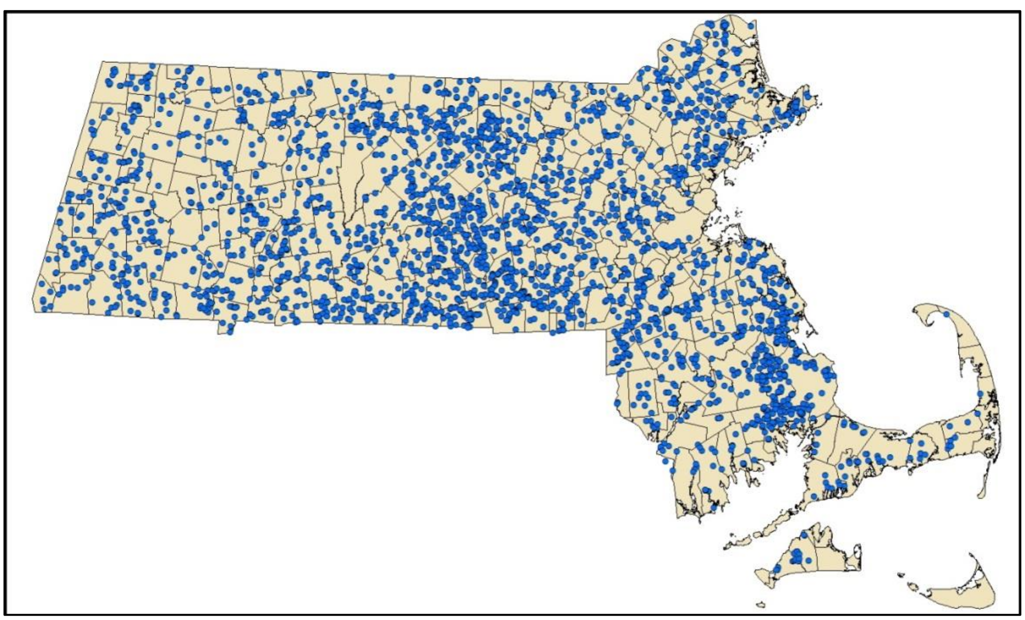

Figure 2-4. Locations of all dams in Massachusetts.

Two major dams that exist within the Commonwealth were directly included in the SLAMM modeling effort. The Charles River Dam in Boston and Cambridge and the Amelia Earhart Dam on the Mystic River in Somerville and Everett (Figure 2-5). Both of these structures provide major flood control functions for the surrounding Boston metropolitan area and are currently regularly maintained and operated to keep upstream water levels at certain elevations. Unlike many of the small dams statewide, these dams will likely persist and receive regular maintenance for the foreseeable future since they protect major urban infrastructure from both coastal storms and climate change conditions. As such, these two dams, with their associated crest elevations were input as a dam raster in the Boston regional panel model run.

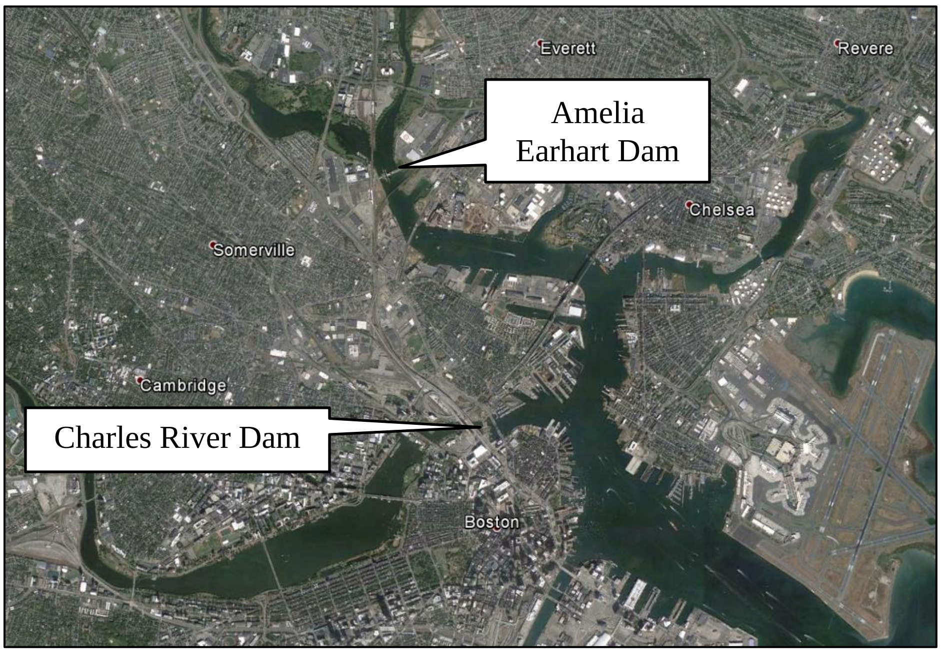

Figure 2-5. Location of the Charles River Dam and the Amelia Earhart Dam.

2.2.8 Impervious Surface

The SLAMM model provides the opportunity to include impervious surface data as an input data source. Impervious surface is entered as a percent imperviousness raster; any dry land with a percent imperviousness greater than 25% is assumed to be "developed dry land".

MassGIS provides an Impervious Surface raster layer for the entire state of Massachusetts with a 1-meter cell size. The surfaces were extracted using semi-automated techniques from April 2005 color orthoimagery. Impervious surfaces are defined as all constructed surfaces, such as buildings, roads, parking lots, brick, asphalt and concrete, as well as area of man-made compacted soil or material, such as mining or unpaved parking lots.

While this MassGIS raster could have been scaled and used as input in the SLAMM modeling scenarios, the decision was made not to incorporate impervious surface data into the SLAMM runs. Allowing the SLAMM model to utilize the impervious layer would "protect" developed upland areas (i.e. impervious areas would not be allowed to convert to other land cover types); however, this approach would have prohibited marshes and wetlands from expanding into currently "developed" areas. While in reality this may likely happen (marsh migration would halt at the impervious boundary), this approach to the modeling does not inform stakeholders where the marsh may desire to migrate given the elevation landscape if the impervious features were absent. Since one of the project goals was to determine how and where the marsh may want to migrate in response to sea-level rise, it was desired to determine which systems were susceptible to ecological losses due to inability to adjust to the changing climate both independent of the impervious landscape and with it in place. As such, the SLAMM model simulations were run without the impervious layers and subsequently the impervious layer was also overlain on the results. As such, although the impervious surface layer was not included as part of the model simulations, it was incorporated into the post-processing procedures. By overlaying the impervious surface layer on top of the "unprotected" SLAMM results, one could identify areas where marshes would likely migrate if given the opportunity, as well as areas where this marsh migration will intersect developed areas. Therefore, both results can be evaluated to better target and plan management activities, and identify specific areas that may be prone to loss of habitat. For example, marshes that are restricted from migration due to either infrastructure concerns or natural elevations may be systems that require focused attention for improved deposition or marsh restoration projects (e.g., thin layer deposition).

2.2.9 Sea-Level Rise Projections

SLAMM contains a variety of built in sea-level rise scenarios based on the Intergovernmental Panel on Climate Change (IPCC) projections, but the recent update to the SLAMM model allows for custom, user-specified sea-level rise end values. Based on a user entered end value, SLAMM will effectively scale the IPCC's A1B[1] scenario to estimate time-varying sea-level rise that will result in the specified degree of sea-level rise by 2100. As such, while this approach does not allow user-specified rates, it does allow specification of a specific amount of sea-level rise expected by 2100 using the most recent projections and scenarios.

To ensure we utilized location-specific sea-level rise rates, we compiled information on historic trends in local sea-level rise from NOAA water level gages in three different locations in Massachusetts:

1. Boston (8443970) – 2.80 mm/yr
2. Woods Hole (8447930) – 2.82 mm/yr
3. Nantucket (8449130) – 3.55 mm/yr

[1] The A1 scenario describes a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system distinguished by their emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (IPCC 2000).

The sea-level rise projections below (Table 2-6) indicate the total expected change in relative sea level between the start date of the model (2011) and the final out year (2100). Linearly projecting the historic rates listed above out into the future corresponds to the low sea-level rise scenario presented below. Intermediate-Low, Intermediate-High, and High sea-level rise scenarios correspond to the projected rates of sea-level rise developed by Parris et al. (2012) for the U.S. National Climate Assessment, and discussed earlier in this report, but are adjusted for relative conditions in the northeast, and specifically at the Boston, Nantucket, and Woods Hole locations.

Parris et al. (2012) presents projected rise in global mean sea level; however, over the 21st century and beyond, relative sea level will be influenced by several local and regional scale processes. For example, melting of land-based ice does not result in uniform sea-level rise across the globe due to the dispersion of mass, previously concentrated in ice. Locations near a melting ice sheet experience less sea-level rise than those further away. (Mitrovica et al., 2011). Melting of certain ice sheets will produce more or less relative sea-level rise for the Massachusetts coast. For example, if the West Antarctic Ice Sheet contributes more than the Greenland Ice Sheet, relative sea-level rise in Massachusetts will be substantially more than the global average. Projections of relative sea-level rise in previous studies (CZM, 2013; Bosma et al., 2015) do not include these considerations of the source of the meltwater and therefore may not accurately represent the relative sea-level rise.

Additionally, changes in the location and strength of ocean currents or prevailing winds may cause local changes in sea-level rise. For example, along the U.S. Atlantic coast, including Massachusetts, a dynamic sea-level rise can be triggered by a reduction in the strength or positioning of the Gulf Stream (Yin and Goddard, 2013; Kopp, 2013). Additional ocean dynamic mechanisms combined with thermal expansion (Yin, 2012) also can potentially produce higher relative sea-level rise along the New England coast.

Finally, the combination of glacial isostatic adjustment, tectonics, and sediment compaction, which is generally referred to as subsidence, must also be considered at a local level. Several estimates of net subsidence using various approaches and assumptions tend to yield similar results. Subsidence at the tide gauge locations utilized in this report (Boston, Nantucket, and Woods Hole) should be independent of climate change, so the observed subsidence rate at these locations is applied to the scenarios presented in Table 2-6.

In the current assessment, all these local factors are considered when assessing the relative sea-level rise rates considered. This takes into account the gravitational and rotational effects of changing land-ice mass, ocean dynamic effects, and land-water storage. As such, a probabilistic approach, utilizing a methodology similar to that developed by Kopp et al. (2014), is applied to determine a probability distribution of relative sea-level rise. Ideally, this would provide a distribution of relative sea-level rise rates with associated uncertainties for each scenario (e.g., intermediate-low [RCP2.6], intermediate-high [RCP4.5], and high [RCP8.5]); however, SLAMM only allows discrete input as an endpoint of the overall relative sea-level rise. Therefore, values presented in

Table 2-6 were selected from the overall distribution that fall within the 67% probability range (16.7th to 83.3rd percentiles) for each scenario. This range of probabilities is deemed the likely range by IPCC. These values (Table 2-6) were used as sea-level rise input values for the SLAMM model simulations. These values are expected to be continually updated as new information on contributing processes continues to evolve.

Table 2-6. Amount of sea-level rise predicted by 2100 based on historic sea-level rise data in three different locations (assuming a 2011 start time).

Scenario	Boston	Nantucket	Woods Hole
Low	0.249 m	0.316 m	0.251 m
Intermediate-Low (RCP2.6)	0.706 m	0.772 m	0.707 m
Intermediate-High (RCP4.5)	1.385 m	1.452 m	1.387 m
High (RCP8.5)	2.164 m	2.231 m	2.166 m

2.2.10 Overwash

SLAMM also includes an overwash feature that attempts to estimate, in a rudimentary way, the overwash process associated with barrier beaches. The theory is based on observations of existing overwash areas (Zaremba and Leatherman, 1986) and inputs need to be based primarily on professional judgment. Testing of the overwash module in SLAMM for the Massachusetts coastline proved to produce unrealistic results and ultimately is overly simplistic in the approach. The developer has indicated that *"the state of our practice has been to not use the overwash model. It produces streaky unreasonable output at under 30 meter (cell size) and we have not had funding to update and refine the model."* (SLAMM Forum, Warren Pinnacle Consulting). Although the developer hopes to improve this module in the future, it is not recommended for use in its current state. In addition, given that this project is using 5 meter grid spacing, the overwash parameters were not used in this study.

2.2.11 Main Input File Processing

Although many of the input parameters listed above are entered as specific values within the SLAMM interface, there are a number of additional input files that are required to effectively run the SLAMM model. The program allows for 8 different data files to be entered as American Standard Code for Information Interchange (ASCII) raster files. The first three of these files are required, while the remaining 5 input file types are optional:

- Digital Elevation Model (DEM) File
- SLAMM Categories File
- Slope File
- Dike File (*optional*)
- Percent Impervious File (*optional*)
- Output Sites File (*optional*)
- VDATUM File (*optional*)
- Uplift/Subsidence File (*optional*)

With the exception of the Boston area panel (see Section 2.4.1), none of the optional input files were utilized; due to the two significant dams present in the Boston area (see Section 2.2.7 for further discussion), the SLAMM simulations for the Boston panel also included a dike input file.

To generate the necessary input files, files were processed to ensure all datasets were in a consistent horizontal coordinate system, used the same vertical datum, and all elevation measurements were in the same units. Datasets were processed using a series of batch scripts that converted all datasets to ASCII raster files that used the Massachusetts State Plane Coordinate System (2001) as the horizontal coordinate system, the North American Vertical Datum (NAVD) (1988) as the vertical datum, and meters as both the horizontal and vertical measurement unit. The batch scripts also cropped all input files to the exact extent of the regional panel appropriate for each model run and set the grid size for all output ASCII files to five (5) meters, representing high resolution for a statewide assessment.

2.2.12 Data Gaps and Limitations

As with all models, there are a number of limitations within SLAMM that must be considered when interpreting the results. For instance, the SLAMM model does not effectively incorporate natural processes, such as the impacts of coastal storms and sediment transport, which can have significant influence on shoreline location and sediment dynamics. For example, storms may create new inlets, breaches, or significant erosion that cannot be directly simulated by SLAMM. As discussed, this is highlighted by the limitations associated with using the overwash parameter.

A similar limitation was discovered with the marsh and swamp erosion rates. As discussed in Section 2.2.4, the erosion parameters for horizontal marsh and swamp erosion are only triggered when a 9 kilometer fetch length is met. While this works well for open ocean coasts or large expansive inland water systems, given the numerous enclosed bays and estuaries present in Massachusetts, the majority of coastal wetland areas are not exposed to a 9 kilometer fetch. In essence, this means that even where data existed to document marsh erosion rates, entering these values as input parameters would not be utilized and had no effect on the results.

As with any model, there are uncertainties and simplifications. However, the largest uncertainty may in fact be with the sea-level rise projections themselves. Although this project applied widely accepted and referenced projections, the wide future uncertainty requires simulating multiple sea-level rise scenarios for each location. By doing so, the results reasonably bracket the probable future outcomes, and can be used collectively to guide future coastal management decisions. Additionally, it is important to note that the SLAMM results produced for this report are useful at a large scale, to gain a general understanding of the trends expected in changes to wetland areas given certain sea-level rise scenarios. If there was interest in how sea-level rise would affect a site-specific project or property and long-term management practices at that location, it may be appropriate to rerun the simulations using more targeted site-specific data.

Despite these limitations, the SLAMM results presented with this report still provide a valuable tool to identify future coastal wetland migration, detect ecological concerns, and provide valuable information to help prioritize marsh systems that may be most vulnerable to the changing climate.

2.3 PILOT ANALYSIS

2.3.1 Parameter Sensitivity Analysis

Although SLAMM contains an internal sensitivity analysis option, a manual sensitivity analysis was performed in order to better control the variation and change in input parameters. We ran SLAMM using a range of values for each parameter, including not only normal expected values, but also extreme values, to assess the responsiveness of the model to changes with each of the parameters. The primary purpose of the sensitivity analysis was to determine parameters that were either (1) extremely sensitive to changes, or (2) had insignificant effect on the results. As such, this prioritized the importance of searching for accurate data inputs throughout the state. For example, if results were fairly insensitive to a certain parameter, then gathering site-specific data for that particular parameter was deemed unimportant. In addition, there were already certain parameters, as discussed throughout this section, which did not influence the results due to the methodology and algorithms applied by SLAMM (e.g., marsh erosion due to the fetch algorithm). This section includes a discussion of the model parameters that were evaluated, an explanation of the setup used for the qualitative sensitivity analysis, and summary of the relative model sensitivity to each parameter.

After the initial assessment of the SLAMM algorithms, Woods Hole Group evaluated a select set of model parameters and their impacts on each resource classification. Some parameters were not tested due to their obvious importance (e.g., tidal range), while others were left out due to their inertness at the SLAMM algorithm level (e.g., frequency of overwash). Table 2-7 presents the list of the model parameters that were evaluated and a brief explanation of the parameter. In order to run numerous iterations with slight variations in each parameter, WHG selected a small portion of the Massachusetts coastline in the Town of Sandwich to facilitate processing of the sensitivity analysis. The modeled coastline extends from just east of the Cape Cod Canal, east to the town border with Barnstable. The total length of coastline modeled was approximately 5 miles and included the Town Neck and Scorton Creek estuaries. WHG selected this region due to land type variability present within a relatively small geographic area. WHG developed a SLAMM model grid with a 5-meter resolution for the wetland, elevation, and slope input files. The model grid extended approximately 0.5 miles into open water and approximately 0.5 miles inland. Figure 2-6 shows the present day wetland classifications for the model grid.

Table 2-7. Description of model parameters used in the sensitivity analysis.

Model Parameter	Parameter Description
Historic Trend	The historic rate of sea-level rise, used to estimate land subsidence or uplift.
Salt Elevation	Elevation where freshwater wetlands begin.
Land Type Erosion	Horizontal erosion rates for particular land type categories: Marsh – applies to regularly/irregularly-flooded marshes and transitional marshes only where they interact with open water. Swamp – applies to all swamps, as well as mangrove swamps (not present in Massachusetts). Tidal Flat – applies to tidal flats and estuarine beaches, as well as to ocean beach (assuming Bruun rule is not used), but will not apply to tidal flats unless the calculated fetch is greater than 9 kilometers Note that horizontal erosion rates can apply to multiple land types.
Land Type Accretion	Vertical accretion rate for particular land type, including: regularly-flooded marsh, irregularly-flooded marsh, tidal-fresh marsh, inland-fresh marsh, and tidal swamp. Mangrove erosion was not evaluated since mangroves are not present on the Massachusetts coastline.
Beach Sedimentation Rate	Vertical accretion rate for beaches and tidal flats.

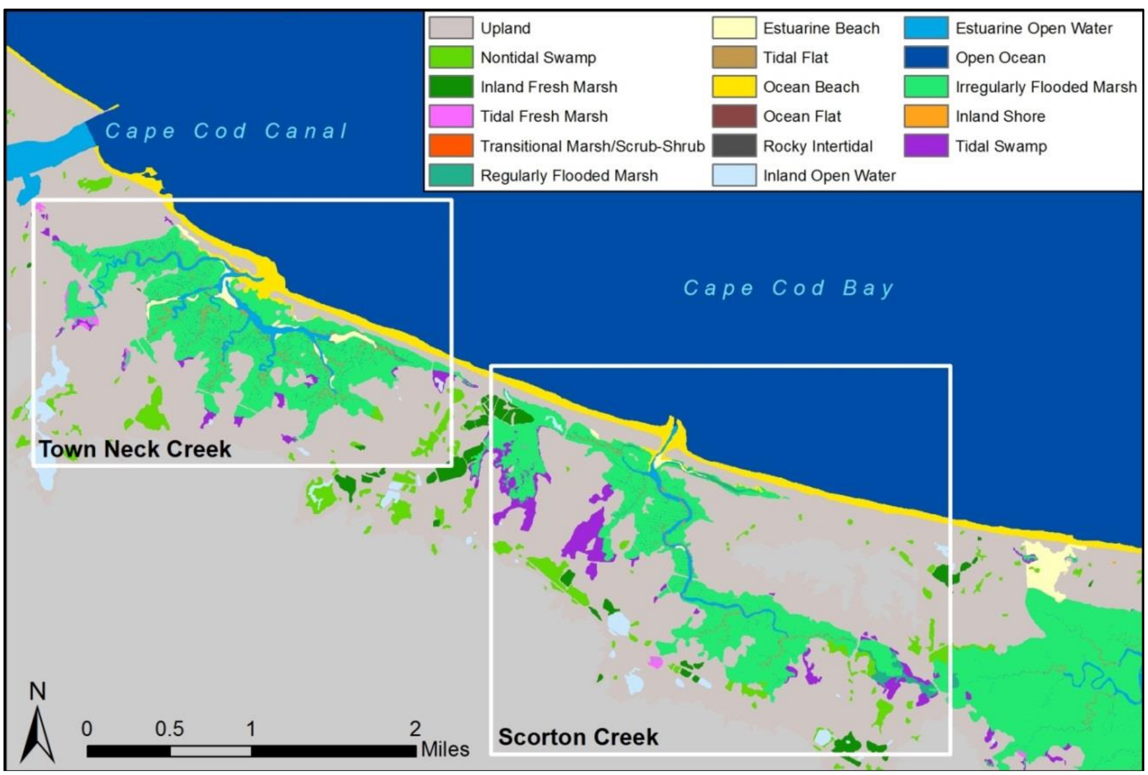

Figure 2-6. Sensitivity analysis model grid extent.

After setting up the model, WHG ran the model with all model parameters set to zero in order to establish a baseline case where only sea-level rise and tidal range drove model predictions. WHG then progressively adjusted individual model parameters in order to qualitatively evaluate how different resource types responded to different model parameters. The SLAMM technical documentation provides a detailed explanation of how each model parameter influences the algorithms of the model, but the documentation does not provide any guidance on reasonable ranges for any of these model parameters. WHG conducted a brief literature review in order to get a sense of reasonable ranges for the parameters in relation to the New England coastline. Table 2-8 lists each model parameter that was evaluated, a reasonable range for the parameter, and where applicable, an explanation of the logic used to develop the reasonable range.

In addition to understanding how model results might change due to parameter variability within reasonable ranges, WHG was also interested to determine if the example model was completely insensitive to changes in any of the model parameters. To that end, WHG also evaluate the example model over a much larger range of values than the range that might reasonably be expected to occur with changes ranging an order of magnitude larger than presented in Table 2-8.

After the base case model run was completed, WHG proceeded to conduct a series of model runs varying each parameter independently and through the full range of values reported in Table 2-8. Table 2-9 provides a summary of the results of the sensitivity analysis. For each combination of parameter and resource category, an assessment of the sensitivity broken up into four categories (--: insensitive, Low: minimally sensitive, Mid: reasonably sensitive, and High: very sensitive). Table 2-9 excludes resource categories that were insensitive to all parameters.

The results of this sensitivity analysis demonstrated that Historic Trend and Salt Elevation are the most significant model parameters, at least in terms of the number of different wetland types influenced. Neither Marsh Erosion nor Swamp Erosion has any impact on the land types within the example model due to the fetch limiting algorithm in SLAMM. The most sensitive resource classifications (those impacted by the most parameters) are tidal flats, transitional salt marsh, and regularly-flooded marsh, which is expected. The rest of the land types tend to be responsive to a few parameters, but relatively insensitive to other model parameters. Accretion rates and erosion rates do influence individual resource classifications, but the influences are more concentrated within a subset of classifications.

The results of the parameter sensitivity analysis also provided guidance on where data needs were more essential. It is important to note, however, that the specific sensitivity values and the qualitative assessments of each parameter are specific to this example model. While this area represents a reasonable cross-section of resource classifications and geometries that could be expected across the state of Massachusetts, it is feasible that parameter sensitivity may fluctuate at varying site-specific locations. In addition, the most critical model inputs for SLAMM are the non-parameter values of elevation and slope, which are discussed in section 2.3.2.1. The sensitivity to model parameters depends heavily on the slope of the land. As an example, an existing salt marsh that has a relatively flat slope will be much more responsive to changes in historical sea-level rise than a similar salt marsh that has a much higher slope; the same increase in water level will cause a substantially greater loss in salt marsh area for the flat salt marsh than for the steep salt marsh. This behavior is similarly applicable to all resource categories. Therefore, this sensitivity assessment should only be used as a reference point for how different land types respond to various model parameters along the rest of the Massachusetts coastline.

Table 2-8. Model parameters and modeled value ranges.

Model Parameter	Reasonable Range	Explanation
Historic Trend	1.5 – 4.0 (mm/yr)	Values available from NOAA (2014a) and range based on values reported along New England coastline.
Salt Elevation	40% - 60% of tidal range	SLAMM technical documentation indicates this value should be approximately 50% of the great diurnal tide range (meters above mean tide).
Marsh Erosion	0 – 2 (m/yr)	Fagherazzi (2013) reported range of values for bays, lagoons, estuaries and deltas.
Swamp Erosion	0 – 2 (m/yr)	See Marsh Erosion.
Tidal Flat Erosion	0 – 2 (m/yr)	See Marsh Erosion.
Regularly-Flooded Marsh Accretion	0 – 2.5 (mm/yr)	Donnelly and Bertness (2001) reported range of accretion for salt marsh.
Irregularly-Flooded Marsh Accretion	0 – 2.5 (mm/yr)	See Regularly-Flooded Marsh Accretion.
Tidal-Fresh Marsh Accretion	0 – 2.5 (mm/yr)	See Regularly-Flooded Marsh Accretion.
Inland-Fresh Marsh Accretion	0 – 2.5 (mm/yr)	See Regularly-Flooded Marsh Accretion.
Tidal Swamp Accretion	0 – 25 (mm/yr)	No specific information about swamps, but primary difference between marshes and swamps is woody plant life present in swamp, assume deciduous plant life leads to ten-fold increase in accretion.
Swamp Accretion	0 – 25 (mm/yr)	See Tidal Swamp Accretion.
Beach Sedimentation Rate	0 – 10 (mm/yr)	A review of multiple previous SLAMM modeling studies indicated assume range of 10 mm/yr.

Table 2-9. Relative sensitivity of SLAMM model to parameters.

Parameter	Undeveloped Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Ocean Beach	Estuarine Open Water	Open Ocean	Irreg.-Flooded Marsh	Tidal Swamp
Historic Trend	Low	Low	Low	--	High	High	Low	High	Low	Low	--	Mid	Low
Salt Elev.	Low	Low	Low	Low	High	High	Low	--	Low	--	--	Low	Mid
T. Flat Erosion	--	--	--	--	Mid	--	--	High	Mid	High	Low	--	--
Regularly-Flooded Marsh Accretion	--	--	--	--	Low	High	--	High	--	--	--	--	--
Irregularly-Flooded Marsh Accretion	--	--	--	--	--	High	--	High	--	--	--	Low	--
Tidal/Inland Fresh Marsh Accretion	--	--	Low	Low	High	Mid	--	Mid	--	--	--	--	--
Tidal/Swamp Accretion	--	Low	--	--	High	High	--	High	--	--	--	Low	Mid
Beach Sed. Rate	--	--	--	--	--	Low	--	High	--	--	--	--	--

2.3.2 Pilot Site – Great Marsh

Prior to running the model simulations for the entire state, Woods Hole Group evaluated the modeling performance at a pilot site chosen cooperatively with MA CZM: the Great Marsh area. Evaluating this relatively smaller site first allowed for validation against existing mapped wetlands, accretion parameter sensitivity analysis, an elevation uncertainty analysis, and a cell size sensitivity assessment. The results of this pilot analysis were then used to assist in the development of the recommended plan for the statewide model application. Additionally, because of extensive research already conducted throughout Great Marsh, more detailed data than are expected to be available for the statewide model were available for use in the pilot study, allowing full utilization of SLAMM's functionality. Detailed data were compiled for the Great Marsh area with the help of CZM, Massachusetts Division of Ecological Restoration (DER) and the Marine Biological Laboratory (MBL) in Woods Hole.

2.3.2.1 Elevation Sensitivity Analysis

A sensitivity assessment was also conducted directly on the elevation data. These SLAMM simulations were conducted to determine whether the uncertainty in the accuracy of the available LiDAR data would affect the ultimate model results. The largest accepted vertical error for LiDAR utilized for this project is ±15cm. To evaluate the effects a change of this magnitude could have on the SLAMM model results, Woods Hole Group ran pilot runs in the Great Marsh area with three elevation scenarios: 1) the original elevation, 2) all original elevations plus 15 cm, and 3) all original elevations minus 15cm. All three runs were conducted in the Great Marsh area, which had a high amount of available data for other inputs compared to other areas of the state. All elevation analysis simulations were run using a fixed 1-meter sea-level rise by 2100. Table 2-10 presents the results of the elevation sensitivity analysis. All values within the table are presented in hectares for each resource classification. Outputs from SLAMM were recorded in 2050 and 2100 and Table 2-10 shows the fluctuation in area associated with each elevation change (e.g., plus or minus 15%). The range of the differences between the simulations is also presented in Table 2-10.

Given the narrow elevation range, relative to the tide levels, at which marsh species survive, it is unsurprising that minor elevation changes have the biggest impact on the ultimate areas of irregularly- and regularly-flooded marsh. When the elevations were artificially lowered, the results indicate that a larger area will be covered with regularly-flooded marsh and a decrease in irregularly-flooded marsh area. Inversely, when the elevations were artificially raised, the results indicated a decrease in the area of regularly-flooded marsh and an increase in irregularly-flooded marsh area. While other wetland types were also affected by these changes, such as tidal flat, estuarine open water, and undeveloped dry land, none were altered to the same extent and the changes are well within acceptable tolerances given the overall area of each resource type. Furthermore, regularly-flooded and irregularly-flooded marshes are salt marsh and salt/brackish marsh habitat types, respectively. Also, regularly-flooded marsh can generally be thought of as low marsh, and irregularly-flooded marsh as high marsh. The change is therefore more representative of altering the dominant species that would be present, rather than a major habitat type change.

In addition to only minor changes caused to the majority of the wetland type areas, it is important to note that these errors are the maximum likely to be found within the LiDAR datasets used. In actuality, the majority of the true elevations will be much closer to the elevations presented in the dataset. Finally, the relatively minor error potentially associated with the LiDAR datasets (±15cm) is dwarfed by the uncertainty inherent in the sea-level rise projections. Once again, it is therefore useful to consider all the sea-level rise scenarios from a particular map panel together to determine a range of probable outcomes.

Table 2-10. Elevation analysis results. (All values are in hectares.)

	Initial inputs	2050			Range	2100			Range
Wetland Type	**original**	**-15cm**	**original**	**+15cm**		**-15cm**	**original**	**+15cm**	
Undeveloped Dry Land	4,523	3,492	3,535	3,574	82	3,282	3,335	3,387	105
Swamp	413	246	252	257	12	222	227	232	10
Inland-Fresh Marsh	166	45	48	52	7	38	40	41	3
Tidal-Fresh Marsh	7	3	3	4	1	1	2	2	1
Trans. Salt Marsh	3	77	76	90	13	106	106	106	(0)
Regularly-Flooded Marsh	223	646	505	413	(234)	2,872	2,293	1,143	(1,729)
Estuarine Beach	38	26	32	36	10	12	14	17	5
Tidal Flat	679	1,471	1,551	1,716	245	1,247	1,262	1,296	50
Ocean Beach	155	161	159	160	(1)	188	180	172	(15)
Inland Open Water	60	20	21	30	10	17	17	18	1
Estuarine Open Water	752	1,190	1,080	879	(311)	1,483	1,435	1,372	(112)
Open Ocean	1,166	1,172	1,170	1,166	(5)	1,179	1,176	1,174	(4)
Irreg.-Flooded Marsh	2,635	2,281	2,395	2,446	166	190	748	1,873	1,682
Tidal Swamp	31	21	23	26	5	14	15	17	3

2.3.3.1 Cell Size Comparison

Another goal of the pilot site analysis was to determine the appropriate cell size to utilize for the statewide model simulations. Smaller cell sizes allow more detailed and site-specific results, but at the expense of increased processing time. Using the same input values, and an intermediate-high sea-level rise scenario, the Great Marsh pilot area was evaluated using both a 2-meter and a 5-meter cell size. A zoomed-in area of the results is presented in Figure 2-8. While some differences can be seen, the 5-meter resolution results are comparable to those developed at a 2-meter resolution. While 2-meter resolution would be useful for a project focused on a single site, given that the goal of this project is to develop statewide results, the needs of the project did not require a higher resolution than 5-meters. Not only were the discrepancies between the 2-meter and 5-meter SLAMM outputs insignificant (see Figure 2-7), but the differences between the input elevations and resource classifications were also minimal.

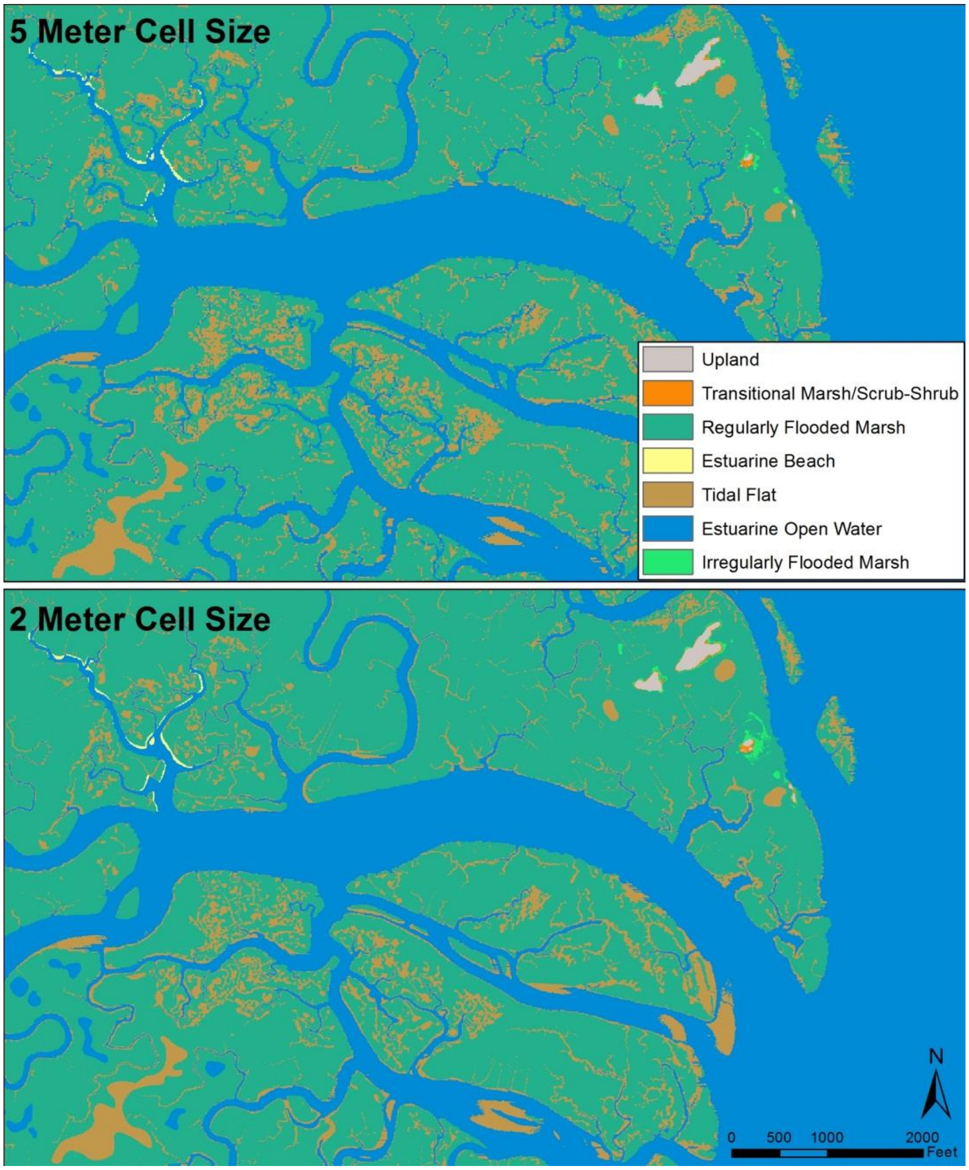

Figure 2-7. Comparison of model results using two different cell sizes.

2.3.3.2 Comparison of Accretion Inputs

The Great Marsh estuarine system is one of the few places in Massachusetts with a substantial marsh accretion dataset. This provided not only relatively accurate, site-specific data in the form of static accretion rates, but also the opportunity to run the Marsh Equilibrium Model (MEM - Morris et al., 2002) and create site-specific, time-varying accretion rates from the observed static rates, suspended sediment loads, vegetative cover, etc. These time-variable accretion rates, calculated for both the regularly-flooded and irregularly-flooded marsh resources under the various sea-level rise scenarios (low, intermediate-low, intermediate-high, and high), could then be input into SLAMM and a comparison of SLAMM results with static accretion rates and time-variable accretion rates could be performed. Specific input parameters utilized to define the MEM output and specify the time varying accretion rates in the SLAMM runs can be found on the companion hard drive to this report.

The site-specific accretion data from the Great Marsh estuary, in the form of surface elevation table (SET) data, were also useful in justifying the use of the historic sea-level rise trend as a proxy for marsh accretion rates statewide. As discussed in Section 2.2.3, there is little site-specific accretion data available for marshes throughout the rest of the state. Since salt marsh accretion in Massachusetts has generally kept pace with sea-level rise to date, for the statewide analysis it was assumed that the rate of marsh accretion is approximately equivalent to the historical rate of sea-level rise. That the measured Great Marsh SET data was similar to the historical rate of sea-level rise further supported the use of the historic sea-level rise trend as an accretion rate proxy. Figures 2-9 and 2-10 show the resulting land cover areas by the year 2100 using the static and MEM accretion inputs, respectively.

A comparison of results developed using the two different accretion inputs shows that, particularly at higher sea-level rise scenarios (intermediate-high and high), the static and MEM accretion inputs produce substantially different results for regularly-flooded and irregularly-flooded marshes. The area of projected tidal flats by 2100 is also dramatically different between the two inputs. Figure 2-8 shows the 2100 output of a zoomed-in area of the Great Marsh panel from the intermediate-high sea level rise scenario, which shows this vast difference in the amount of irregularly- vs. regularly-flooded marsh, and tidal flat extent. When the MEM results are incorporated, the accretion rate is allowed to vary overtime, and at this particular location, increase enough to allow regularly-flooded marsh habitat to accrete at a rate high enough to keep pace with sea-level rise, thus remaining marsh. When only static accretion rates are entered, at the intermediate-high and high sea-level rise scenarios, sea level out-paces the marsh accretion rates by the year 2100. This results in irregularly-flooded marsh conversion to regularly-flooded marsh, and regularly-flooded marsh conversion to tidal flat.

The discrepancy between the two sets of results begs the question: "Which results are the most accurate?" However, given the paucity of accretion data for the remainder of the state, and the inability to incorporate time-variable accretion data inputs into the majority of the statewide model runs, this exercise can instead be used as an important discussion point and a call for more data collection statewide. Given the usefulness of comparing the different scenarios predicted by the different accretion inputs, however, Woods Hole Group provided both sets of SLAMM outputs, one with time-variable MEM data, and one with a static accretion rate based on the local, historic sea level trend for the Great Marsh panel.

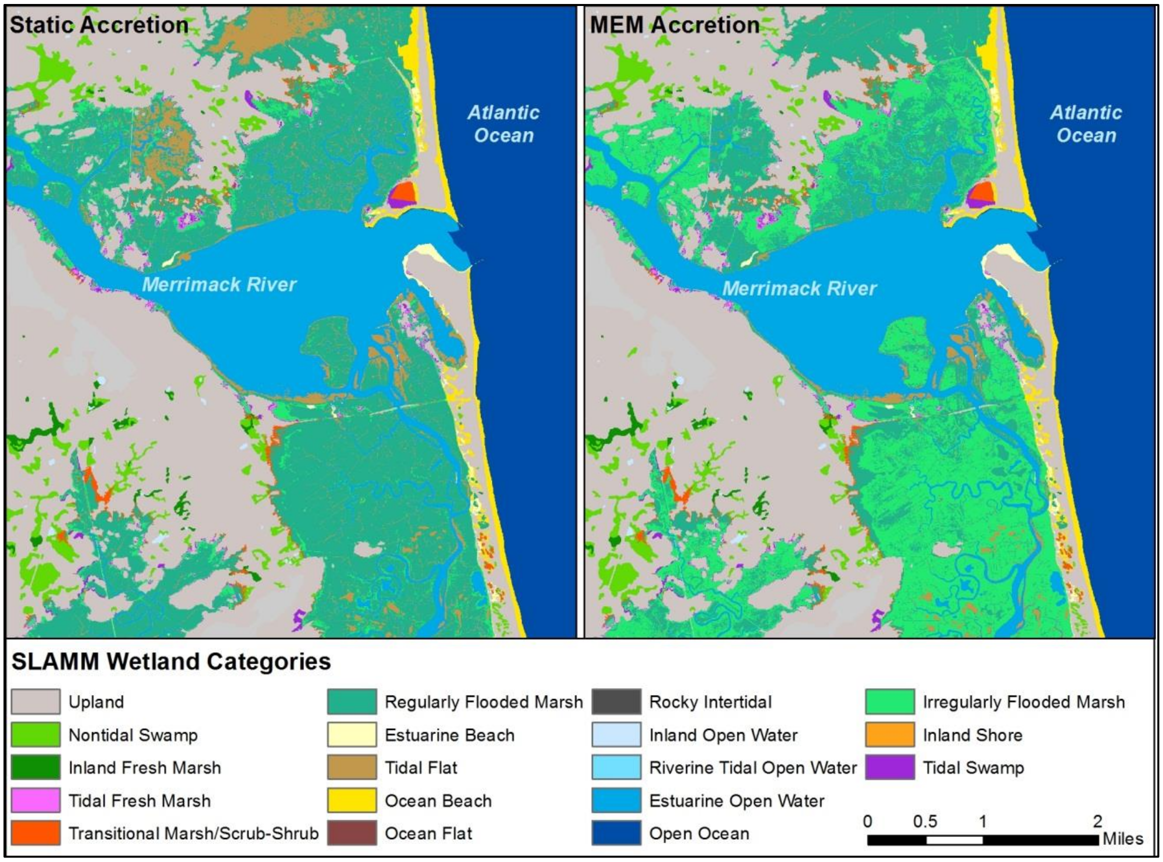

Figure 2-8. Comparison of model results for 2100 using two different accretion inputs.

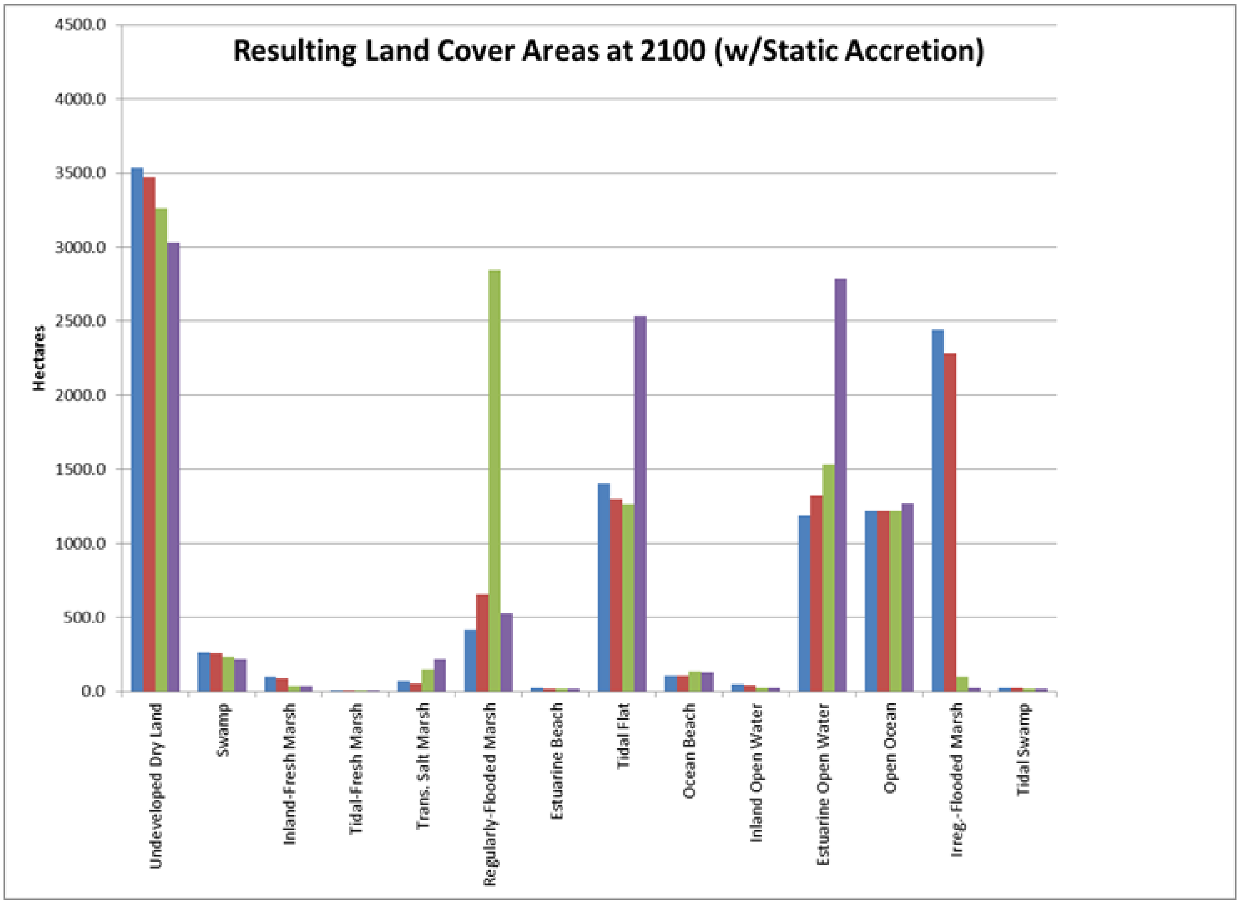

Figure 2-9. Resulting land cover areas within the Great Marsh panel by 2100 using static accretion inputs.

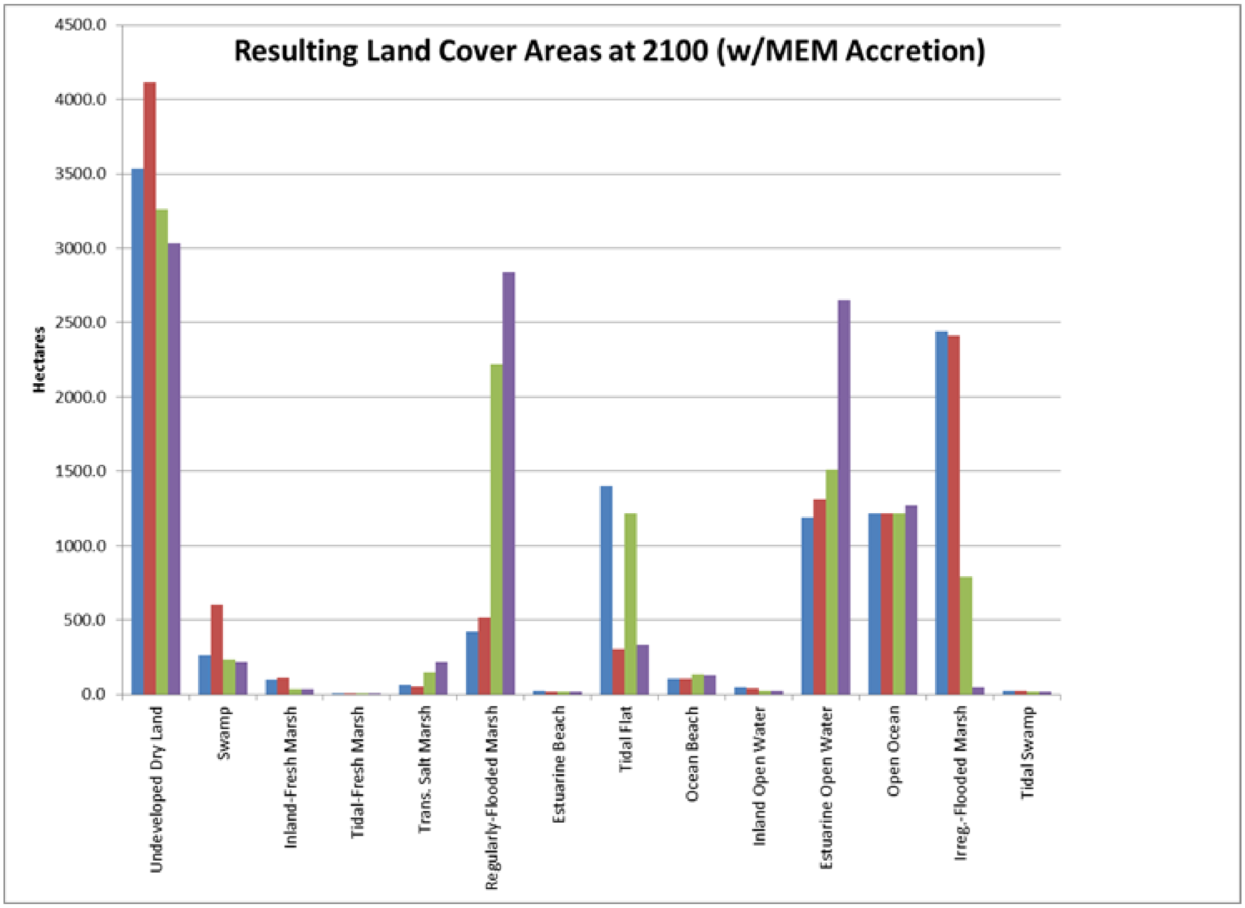

Figure 2-10. Resulting land cover areas within the Great Marsh panel by 2100 using MEM accretion inputs.

2.3.3.3 Results and Lessons Learned

Executing an initial set of model simulations in an extensively studied area provided a better understanding of the model prior to implementing it statewide. The wealth of field data collected in the Great Marsh area provided an opportunity to utilize more detailed information for the Great Marsh pilot analysis than would have been available at a statewide scale. Such a full utilization of the SLAMM model provided a thorough understanding of the role of various input parameters. The pilot results, and the understanding of the model, could then be used to refine what additional data acquisition would still be necessary to appropriately complete the statewide model. It also provided the ability to target key future data collection efforts that could be used to further improve the predictive ecological modeling.

This analysis also gave us insight into what data to utilize as accretion rate inputs for the statewide model, as well as confidence in that chosen approach. A review of the pilot study results run from simulations utilizing the average measured static accretion rates, as well as the calculated time-variable accretion rates derived from MEM, demonstrates that while the two input types do yield different results, major differences are not seen until

2100 at a high SLR scenario. Given that for the majority of out-years and SLR scenarios the results of the two accretion input types were similar, combined with the paucity of accretion data elsewhere in the state, a static accretion rate was deemed a suitable choice. This, coupled with the wide variability and uncertainty in the sea-level rise projections for out years beyond 2070, likely means that static accretion rates were suitable for near to mid-term projections. Additionally, although specific accretion rate data are not available for most locations in the study, the local, long-term rate of sea-level rise was utilized as a proxy (in the absence of measured accretion rates) for a static accretion rate for each model simulation.

2.4 STATEWIDE ANALYSIS

This section discusses the methods, results and guidance for interpretation of the statewide SLAMM model simulations. One of the main goals of the statewide analysis, and this project in general, was to identify coastal wetland areas susceptible to losses caused by projected sea-level rise in order guide future conservation planning and coastal management decisions. The results from this analysis can be used effectively to identify change in wetland type, as well as the loss of wetland area due to sea level rates exceeding accretion rates or due to developed structures and topographic restrictions preventing landward migration.

2.4.1 Panel development

Due to the large area under consideration for statewide modeling, and the file size restrictions for running SLAMM, sub-regions were required for model simulations. The entire Massachusetts coast, including the Taunton River estuary, as well as the islands of Martha's Vineyard, Nantucket and the Elizabeth Islands, was captured using 18 individual panels (Figure 2-11). These boundaries were developed to maximize the efficiency of the SLAMM model executable, allowing each town to be entirely encompassed within a single panel where possible. Even so, the results from some towns still need to be presented in two parts due to the unique locations of the town's shorelines and the influence from two discrete bodies of water with different tide ranges. For example, the Town of Barnstable's northern shoreline borders Cape Cod Bay, while its southern shoreline borders Vineyard Sound. As a result, the results from two panels (i.e., Cape Cod Bay and Cape Cod Vineyard Sound West) will be required to gain a full picture of the projected sea-level rise impacts in Barnstable.

Woods Hole Group then developed a unique script that cropped input rasters to exclude any areas: 1) outside the model run boundary, or 2) above 60 feet of elevation. By taking a non-rectangular approach to input file creation, this method significantly reduced the input file size by eliminating upland areas not likely affected by coastal flooding and sea-level rise.

2.4.2 SLAMM Specifications

In addition to the base input data (outlined in Appendix A, Table A-3), additional inputs were entered in the statewide runs. Decisions made specifically for the statewide runs include development of subsets within various panels, and selection of various SLAMM modules within the executable.

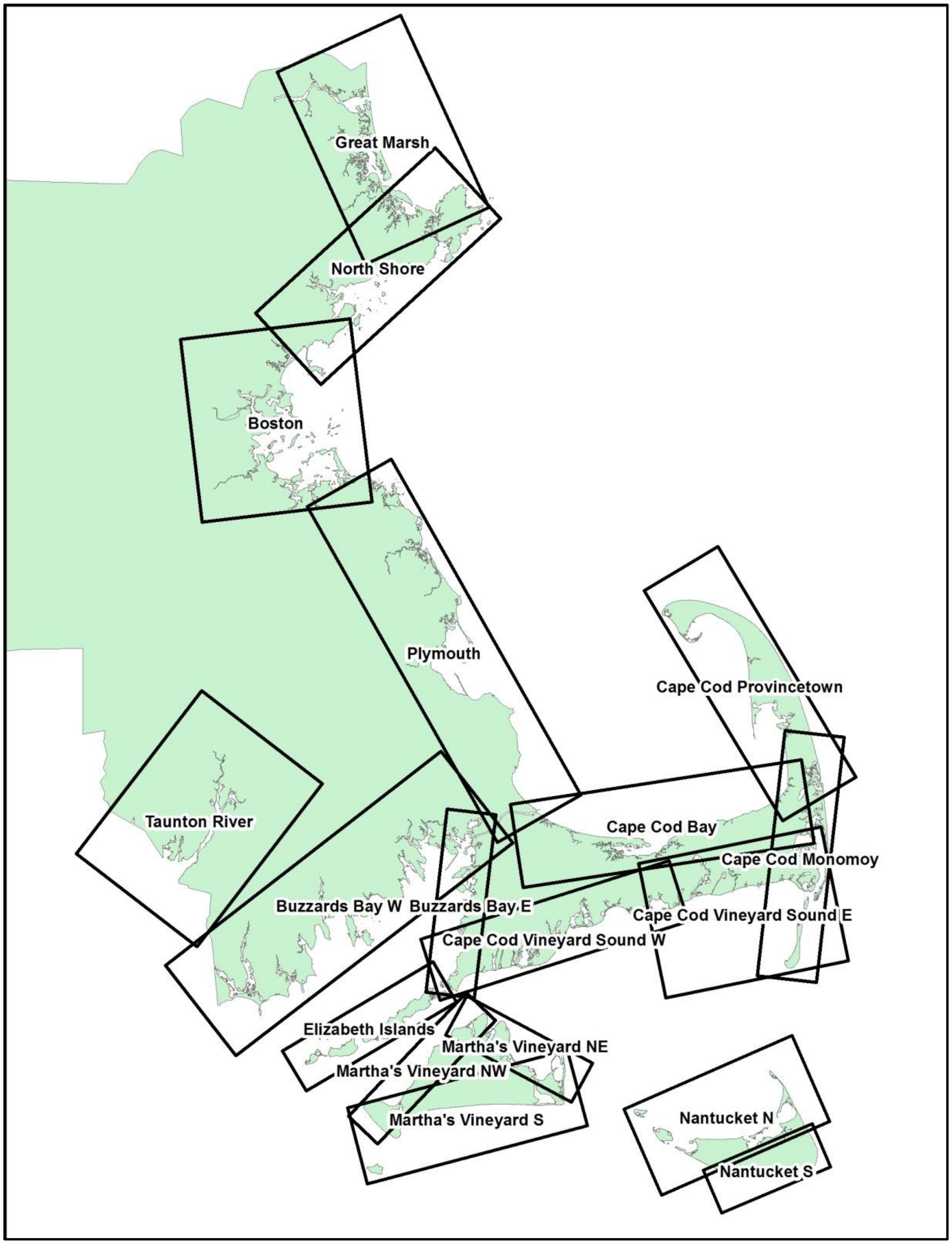

Figure 2-11. Statewide model simulation panel locations.

2.4.2.1 Subsets

Subsets are an important component in the SLAMM model, which allow a user to specify different input values for specific areas within the overall model domain. Three different types of subsets were specified throughout the statewide runs when necessary.

1. Tidally restricted areas.
2. Stretches of shoreline that had a unique shoreline erosion rate.
3. Large (USGS-gaged) rivers that contributed a substantial freshwater flow to the system.

All subsets, and the unique data associated with them, are listed in Appendix A, Table A-4. An example of how these subsets appear geographically is presented in Figure 2-12.

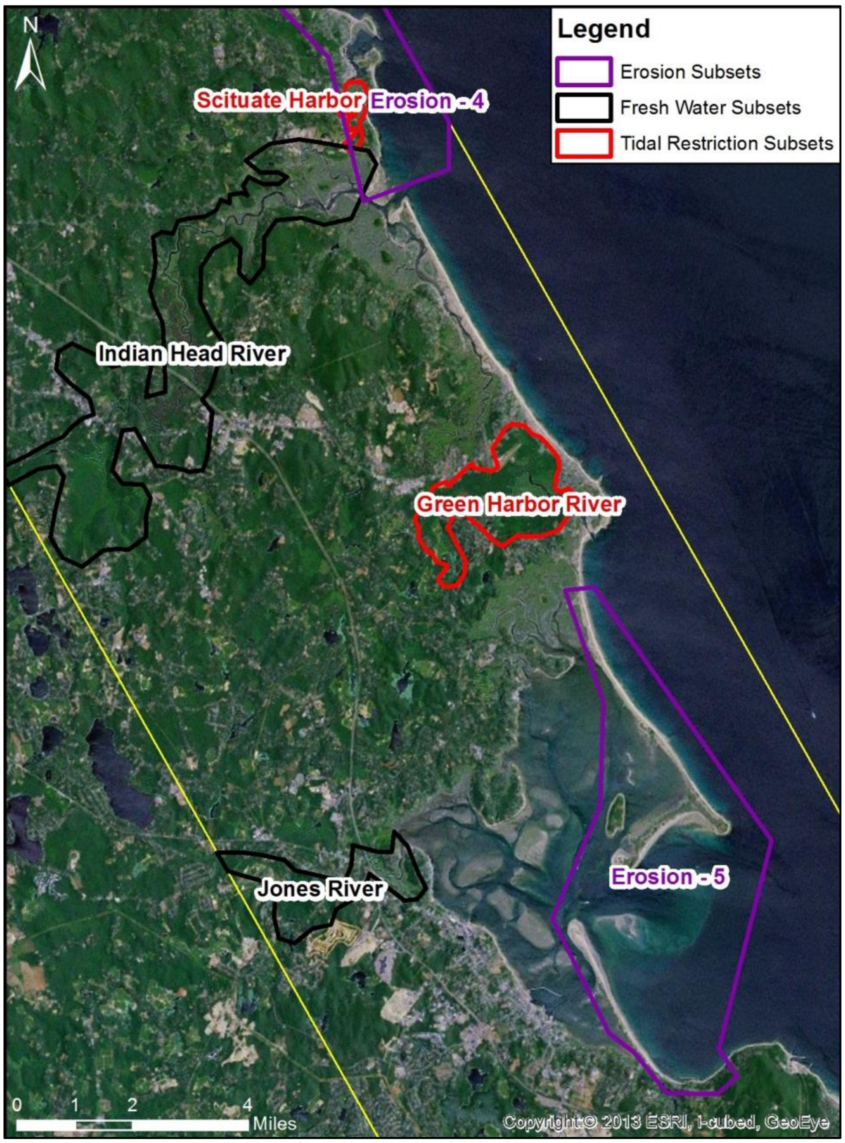

Figure 2-12. Example of SLAMM subset areas from the Plymouth panel.

2.4.2.2 Protected vs. Unprotected Land

SLAMM allows two options for protecting upland areas: dividing the upland classification in the wetland input layer as either "developed upland" or "undeveloped upland", or through the inclusion of an impervious surface input layer. SLAMM will consider any location with impervious surface to be "developed upland." With either of those two input types, SLAMM allows the user to select whether to protect only developed upland, protect all upland, or neither. When areas are protected, they will not convert to other habitat types during simulations, preventing the capability of wetlands to migrate inland.

Because one of the goals of this project is to identify areas where wetlands will need to migrate to adapt to sea-level rise, prohibiting their expansion through the selection of SLAMM's "Protect" option would have minimized the information produced. By not protecting any upland areas, and then post-processing the results using the statewide impervious surface raster from MassGIS, we can identify the areas where marshes will need to migrate, and areas where such a migration will directly conflict with existing development. As such, results are available within each panel both with inclusion of impervious areas, and without impervious areas; however, SLAMM is always allowed to migrate based on the elevation and slope information, regardless of impervious areas.

2.4.2.3 Model Time Steps

The NWI wetland layer was the best input wetland layer available for the entire state of Massachusetts, as discussed in Section 2.2.2. The NWI data maps were developed at a large scale, and are best suited to regional or watershed level analysis, such as this project. Because this project produces digital data deliverables that can also be viewed at a small, site-specific scale, it is important to have the most accurate wetland input layer possible. SLAMM has specific tidal and land elevation range rules for individual wetland types that will change the NWI classifications over the first couple model iterations, even in the absence of any influence of sea-level rise, accretion, or any temporal changes such that the wetland classifications match up with the SLAMM rules. While the SLAMM rules can be adjusted for site-specific wetland variations, on a statewide level, this was not realistic. Consequently, SLAMM will locate and convert fine scale wetland areas, such as an adjustment between Open Ocean and Ocean Beach, or between regularly-flooded marsh and tidal flat based on the elevation input. During initial test simulations the output results for 2020 and 2030 often showed significant changes in wetland area. However, most of these changes were due to a SLAMM reclassification process based on LiDAR elevations rather than due to the influence of sea-level rise.

This section presents two examples of how this reclassification impacts the wetland classifications, and therefore the total area changes for each wetland type. Figure 2-13 shows an example from Barnstable Harbor where the original NWI layer classified most of the area as either irregularly-flooded marsh or estuarine beach. However, after two ten-year iterations (2020 and 2030), many of the smaller tidal creeks are captured (now classified as tidal flat), and a large area clearly submerged on a regular basis (see upper right image in Figure 2-13), is now classified as tidal flat instead of irregularly-flooded marsh. Additionally, Figure 2-14 shows an example from Mattapoisett where the original NWI layer indicates a wide Ocean Beach, as well as significant Ocean and Tidal Flats. However, after two ten-year iterations (2020 and 2030), the Ocean Beach is much narrower, having been replaced by Open Ocean. The Ocean and Tidal Flats are replaced by open water categories as well. When compared to the aerial photo shown in the upper right corner of Figure 2-14, it is clear these initial reclassifications made by SLAMM are actually more representative of features on the ground. This is unsurprising given that SLAMM is utilizing the LiDAR, which can capture fine changes in elevation, to drive these reclassifications.

It is important to note that these same changes take place with two small time steps (2012 and 2013) and zero sea-level rise, zero accretion, and zero erosion, confirming that these changes represent a more refined classification of *current* wetland categorization, rather than changes caused by sea-level rise. As such, the NWI wetland input data was pre-processed using a two-time step, zero sea-level rise SLAMM run to produce an updated wetland baseline layer to represent starting conditions for all statewide panels. It was from this baseline that future sea-level rise changes were characterized.

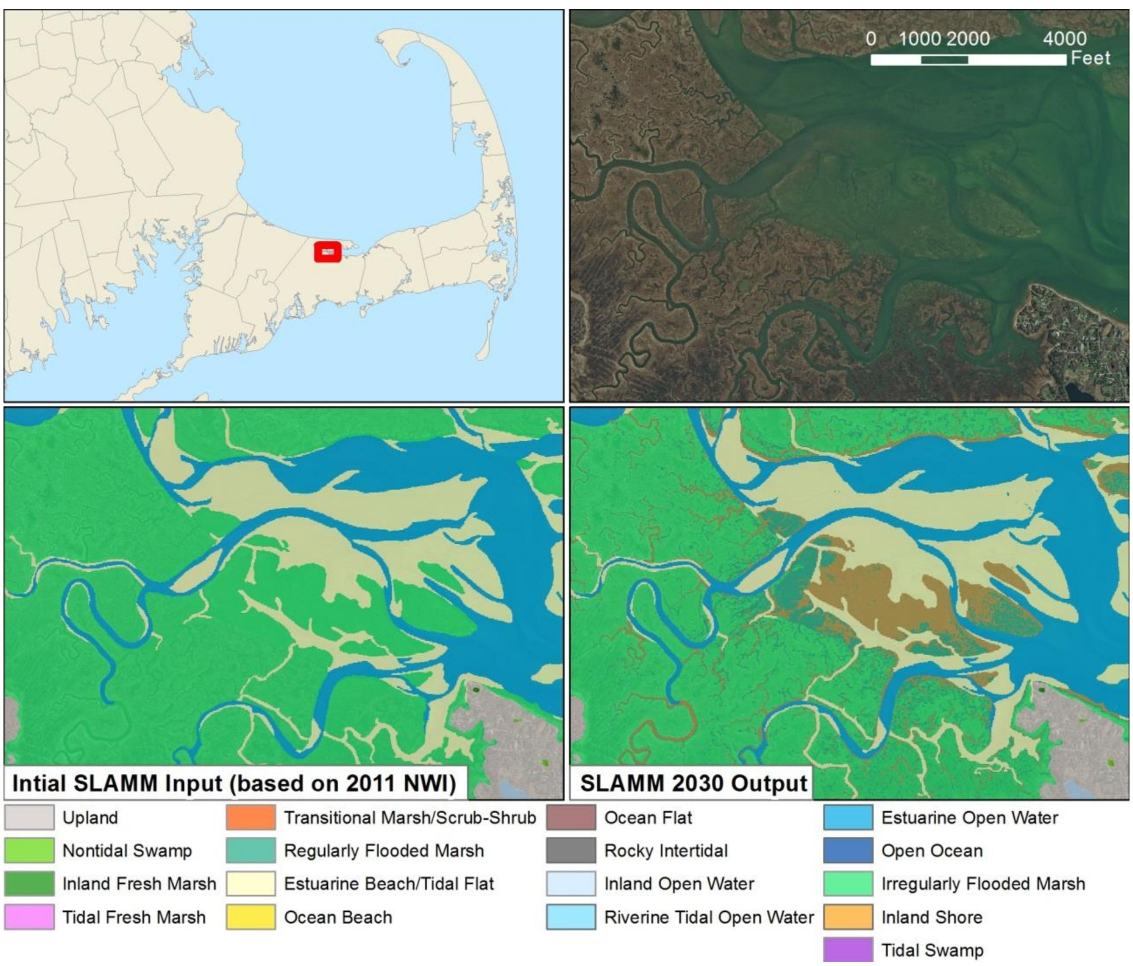

Figure 2-13. Wetland reclassification based on SLAMM decision tree – Barnstable Harbor example.

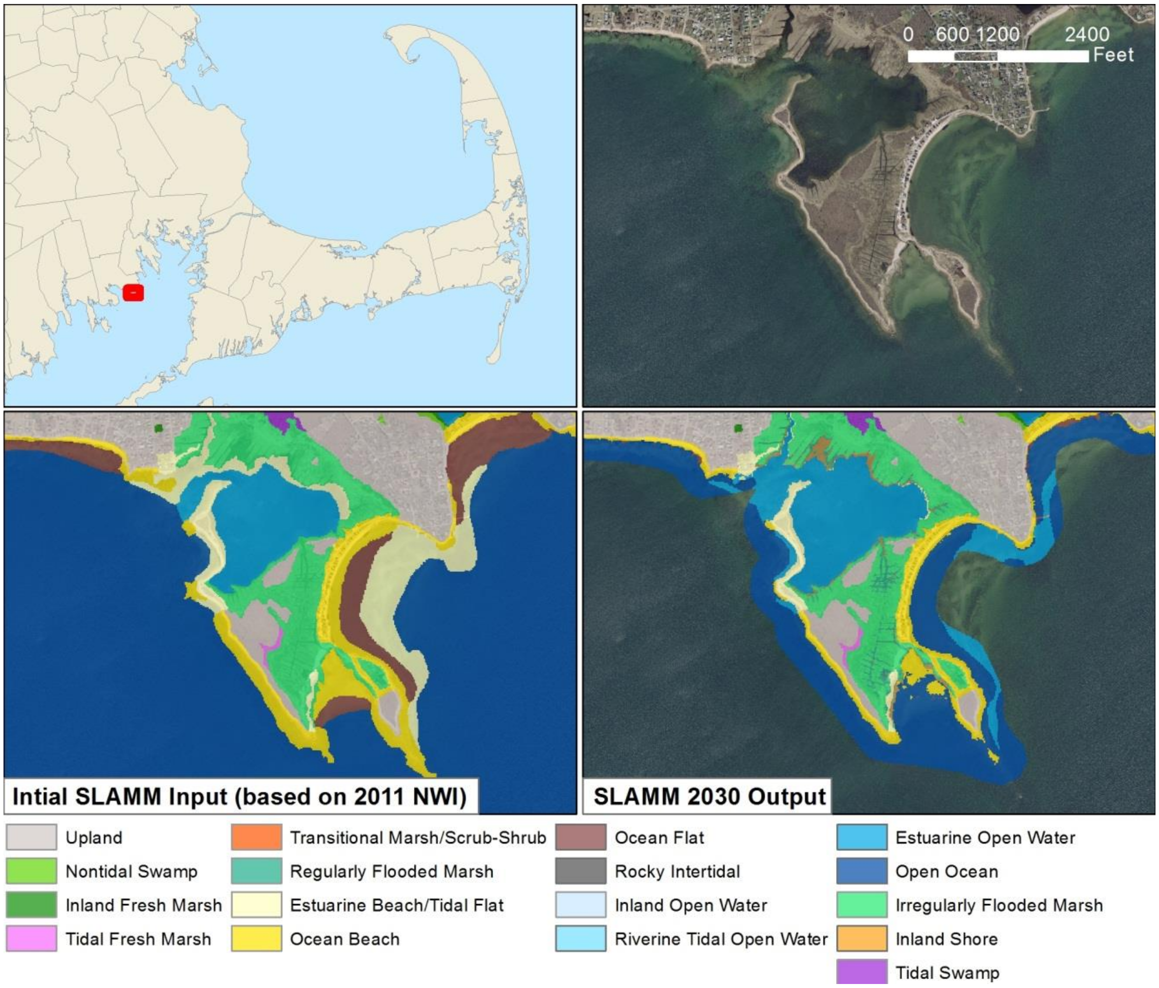

Figure 2-14. Wetland reclassification based on SLAMM decision tree – Mattapoisett example.

After the initial reclassification time steps (no sea level rise, erosion, or accretion included), these baseline wetland layers were then used to simulate out year conditions. When considering time-steps for the model and out-years for data deliverables, this analysis produced GIS and tabular outputs related to projected wetland areas for the out-years 2030, 2050, 2070, and 2100. Because simply setting these dates as time-steps for the model simulation would have only resulted in 4 model iterations, the model was run at 10-year intervals after 2011 (i.e., 2011, 2020, 2030, 2040, etc.). These more frequent time steps allow SLAMM to have 10 full model iterations between 2011 and 2100. By using a 10-year interval for the model, each wetland cell has more opportunities to experience small changes, and the final outputs represent more refined results.

2.5 RECOMMENDATIONS FOR IMPROVED SIMULATIONS

To improve the SLAMM model results, and specifically to improve outputs for targeted site-specific assessments, this section offers a number of recommendations for supplemental data collection or modification of the model. First, there is a paucity of accretion data throughout the state of Massachusetts. Only a couple salt marsh locations have been monitored sufficiently to allow the incorporation of accurate, field-measured accretion data into SLAMM, and there was no readily available data for accretion rates in the other wetland resource classifications (e.g., tidal flats). More site-specific data collection would allow for improved data inputs, and allow for tandem application of SLAMM and MEM models in areas other than Great Marsh.

Another data acquisition task that would improve the model results is additional data about the specific tidal ranges in restricted water bodies. As discussed above in the Parameter Sensitivity Analysis section, tidal range was one of the most influential input parameters. However, this study was only able to incorporate accurate tidal restriction data if they existed and were publically available or provided by project partners. There are a number of small, unstudied, restricted water bodies for which the model could have been improved if more accurate tidal range input were available to allow for subsetting these locations. Therefore, if there is a specific area of concern in the vicinity of a restricted water body for which tidal restriction data were not available, the SLAMM results presented with this report could be improved by collecting site-specific tide data and rerunning that portion of the SLAMM panel with regional subset input data that accurately reflects the tidal range.

Another way model results could be improved is to increase the accuracy of the wetland input layer. As the starting point for all subsequent changes, this layer is crucial in the implementation of the SLAMM model. As discussed in Section 2.2.2, we chose to utilize the 2011 NWI layer instead of the MassDEP wetland layer from the 1990s. The MassDEP layer is currently being revised and could be substituted for the NWI layer in the future. Although the MassDEP wetland data are likely more geographically accurate in terms of wetland boundaries (because MassDEP doesn't divide salt marsh into sub-categories, such as regularly- and irregularly-flooded marsh), converting these areas into appropriate SLAMM wetland codes would be more difficult than using the NWI layer. Despite potential difficulties, the use of an updated MassDEP wetlands layer should be considered for future SLAMM modeling. Particularly if a small, targeted area is being modeled, careful attention should be given to assess whether the chosen wetland layer accurately represents the wetland types and boundaries on the ground. Furthermore, although it was outside the scope of this current project, it would be useful to run the SLAMM model twice for a particular area using each of the wetland inputs to evaluate differences generated by each input.

If there is a major conditions change in the future, the SLAMM model should be rerun for that specific area to accurately reflect the probable wetland changes given the new environment. Examples of this could include major beach nourishment or dune restoration projects, breaches, significant neighborhood development, flood protection projects, or marsh restoration projects. The input data developed for this study could be updated to more refined site-specific assessments fairly easily, and the inputs and associated files could be readily modified to provide refined analyses for site-specific projects in the future. The models can also be readily re-simulated if changes to the landscape were realized (e.g., a significant coastal storm causes the formation of a new breachway or inlet), and updated LiDAR data were obtained and utilized.

There are additional comparisons that could help evaluate the role of specific parameters. For example, the SLAMM model provides the option to input an impervious surface layer, which SLAMM can use to determine which areas are developed and can be "protected" during the simulations. By selecting the option to protect these areas, SLAMM prohibits cells defined as developed, as indicated by the impervious surface inputs, from changing at all during the simulation. For this project, all simulations were only run once with this protect option turned off. This allowed for an assessment of the results under a scenario where currently developed lands are allowed to change, as well as an evaluation of how much of the future wetland area would be prohibited from forming by post-processing the results and using an impervious surface overlay. It is possible this oversimplifies how protecting these areas would affect the results. For instance, it is unknown how protecting developed upland influences the model's treatment of low lying, undeveloped areas behind these protected cells. Although outside the scope of this current project, additional comparative simulations could be performed to evaluate whether areas behind protected cells are allowed to change as rising water levels induce inundation, and if so, if those areas are changed differently than when developed areas were not protected.

Finally, although SLAMM effectively incorporates a number of coastal processes parameters, such as tide range, sea level rise, and marsh accretion, there are also a number of available input parameters for coastal processes not as well developed within the model. Three examples of these limitations, as discussed earlier in this section, are the overwash, erosion and fresh water parameter inputs. First, SLAMM allows the user to specify an overwash frequency, but then the user documentation mentions that unreasonable results will be produced at resolutions finer than a 30-meter cell size. Second, various erosion inputs are allowed for different wetland types, including regularly- and irregularly-flooded marsh, and tidal flats; however, these rates of erosion are not actually applied in the model unless a 9 km fetch is present. Finally, SLAMM allows input values for various freshwater parameters. However, according to the parameter sensitivity analysis, substantially varying these parameters has limited effect. These examples demonstrate that while the SLAMM model produces wetland change projections useful for future planning discussions, there are still a number of refinements that would improve the model.

These recommendations represent ways in which statewide or site-specific SLAMM outputs could be improved. Despite the potential for improvement in the future, the results presented in this report, as well as the associated digital data on the companion hard drive, are useful as a general planning tool. These results show a probable set of projected impacts on coastal wetlands expected from projected sea-level rise scenarios across the coastal region of the Commonwealth of Massachusetts, and can be used to address a number of important questions regarding the fate of coastal marsh systems throughout coastal Massachusetts, and to inform the need for future field and modeling studies.

3.0 SLAMM RESULTS AND COMPANION DIGITAL DATA

This section of the report provides a summary of the results from the statewide SLAMM modeling. The discussion below provides an example analysis and discussion of a subset of the map and tabular SLAMM output results. The remainder of the raster results and tabular outputs (in .csv format) can be found on the companion hard drive to this report, and are subject to stakeholder review and interpretation.

3.1 DISCUSSION OF EXAMPLE MAPS

This section provides a map with the starting wetland classifications for the Great Marsh panel (with static accretion rates), as well as results from the intermediate-high sea-level rise scenario from the 2030, 2050, 2070 and 2100 projections. Three other example map sets are included for the intermediate-high sea-level rise scenarios for the Great Marsh (with MEM accretion rates), Plymouth and Buzzards Bay West panels in Appendix B. For each of the example map sets provided, the SLAMM output tables detailing the projected area of each wetland type at each future time horizon are also included in Appendix B as Table B-1 to Table B-4. Additional map sets and summary tables can be created for other sea-level rise scenarios and/or other map panels using the output rasters and summary data provided on the companion hard drive to this report.

Each wetland type is displayed in a different color identified in the legend located on the bottom left corner of the map. important wetland resource types noted are regularly-flooded marsh (in blue-green), irregularly-flooded marsh (in a bright green), ocean beach (in bright yellow), estuarine beach/tidal flat (in light tan), and transitional marsh/scrub-shrub (in dark orange).

Although SLAMM classifies Estuarine Beach and Tidal Flat separately, we have chosen to symbolize them as one color in the maps presented in this report. There is a particular NWI code, E2USN, that the SLAMM crosswalk conversion table changes to estuarine beach, with a note that E2USN areas should instead be changed to Tidal Flat if not along a shoreline. To accurately reclassify E2USN into SLAMM categorization, it would require each E2USN area to be evaluated individually to determine whether it was along a shore. This level processing was outside the scope of this project, potentially leaving the resulting Estuarine Beach areas confounded by the inclusion of Tidal Flat areas. As a remedy, they are presented together as a single category on the maps.

For the Great Marsh panel, with a static accretion rate input, little change occurs in the wetland type or area between 2011 (Figure 3-1) and 2030 (Figure 3-2). By 2050, however, there are significant changes. For example, north of the Merrimack River, there are two large patches of wetland mapped as irregularly-flooded marsh in 2011 and 2030 that transition to regularly-flooded marsh in the 2050 map (Figure 3-3). Other noticeable changes by 2050 are the Estuarine Beach near the mouth of the Merrimack River and the tidal flats within Plum Island Sound begin to transition to estuarine open water as the sea level rises. Additionally, the ocean beach on the seaward side of Plum Island narrows (i.e., converting to open ocean) through erosion and inundation. These same changes progress through 2070, with the northern patches of regularly-flooded marsh expanding, and the estuarine beach along the Merrimack and the tidal flats within Plum Island Sound practically disappearing. Additionally, by 2070, much of the estuarine beach areas along the creeks in the Ipswich River and Essex Bay convert to estuarine open water for this scenario (Figure 3-4).

Finally, by 2100, almost all the irregularly-flooded marsh converts to regularly-flooded marsh, and the two north areas of marsh that first transitioned to regularly-flooded marsh convert to tidal flat by 2100 (Figure 3-5). Additionally, estuarine beach and tidal flats further convert to estuarine open water, the ocean beach increasingly narrows, and areas of transitional marsh/scrub-shrub start to appear in locations that were dry land areas.

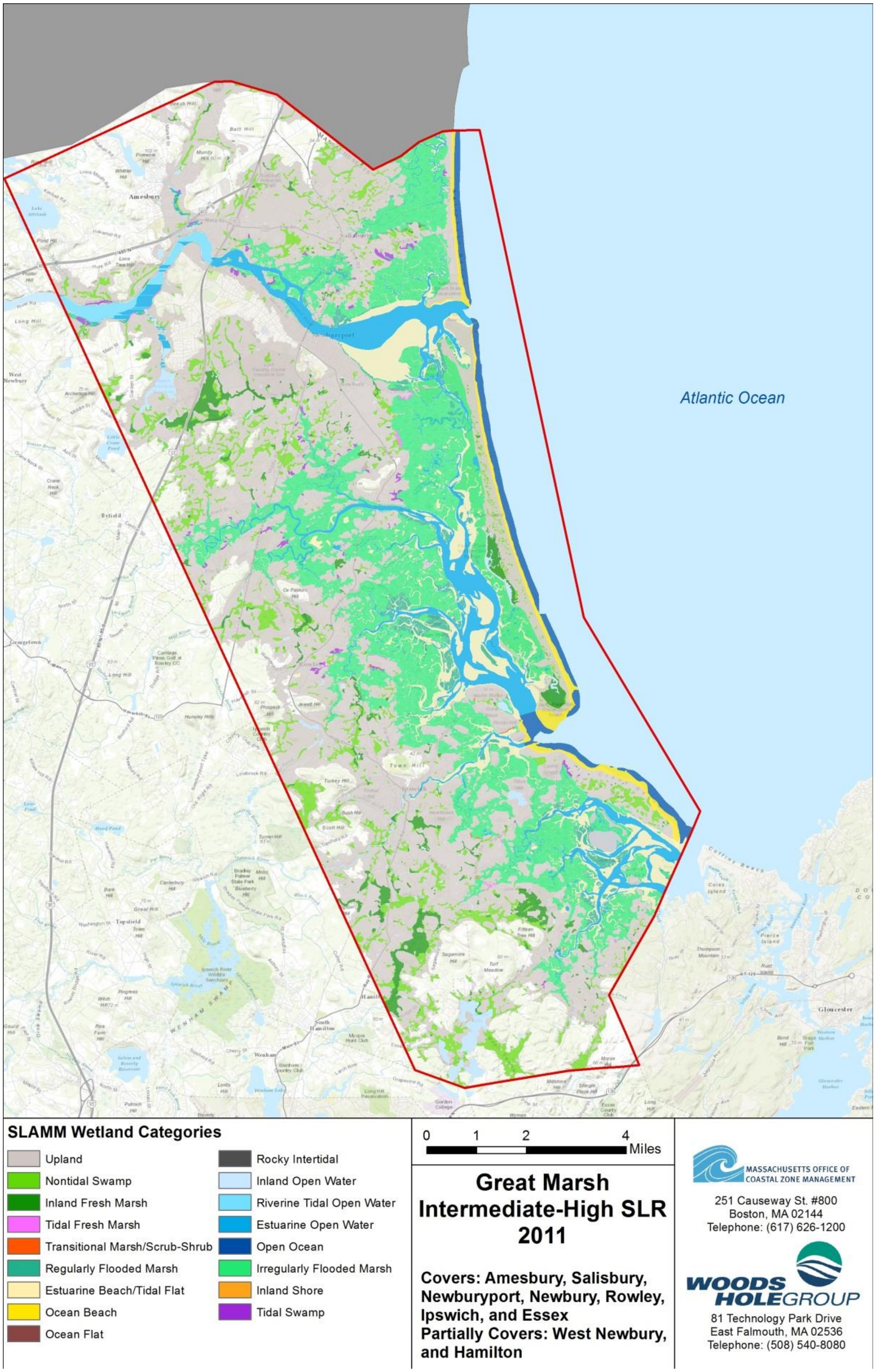

Figure 3-1. Wetland map for Great Marsh initial conditions.

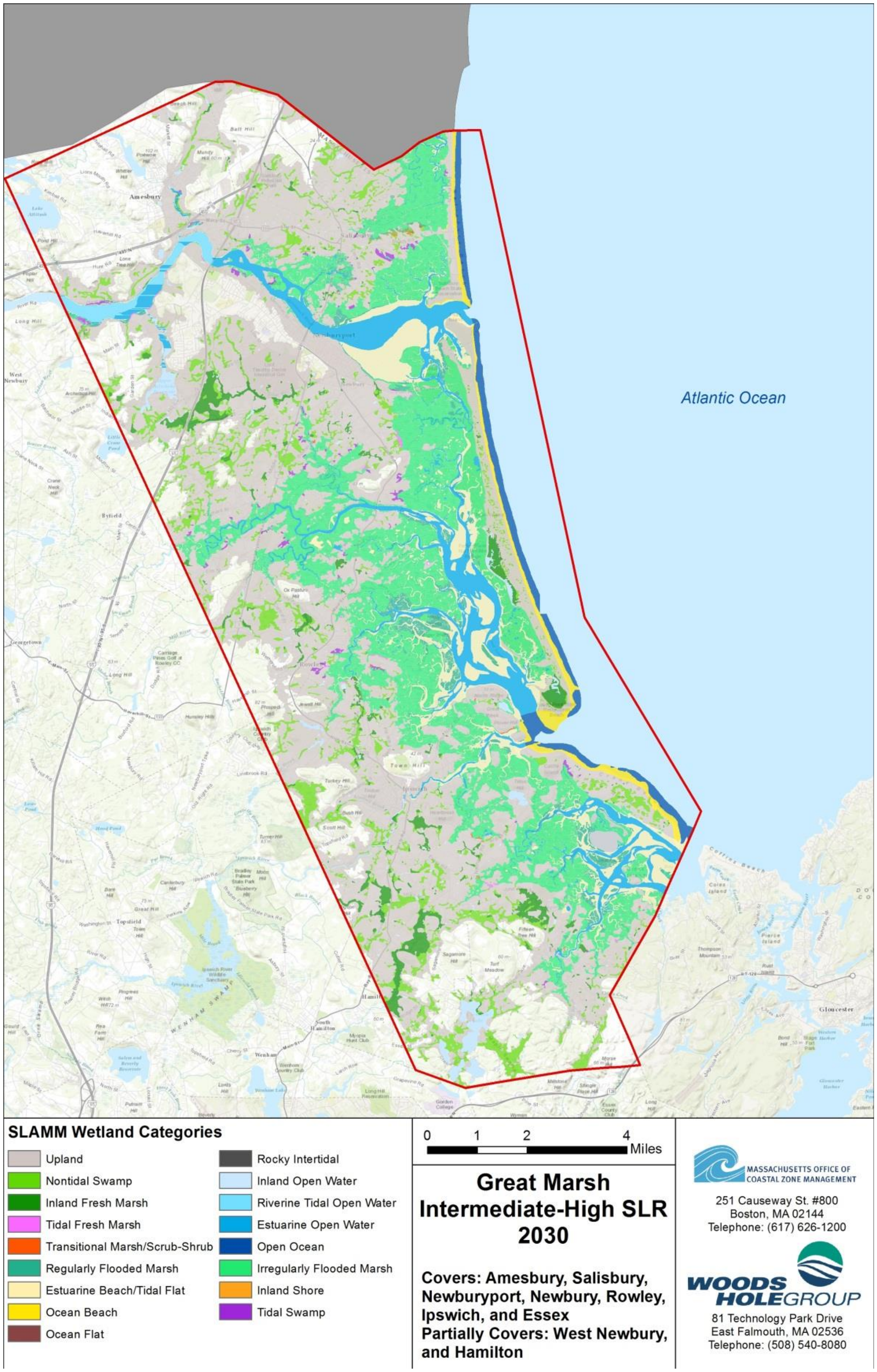

Figure 3-2. Projected wetland map for Great Marsh in 2030 with intermediate-high SLR scenario.

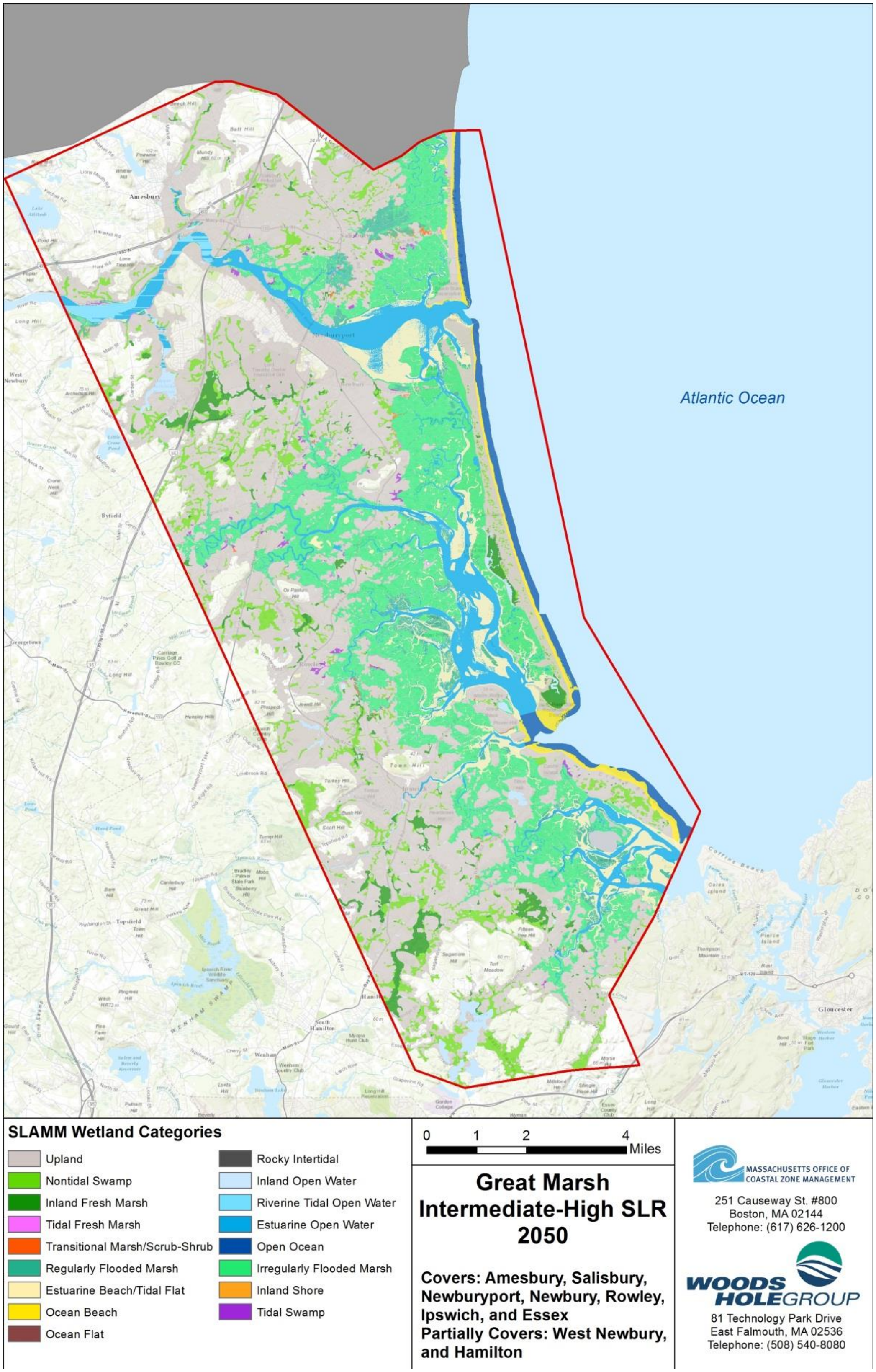

Figure 3-3. Projected wetland map for Great Marsh in 2050 with intermediate-high SLR scenario.

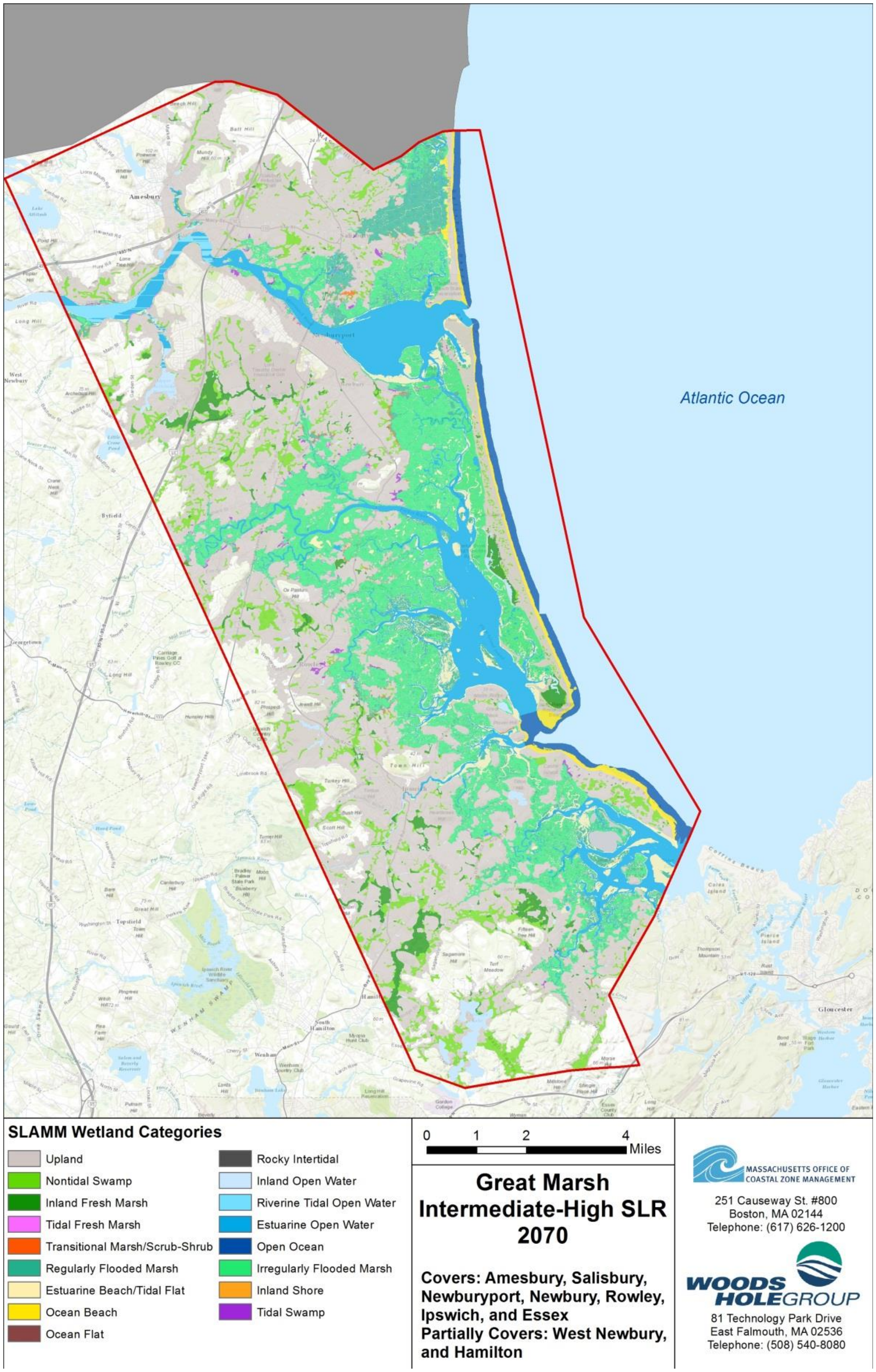

Figure 3-4. Projected wetland map for Great Marsh in 2070 with intermediate-high SLR scenario.

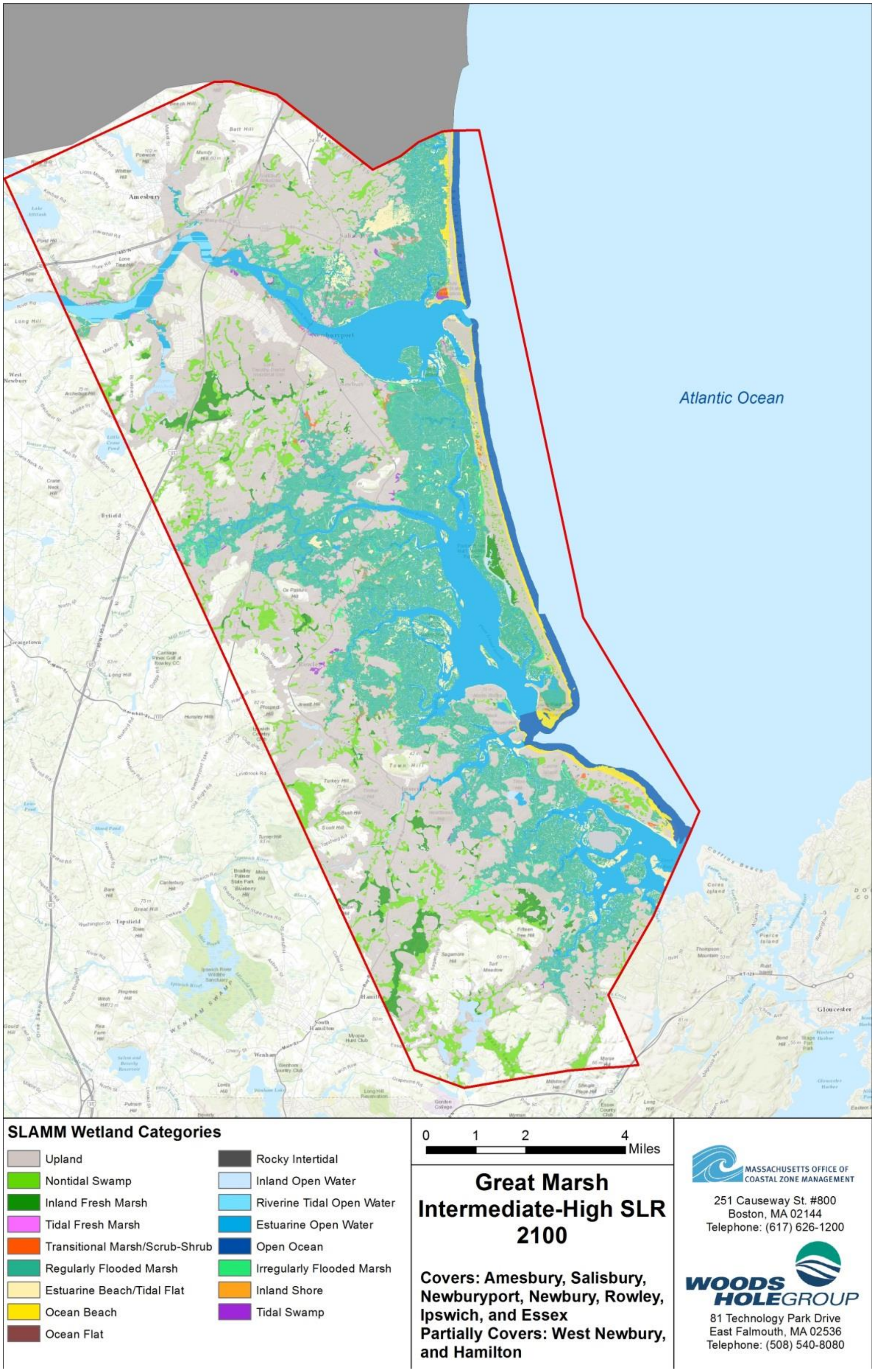

Figure 3-5. Projected wetland map for Great Marsh in 2100 with intermediate-high SLR scenario.

3.2 DISCUSSION OF WETLAND AREA CHANGES

When evaluating a small sub-system within each panel, the maps can identify changes within an area readily. However, when evaluating a large area such as an entire panel, it is difficult to evaluate areal gain or loss from each type of wetland at each time step by analyzing the maps alone. As such, additional graphical summaries for each map panel were created to illustrate regional changes to wetland types. As an example, this section presents the actual wetland area changes that occurred in:

1) two example map panels (Great Marsh and Cape Cod Vineyard South West) for the intermediate-high sea-level rise scenario,
2) three regional areas divided by tidal regime for the intermediate-high sea-level rise scenario, and
3) the combined statewide changes in wetland areas for all four sea-level rise scenarios.

3.2.1 Individual Panel Results

This section discusses two sets of graphs, one for the Great Marsh panel and one for the Cape Cod Vineyard Sound West panel, displaying changes in area for different wetland types for each map panel for the intermediate-high sea-level rise scenario. The first graph in each set displays the wetland types broken out individually (dry land, open ocean, estuarine open water, regularly-flooded marsh, etc.), while the second graph for each of the panels sums the areas from individual wetland categories to create broader categories for simpler comparisons between map panels. Table 3-1 describes which wetland types were combined to create these broader categories. These combined wetland categories (Table 3-1) are used for all graphs in this section, as well as sections 3.2.2 and 3.2.3. SLAMM simulates more than 20 wetland types. Although all types present in Massachusetts were simulated and presented on the maps, to simplify the discussion of specific changes occurring as sea level rises, only the six types listed in Table 3-1 are presented on the graphs.

Table 3-1. Wetland types merged to form combined wetland categories.

Individual Wetland Category	Combined Wetland Category	Graph Color
Dry Land	Dry Land	Brown
Open Ocean	Combined Open Water	Blue
Estuarine Open Water		
Regularly-Flooded Marsh	Combined Marsh	Green
Irregularly-Flooded Marsh		
Transitional Salt Marsh		

For each wetland category, whether individual or combined, the bars on the graphs represent the annual change in area for that wetland type for each 10-year interval (i.e. 2030 to 2040, 2040 to 2050, etc.), with the exception of the first interval, which represents the annual change for a 19-year interval from 2011 to 2030. For a summary of the time period each bar represents, see Table 3-2. Because the rates are annualized, they are comparable. These shorter time-intervals allow a more detailed analysis of when significant changes are taking place that might otherwise be obscured if only the mapped out-years were evaluated. Bars above the x-axis in the graphs indicate there was an increase in area for that wetland type and time interval, while bars below the x-axis indicate there was a decrease in area for that wetland type and time interval.

Table 3-2. Time periods represented by each bar in the annual change graphs.

Bar	Time Period
1	2011-2030
2	2030-2040
3	2040-2050
4	2050-2060
5	2060-2070
6	2070-2080
7	2080-2090
8	2090-2100

The Great Marsh results for the average annual change in area over the evaluation periods shown in Table 3-2 for individual wetland types are shown in Figure 3-6. Some key observations from these results include:

- Most initial changes for all wetland categories are relatively small in magnitude.
- Land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- The changes with the largest magnitude will occur within the regularly-flooded and irregularly-flooded marsh categories. irregularly-flooded marsh is essentially replaced by regularly-flooded marsh. This happens most significantly in the 2070-2080, 2080-2090, and 2090-2100 time steps.
- Only very minor area changes occur within open ocean and transitional salt marsh.

By combining some of these wetland types, as outlined in Table 3-1, the interpretation of these changes is somewhat different. The Great Marsh results for the annual change in areas of combined wetland types are shown in Figure 3-7. Some key observations from these results include:

- As before, most initial changes are relatively small in magnitude.
- As before, land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- With the individual wetland types, large changes were seen in the regularly-flooded and irregularly-flooded marsh categories as one replaced the other, with

the largest changes occurring in the later time steps. When all marsh types are combined, the picture is entirely different. Because the changes experienced in regularly- and irregularly-flooded marsh types essentially cancel each other out, when the combined marsh area is evaluated, the magnitude of area changes is very small. Additionally, until the 2090 to 2100 time period, these combined changes actually result in a net increase in total marsh area.

- The combined open water category appears to have the largest changes of any of the wetland classes analyzed by this graph (Figure 3-7), and the largest change actually occurs in the 2050 to 2060 time period. Although the open water area will continue to increase after 2060, this time period represents a significant turning point within the intermediate-high sea-level rise scenario where, based on the projected water levels and the surrounding elevations, significant changes will occur.

The Cape Cod Vineyard Sound West results for the individual wetland types are shown in Figure 3-8. Some key observations from these results include:

- In contrast to the Great Marsh panel discussed above, where most initial changes were relatively small in magnitude, there are some rather large area changes that occur during the early years in the Cape Cod Vineyard Sound West panel. For example, the largest changes in area to regularly-flooded marsh and irregularly-flooded marsh occur prior to 2050.
- Like the Great Marsh panel, land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- The changes with the largest magnitude will occur within the dry land, estuarine open water and irregularly-flooded marsh categories. Unlike the Great Marsh panel, in the Cape Cod Vineyard Sound West panel irregularly-flooded marsh is not replaced by regularly-flooded marsh. Instead, it appears to be replaced by either estuarine open water or tidal flat during the rest of the model simulation, with the largest changes happening during the middle of the century.
- Only vary minor area changes occur within transitional salt marsh.

By combining some of these wetland types, as outlined in Table 3-1, interpretation of these changes is different. The Cape Cod Vineyard Sound West results for the area changes of combined wetland types are shown in Figure 3-9. Some key observations from these results include:

- As before, land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- When wetland types are combined, decreased dry land and increased open water are the largest annual area changes projected to occur in the Cape Cod Vineyard Sound West area. When the combined marsh area is evaluated, the magnitude of area changes is smaller than it appeared by individual marsh type, but there is still an overall loss of marsh by 2100.

Similar graphs for all remaining map panels are presented in Appendix C.

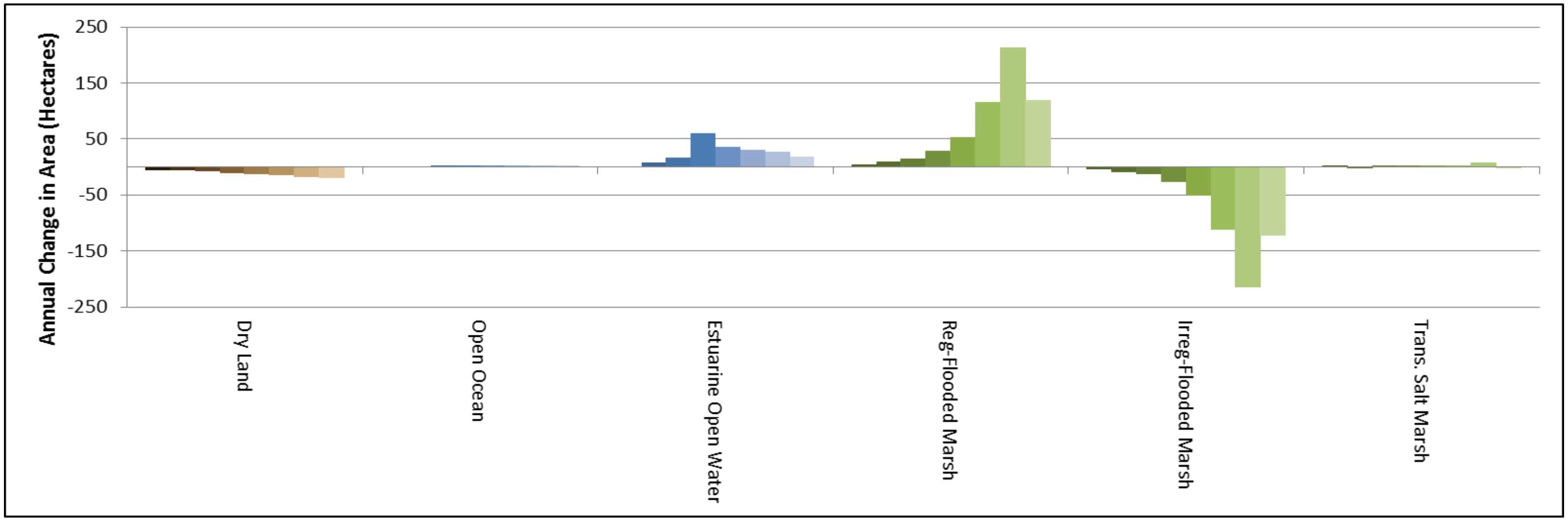

Figure 3-6. **Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Great Marsh (00) panel (with static accretion).**

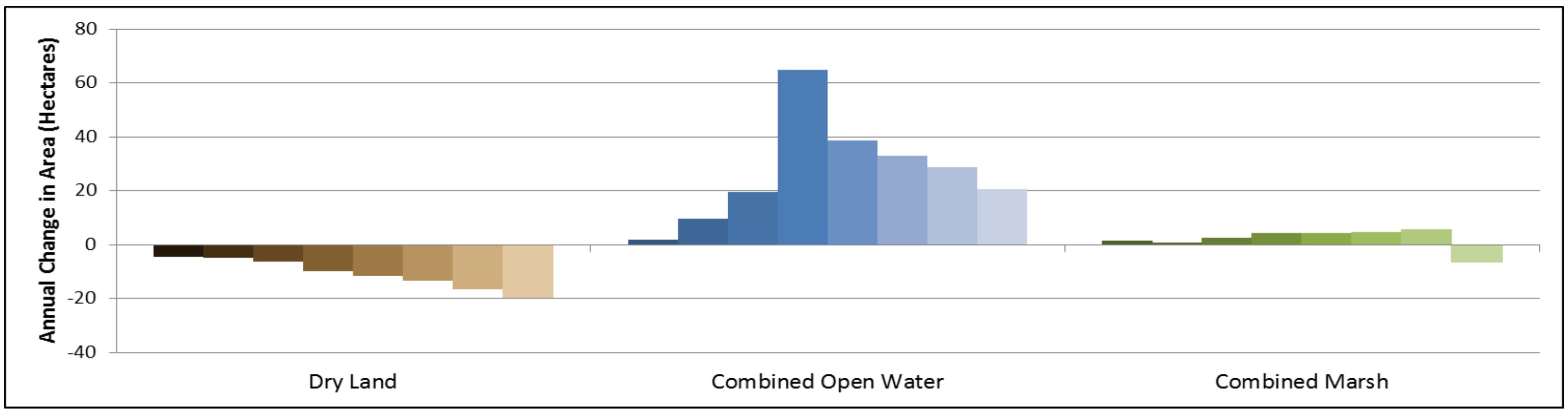

Figure 3-7. **Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Great Marsh (00) panel (with static accretion).**

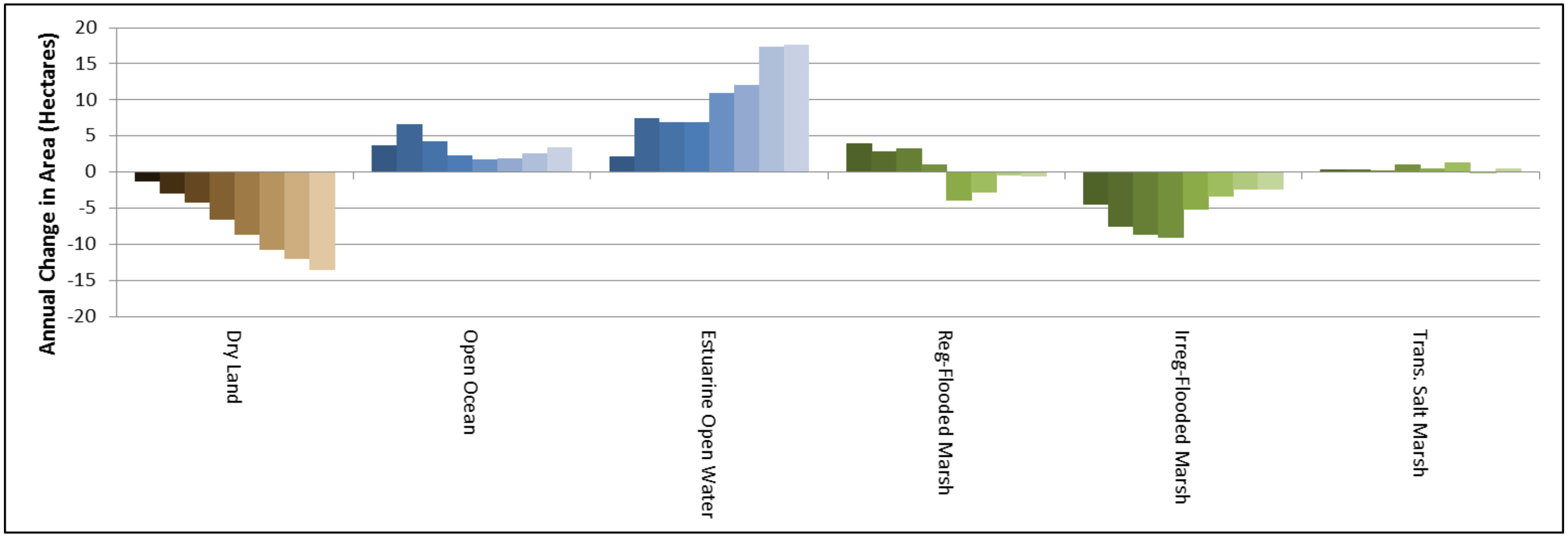

Figure 3-8. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Vineyard Sound West (08) panel.

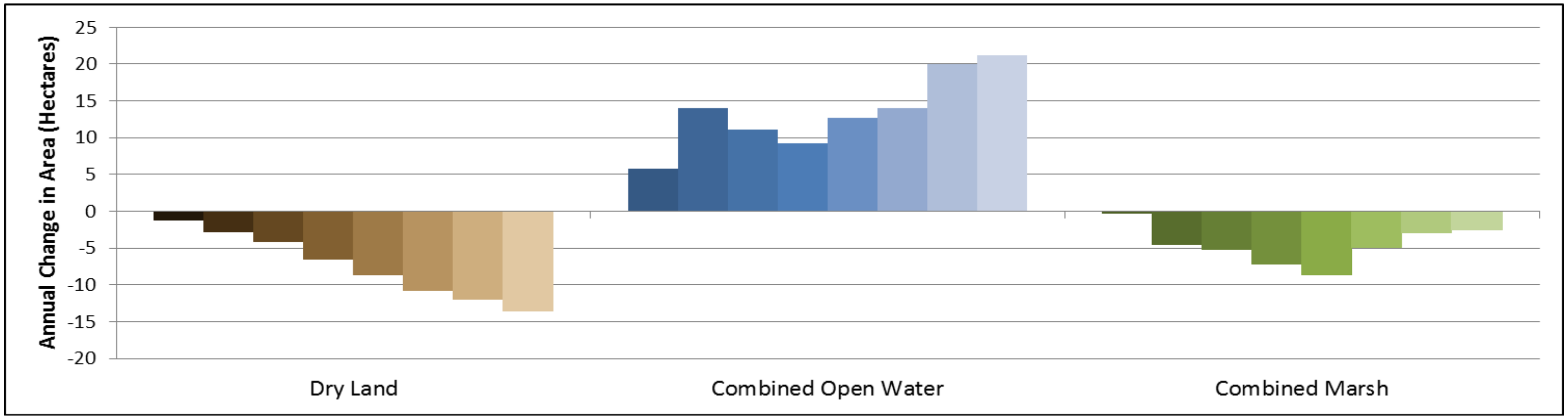

Figure 3-9. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Vineyard Sound West (08) panel.

3.2.2 Regional Results Based on Different Tidal Regimes

This section discusses three sets of graphs, one for each of three regional tidal regimes that display the changes in area for different wetland types for each of the different tidal regime areas for the intermediate-high sea-level rise scenario. Statewide, map panel areas could be grouped geographically and by similar great diurnal tidal range into three classes:

1) "Microtidal": average great diurnal tidal range < 1m; panels 07, 08, 13 to 17
2) "Mesotidal": average great diurnal tidal range 1-1.5m; panels 09, 10, & 12
3) "Macrotidal": average great diurnal tidal range >3m; panels 00 to 05

As discussed in the parameter sensitivity analysis (Section 2.3.1), tidal range is one of the most important parameters for determining the effect of sea-level rise on wetland change. Given the varied tidal ranges present in different parts of the state, it is useful to compare the general trends occurring in these different areas. Table 3-7 shows the individual great diurnal tidal range inputs for each panel simulation and how each was grouped for this comparative tidal range analysis. Due to the unique geography of the Taunton River and Cape Cod Monomoy map panels, these two areas were not included in any of the three groups described in Table 3-7 or the graphs that follow.

Table 3-7. Tidal range groupings based on geography and great diurnal tidal range.

Microtidal		Mesotidal		Macrotidal	
Avg. GDTR < 1 m		1 m < Avg. GDTR < 1.5 m		Avg. GDTR > 3 m	
Vineyard Sound		Buzzards Bay		Massachusetts Bay	
Map Panel	GDTR (m)	Map Panel	GDTR (m)	Map Panel	GDTR (m)
07CCVS East	1.33	09BuzBayE	1.11	00GreatMarsh	2.80
08CCVS West	0.91	10BuzBayW	1.26	01NorthShore	2.95
13MVNE	0.73	12ElizIslands	1.10	02Boston	3.12
14MVS	0.83			03Plymouth	3.11
15MVNW	0.96			04CCBay	3.19
16NantN	1.09			05CCProv	3.07
17NantS	0.83				

As before, the first graph in each set displays the wetland types broken out individually (dry land, open ocean, estuarine open water, regularly-flooded marsh, etc.), while the second graph for each panel sums the areas from individual wetland categories to create broader categories for simpler comparisons between map panels (Table 3-1 lists which wetland types were combined to create broader categories).

As in section 3.2.1 (for each wetland category, whether individual or combined), the bars represent the annual change in area for that wetland type for each 10-year interval (i.e., 2030 to 2040, 2040 to 2050, etc.), with the exception of the first interval, which represents the annual change from 2011 to 2030. Table 3-2 summarizes the time period each bar represents

The combined microtidal results for the individual wetland types are shown in Figure 3-10. Some key observations from these results include:

- Although the largest changes will occur mid- to late-century, some initial changes were relatively large in magnitude, such as the changes to open ocean and regularly- and irregularly-flooded marshes.
- Land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- The changes with the largest magnitude occur within the estuarine open water and dry land categories.
- Only very minor area changes occur within the transitional salt marsh category.

By combining some of these wetland types, as outlined in Table 3-1, interpretation of these changes is somewhat different. The microtidal regional results for the area changes of combined wetland types are shown in Figure 3-11. Some key observations from these results include:

- What appeared to be a significant change in regularly- and irregularly-flooded marshes in the early time periods, is now a relatively small change in magnitude since the marsh types are essentially replacing each other in the first couple decades. The largest total annual losses of marsh habitat will occur in the 2060 to 2070 time period.
- As before, land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- Large changes were seen in the estuarine open water and dry land categories, with the largest changes occurring in the later time steps. When both open water types are combined, the early time periods also experience a significant increase in open water areas. Starting in 2030, annual increases in open water area are projected to be fairly steady.

The combined mesotidal results for the individual wetland types are shown in Figure 3-12. Some key observations from these results include:

- In contrast to the microtidal panel discussed above, where most initial changes were relatively small in magnitude, there are some rather large area changes during these early years in the mesotidal areas. For example, the largest annual changes in area to regularly- and irregularly-flooded marsh occur between 2030 and 2060.

- Like the microtidal region, areas categorized as dry land continually decrease in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- Simulated changes with the largest magnitude occur within the dry land, regularly-flooded marsh, and irregularly-flooded marsh categories. Like the microtidal regional, irregularly-flooded marsh is initially replaced by regularly-flooded marsh in the early decades. By 2060, both marsh types begin decreasing in area. At that point, these areas appear to be replaced by either estuarine open water (or other wetland categories such as tidal flat which are not pictured on these graphs) for the rest of the model simulation.
- Only very minor area changes occur within open ocean and transitional salt marsh throughout the entire simulation.

By combining some of these wetland types, as outlined in Table 3-1, the interpretation of these changes is somewhat different. The mesotidal results for the area changes of combined wetland types are shown in Figure 3-13. Some key observations from these results include:

- As before, land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- With the individual wetland types, large changes were seen in the regularly-flooded marsh and irregularly-flooded marsh. When both open marsh types are combined, the magnitude of change is decreased in the early decades, and compounded in the later decades. The annual loss in marsh area is compounded, particularly from 2060 to 2080, when all marsh types are combined.
- When the change in combined open water area is compared to other combined wetland area changes, the magnitude of these changes appears more significant than either open water type alone. Individually, the regularly- and irregularly-flooded marsh categories appeared to have larger changes, which could be interpreted as loss of marsh. However, with the combined categories, the magnitude of change in the combined open water (growth of open water area) is considerably larger than the projected change in the combined marsh category, indicating that a significant amount of marsh change is transition from irregularly-flooded marsh to regularly-flooded marsh.

The combined macrotidal results for the individual wetland types are shown in Figure 3-14. Some key observations from these results include:

- In contrast to the mesotidal region discussed above, there are generally only small changes occurring initially in the macrotidal areas. For example, the largest changes in regularly- and irregularly-flooded Marsh in the macrotidal areas don’t occur until 2070 to 2080 and 2080 to 2090.
- Like both the microtidal and mesotidal regions, areas categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.

- As in the mesotidal regions, the largest magnitude changes occur within the regularly-flooded marsh and irregularly-flooded marsh categories, where irregularly-flooded marsh is generally replaced by regularly-flooded marsh. Unlike areas with smaller tidal ranges, where this conversion from one marsh type to the other was confined mainly to the early half of the century, under a macrotidal regime regularly-flooded marsh doesn't start to significantly replace irregularly-flooded marsh until the second half of the century.
- Very minor area changes occur within transitional salt marsh, estuarine beach, ocean beach and ocean flat throughout the simulation.

By combining some of these wetland types, as outlined in Table 3-1, the interpretation of these changes is somewhat different. The macrotidal results for the area changes of combined wetland types are shown in Figure 3-15. Some key observations from these results include:

- When combined, the most significant changes still occur in the second half of the century. This is particularly true of dry land and combined open water, which both have their largest magnitude of change after 2050.
- As before, land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- With the individual wetland types, large changes were seen in the regularly-flooded marsh and irregularly-flooded marsh categories. When both open marsh types are combined, however, the magnitude of change decreases as they partially replace each other. Unique to this tidal regime, though, is by 2100 there is actually a net increase in combined marsh area.

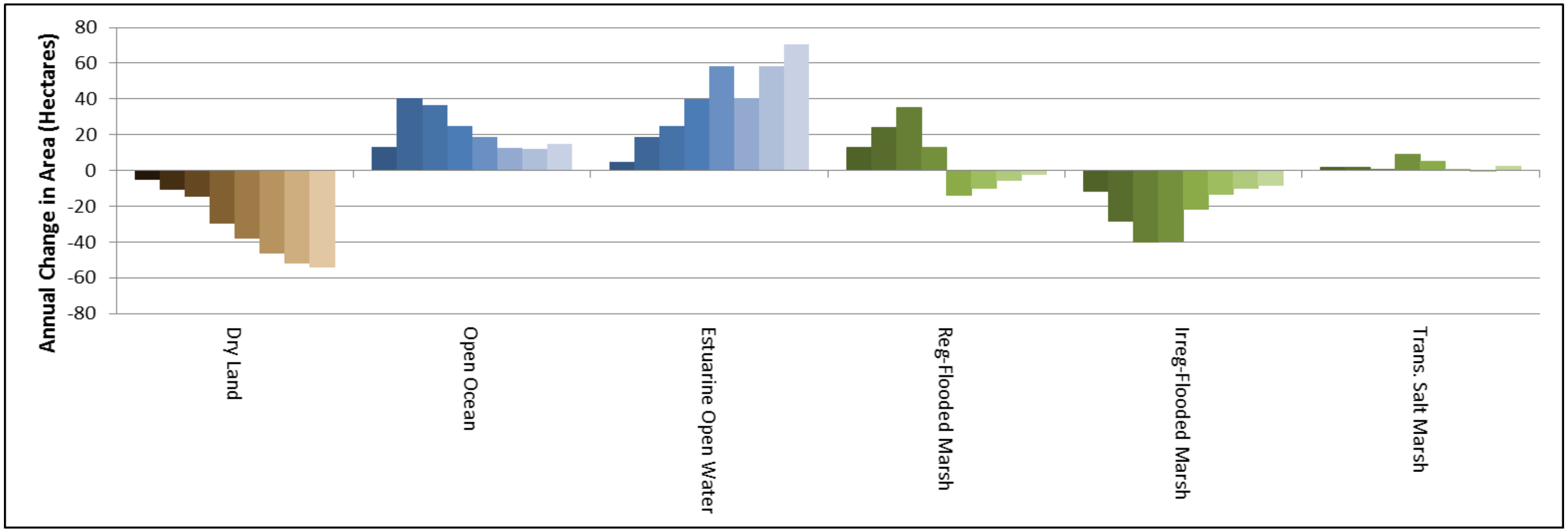

Figure 3-10. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for microtidal areas (average GDTR < 1m; panels 07, 08, 13 to 17).

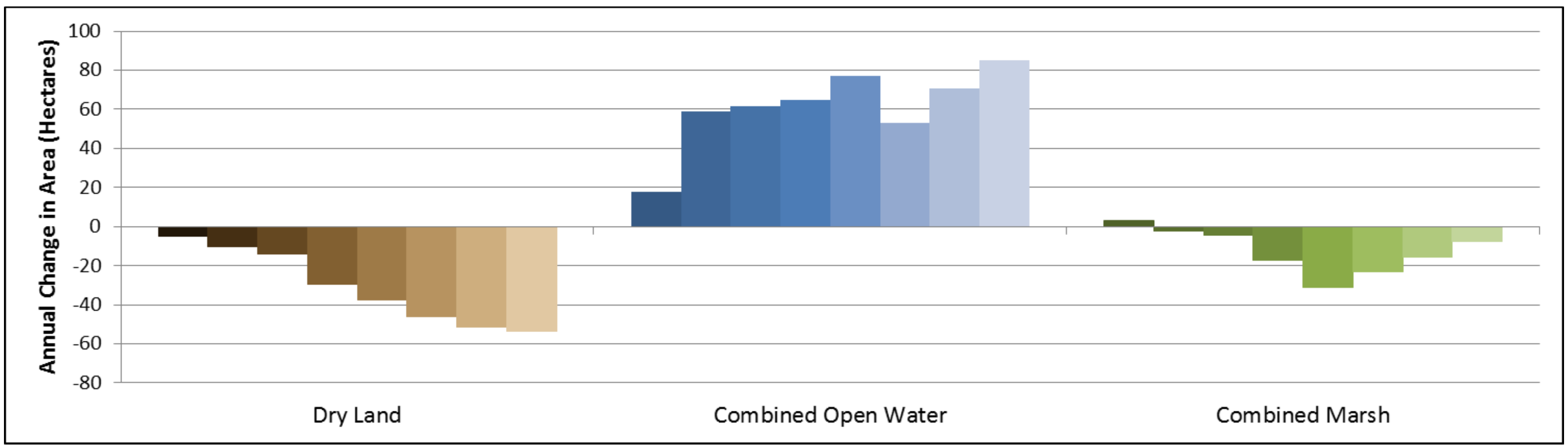

Figure 3-11. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for microtidal areas.

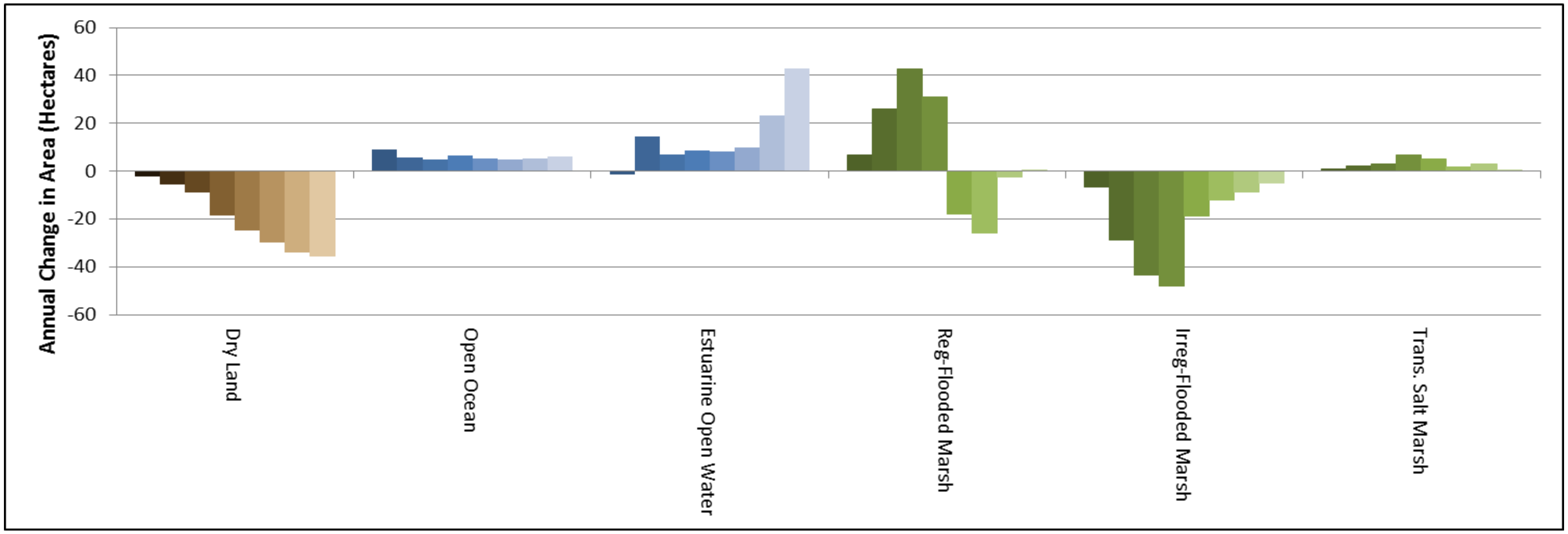

Figure 3-12. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for mesotidal areas (average GDTR 1 - 1.5 m; panels 09, 10, & 12).

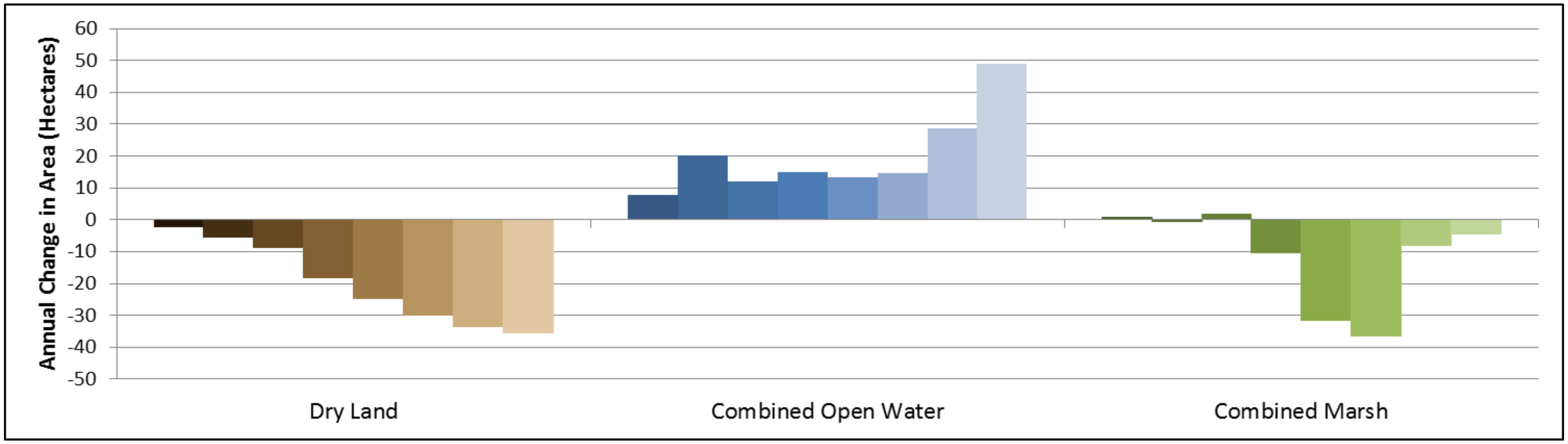

Figure 3-13. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for mesotidal areas.

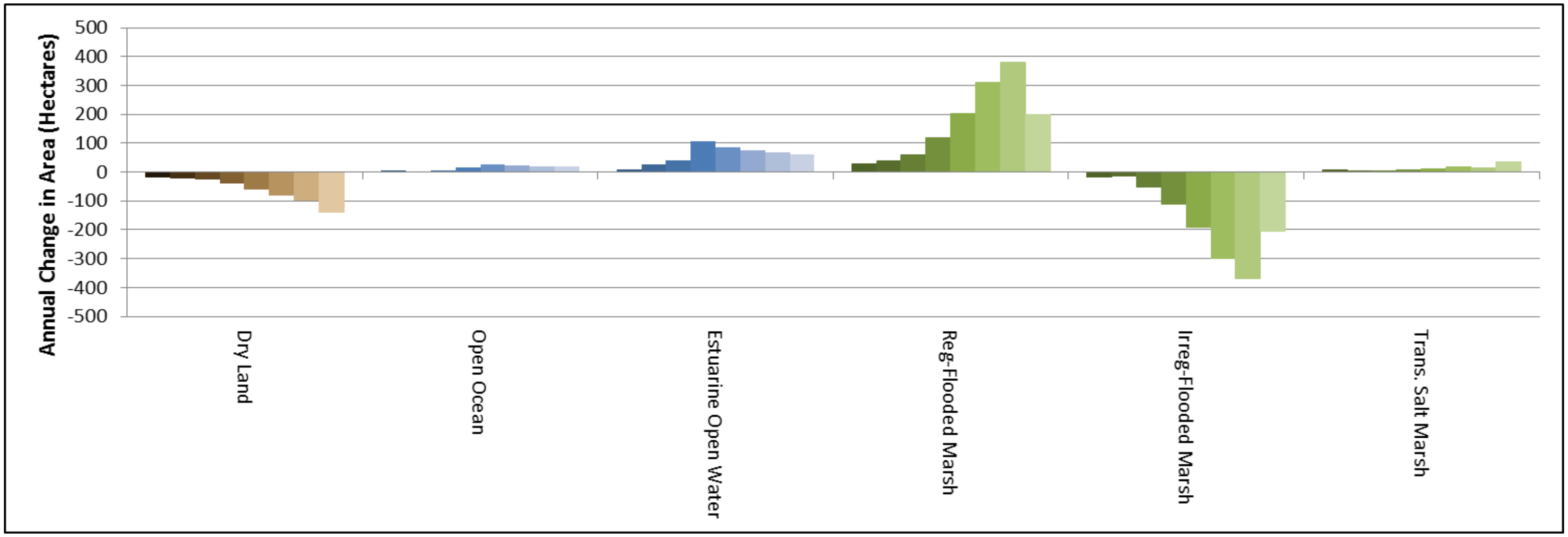

Figure 3-14. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for macrotidal areas (average GDTR > 3 m; panels 00 to 05).

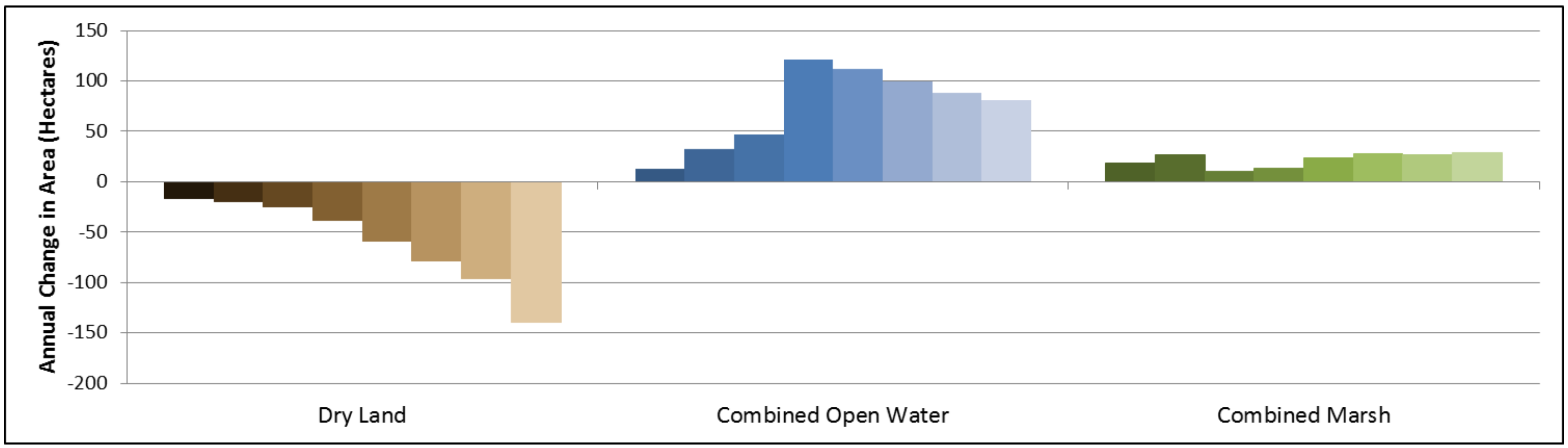

Figure 3-15. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for macrotidal areas.

3.2.3 Statewide Results Based on Different Sea-Level Rise Scenarios

This section discusses four sets of graphs, one for each sea-level rise scenario simulated in this analysis (low, intermediate-low, intermediate-high, and high). For this discussion, annual wetland area change results from all 18 panels have been combined for an inclusive statewide evaluation of the potential changes to coastal wetlands due to sea-level rise.

As before, the first graph in each set displays the wetland types broken out individually (dry land, open ocean, estuarine open water, regularly-flooded marsh, etc.), while the second graph for each panel sums the areas from individual wetland categories to create broader categories for simpler comparisons between map sea-level rise scenarios (refer to Table 3-1 above for a list of which wetland types were combined to create these broader categories).

The statewide results for the individual wetland types for the low, intermediate-low, intermediate-high, and high sea-level rise scenarios are shown in Figures 3-16, 3-18, 3-20 and 3-22. Some key observations from these results include:

- The most significant difference between all four sea-level rise scenarios is the magnitude of the expected changes to wetland areas increases with increasing sea-level rise.
- In the low sea-level rise scenario, the wetland area changes are relatively minor, and with the exception of irregularly-flooded marsh, most changes are relatively consistent over time. Irregularly-flooded marsh, however, is projected to have a relatively large increase between 2030 and 2040, followed by limited subsequent change (Figure 3-16).
- The results from the combined statewide intermediate-low (Figure 3-18) and intermediate-high (Figure 3-20) sea-level rise scenarios display a similar pattern to each other, but differ from the results of the low sea-level rise scenario (Figure 3-16), as significant wetland changes are projected mostly throughout the second half of the century.
- As expected with a greater increase in sea level, the statewide results from the high sea-level rise scenario show the largest potential changes. There is one additional difference with these results: although in the other three sea-level rise scenarios regularly-flooded marsh generally increased throughout the simulations, in the high sea-level rise scenario, the area of regularly-flooded marsh decreases significantly in area after 2070.

By combining some of these wetland types, as outlined in Table 3-1, interpretation of these changes is different. The statewide results for the areas of combined wetland types for the low, intermediate-low, intermediate-high, and high sea-level rise scenarios are shown in Figures 3-17, 3-19, 3-21 and 3-23. Some key observations from these results include:

- As with the individual wetland categories, the most significant difference between all four sea-level rise scenarios with the combined wetland areas results is the magnitude of the expected changes to wetland areas increases with increasing sea-level rise.

- While most of the combined wetland categories show the same general trend across all four sea-level rise scenarios, the combined marsh category responds differently depending on the magnitude of sea-level rise. The area of combined marsh experiences a net gain in the low and intermediate-low sea-level rise scenarios, a small gain and then a minor net loss in area in the intermediate-high scenario, and a net loss with significant changes after 2080 in the high sea-level rise scenario.

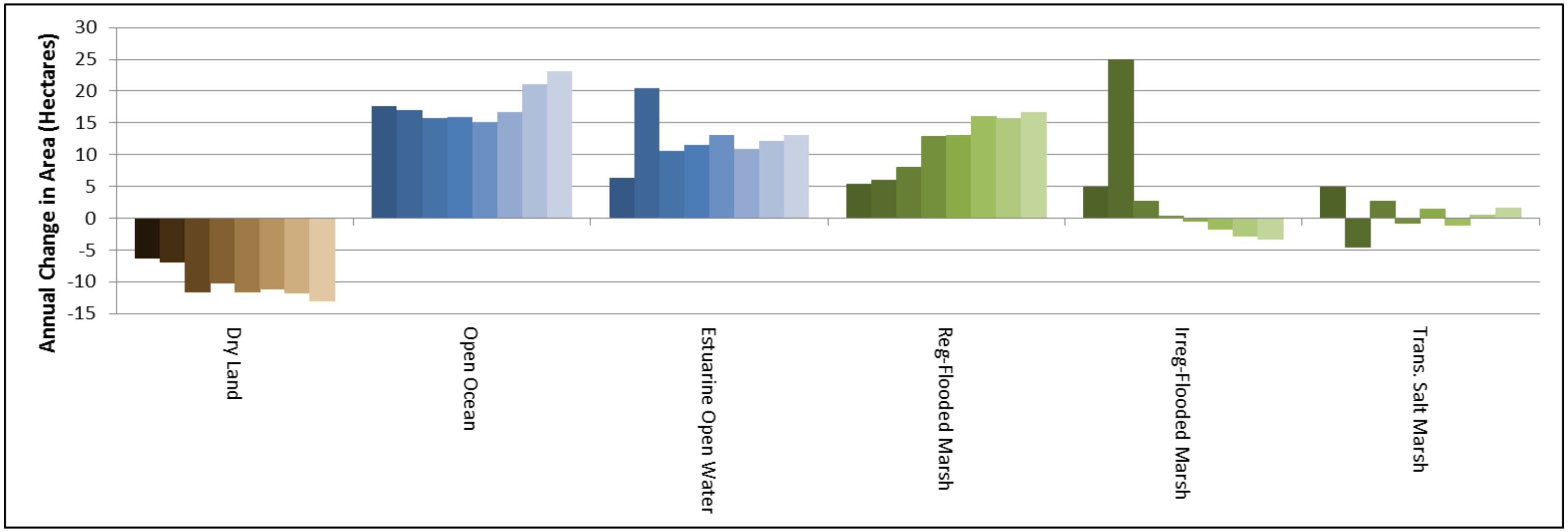

Figure 3-16. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 statewide with a low sea-level rise scenario.

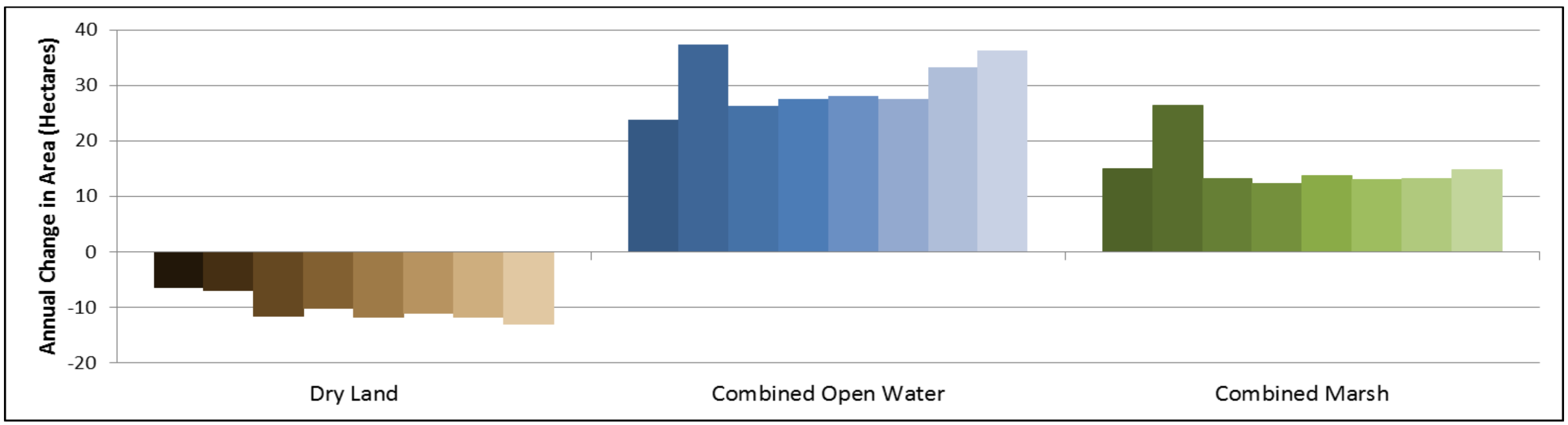

Figure 3-17. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 statewide with a low sea-level rise scenario.

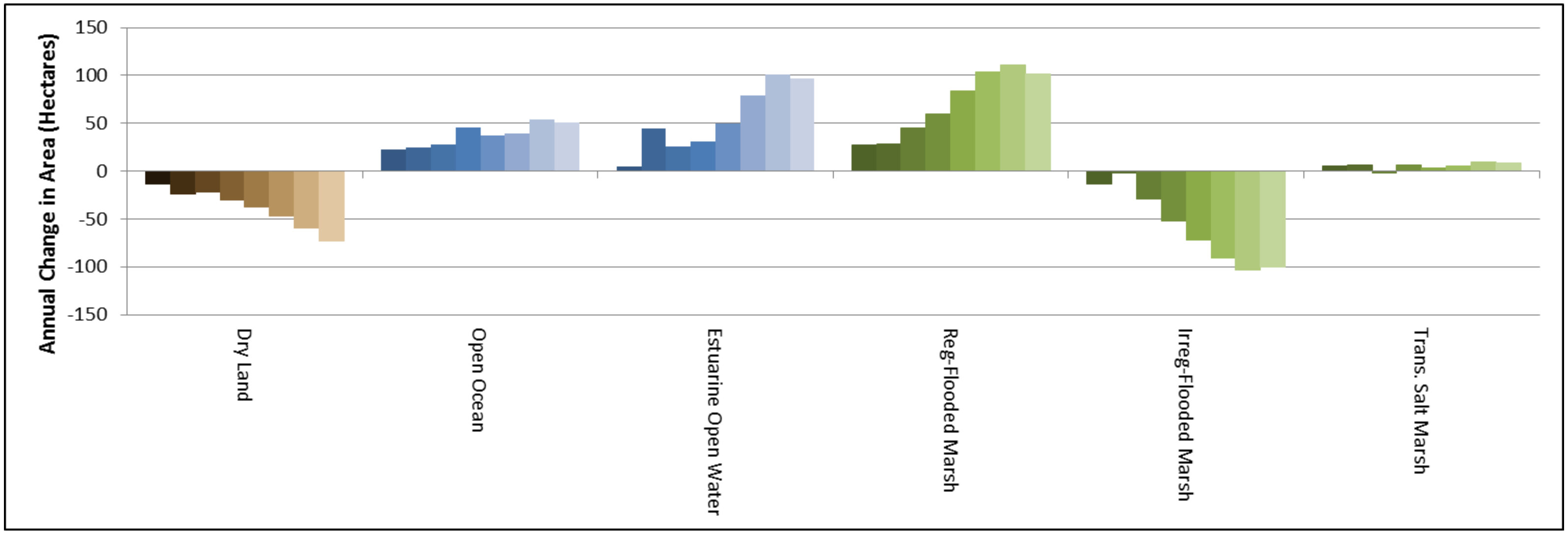

Figure 3-18. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 statewide with an intermediate-low sea-level rise scenario.

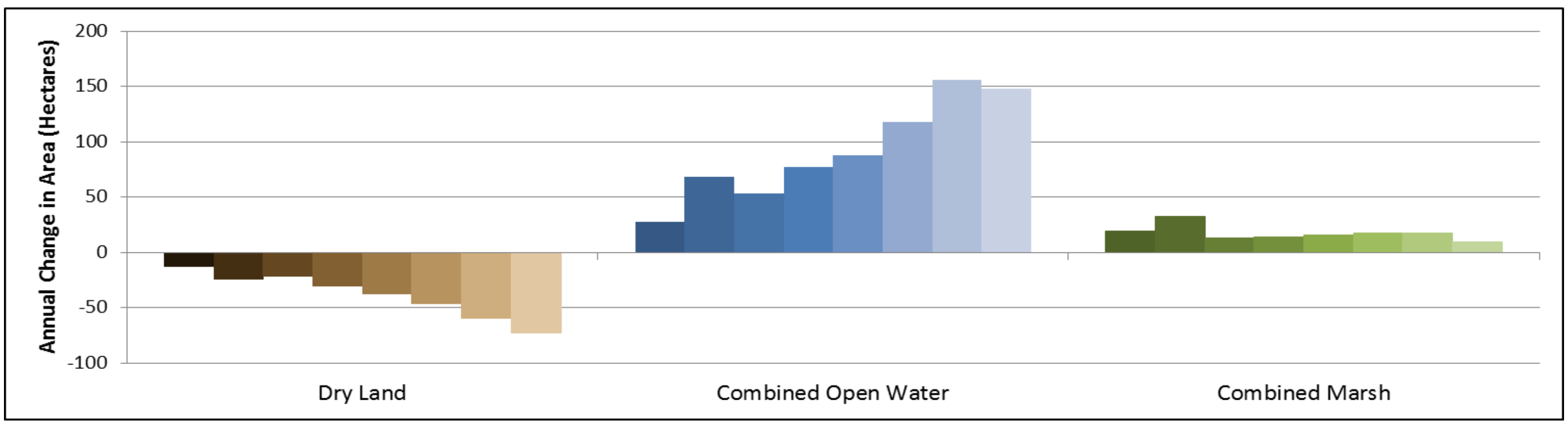

Figure 3-19. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 statewide with an intermediate-low sea-level rise scenario.

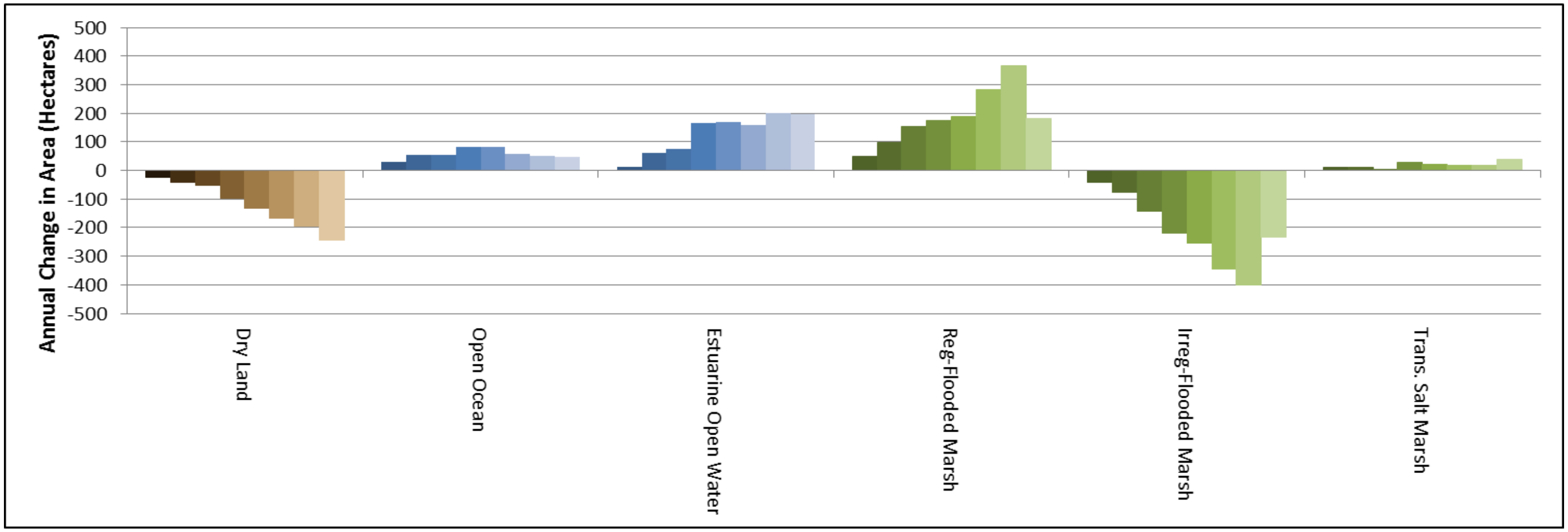

Figure 3-20. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 statewide with an intermediate-high sea-level rise scenario.

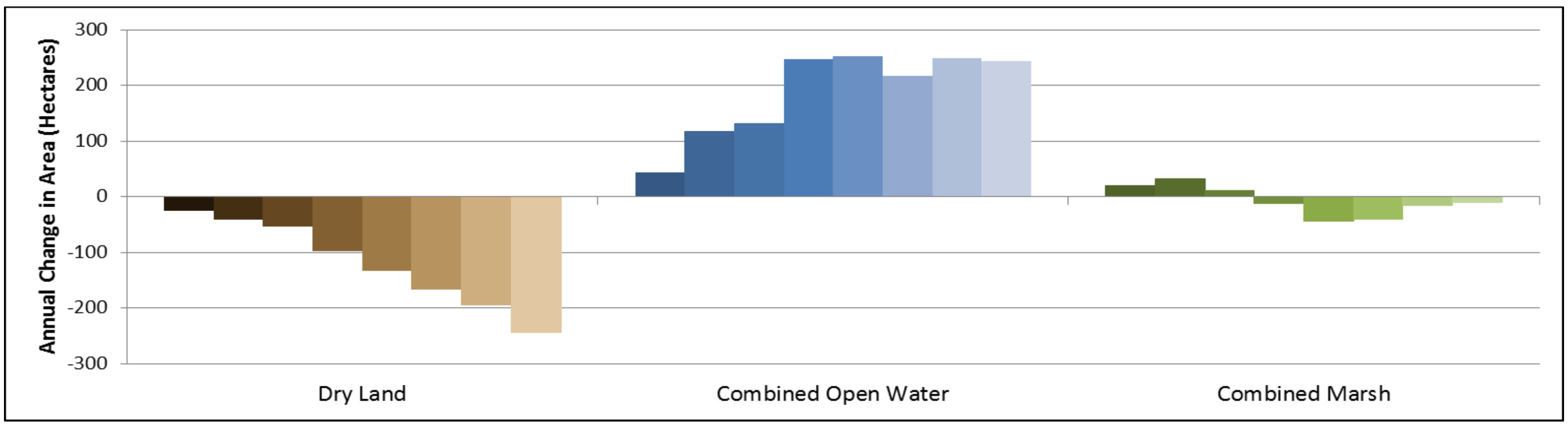

Figure 3-21. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 statewide with an intermediate-high sea-level rise scenario.

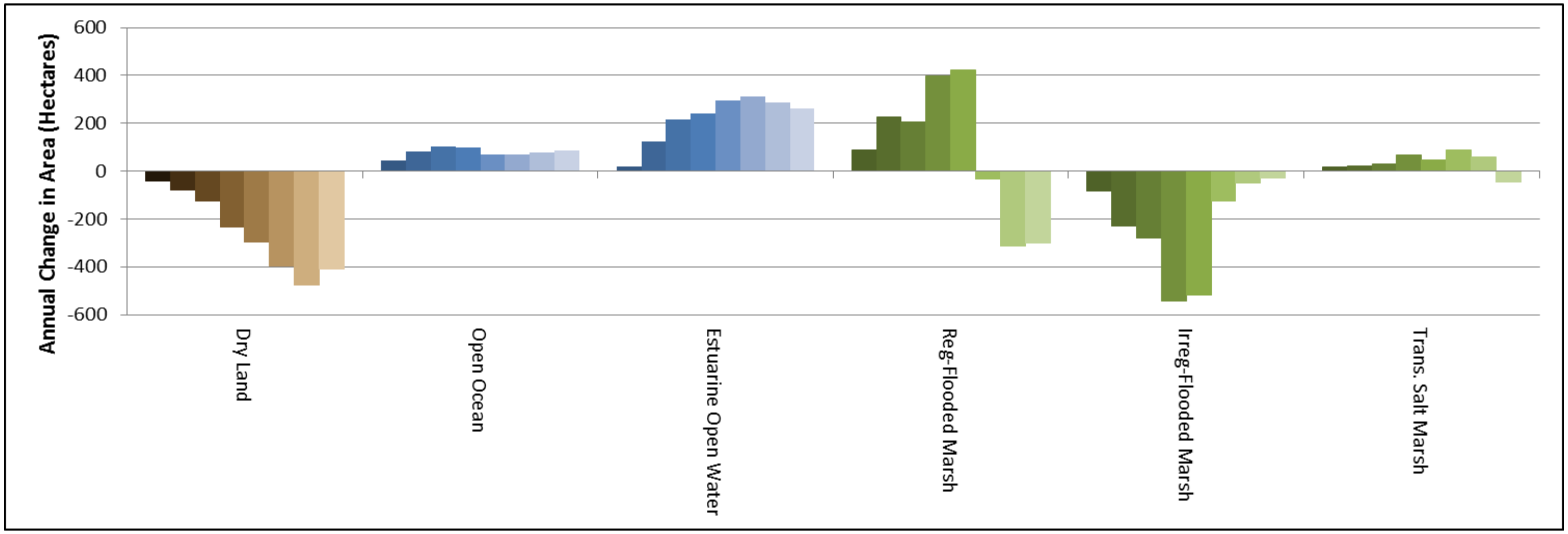

Figure 3-22. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 statewide with a high sea-level rise scenario.

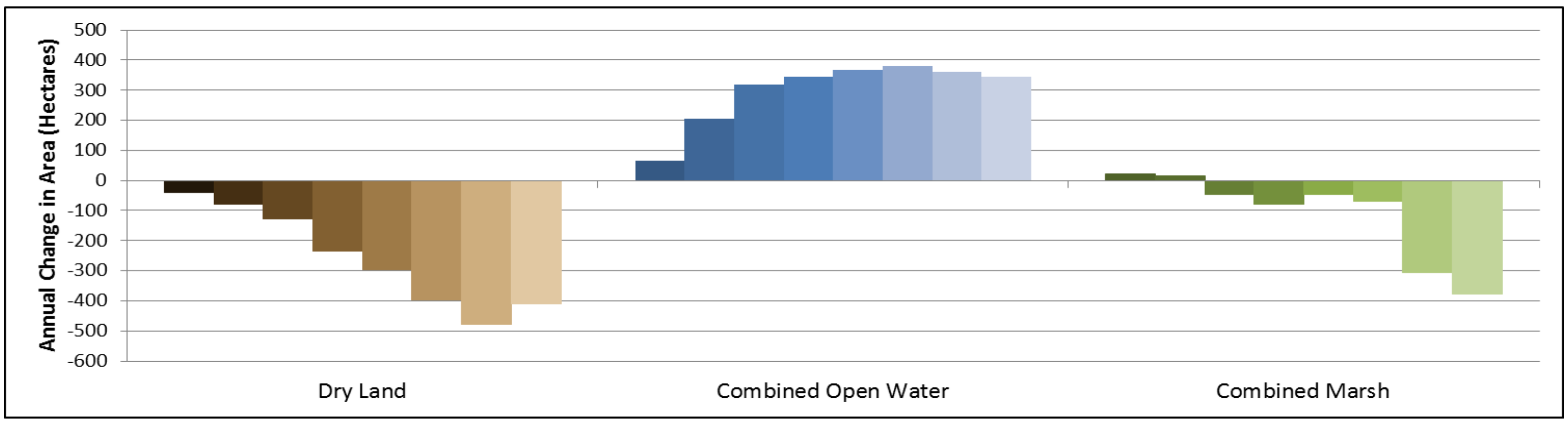

Figure 3-23. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 statewide with a high sea-level rise scenario.

3.3 DATA DELIVERABLE SUMMARY

This section of the report provides a summary of the results from the statewide SLAMM modeling completed under this project. The results listed below provide examples for some of the panels and describe the data that are available in the companion digital data set. Included with this report is a companion digital data set that contains full results from the study, including:

- A readme.txt file describing the digital data on the companion drive to this report, including descriptions of the individual files within each subfolder of the digital data compilation.
- Example maps for three panels in the Commonwealth: Great Marsh, Plymouth, and Buzzard Bay (panels shown in Figure 2-10). These include maps with and without the impervious overlay, for all sea-level rise scenarios, and for the start year (2011) out years 2030, 2050, 2070, and 2100. These maps are also discussed in Section 3.1. There are 40 example maps provided on the digital companion data to this report, which are also presented in Appendix B of this report. These are intended to be examples of maps that could be produced for all map panels, time periods, sea-level rise scenarios, and with and without the impervious overlays.
- The elevation sensitivity analysis, input conditions, all associated SLAMM files, and results in ArcGIS compatible format. These include results for the original LiDAR data, along with cases that artificially increase the elevation by 15 cm universally and those that decrease the elevation by 15 cm universally. These SLAMM runs were completed for the Great Marsh pilot area site. Also included are Microsoft Excel© compatible tables providing results of the change in area for all resource types in the pilot area.
- The pilot site (subset of the Great Marsh system panel) input conditions, all associated SLAMM files, and results are in ArcGIS compatible format. These include simulations and results for static accretion rates and time-variable MEM-generated accretion rates. Results are presented for all sea-level rise scenarios (low, intermediate low, intermediate high, and high) for static and time-variable accretion rates. Also included are Microsoft Excel© compatible tables providing the results of the change in area for all resource types in the pilot area.
- ArcGIS compatible shapefiles for the statewide simulations that show the extents for clipping the panels into Town Boundaries for each map panel.
- ArcGIS compatible shapefiles for all the subset divisions (freshwater subsets, erosion subsets, and tidal range subsets) within each map panel.
- Metadata files for all simulations, including pilot simulations and elevation sensitivity testing, as well as all final statewide runs.
- SLAMM input files and associated files for each statewide map panel simulations.
- Statewide results in ArcGIS compatible format for all map panels and all sea-level rise scenarios. This includes raw SLAMM results and post-processed results produced using the clipping algorithm. Also included for each map panel are summary Microsoft Excel© compatible tables providing the results of the change in area for all resource types in each map panel as a function of time. Results in

these tables are provided every 10 years, while ArcGIS compatible rasters are provided at 2030, 2050, 2070, and 2100.

- The impervious area overlay files in ArcGIS compatible format.

While this section presents a brief overview of the types of results available from this study, it is not intended to provide a complete discussion or interpretation of results for all locations studied. Some example analyses and discussions are included in Section 3. Results also have been used for specific locations and Towns within the Commonwealth as part of other ongoing resiliency and climate change adaptation projects. The maps presented in Appendix B and the graphs presented in Appendix C, as along with the full suite of SLAMM output files presented within the digital data set, are intended as tools that can be used by stakeholders to evaluate a wide variety of potential impacts caused by rising sea levels to the coastal ecosystems throughout the Commonwealth.

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APPENDIX A. DATA SOURCES & MODEL INPUTS

Table A-1. Open Coast Tide Range Input Data

00_GreatMarsh		01_Northshore		02_Boston		03_Plymouth		04_CapeCodBay	
Gage	Range ft	Gage	Range ft	Gage	Range ft	Gage	Range ft	Gage	Range ft
8440466	8.76	8441841	9.57	8443662	10.34	8445138	9.74	8447241	10.46
8440452	8.70	8442417	9.72	8443725	10.35	8446009	9.87		
8441241	9.49	8442645	9.70	8443970	10.27	8446166	10.68		
8441571	9.58			8444525	10.21	8446493	10.53		
8441551	9.46			8444788	10.35				
				8444162	9.82				
Avg	9.20	Avg	9.66	Avg	10.22	Avg	10.21	Avg	10.46

05_CapeCodPTown		06_CapeCodMonomoy		07_CapeCodVSE		08_CapeCodVSW		09_BuzzardsBayE	
Gage	Range ft	Gage	Range ft	Gage	Range ft	Gage	Range ft	Gage	Range ft
8446121	10.08	8447435	6.41	8447495	4.35	8447605	3.80	8447930	2.20
						8447930	2.20	8447685	4.25
								8447355	4.43
Avg	10.08	Avg	6.41	Avg	4.35	Avg	3.00	Avg	3.63

10_BuzzardsBayW		11_Taunton		12_ElizabethIslands		13_MarthasVineyardNE		14_MarthasVineyardS	
Gage	Range ft	Gage	Range ft	Gage	Range ft	Gage	Range ft	Gage	Range ft
8447277	4.08	8447281	4.93	8448248	3.80	8448157	2.13	MVCO	2.72
8447368	4.41	8447386	4.78	8448376	3.73	8448558	2.68		
8447416	4.36			8448251	3.32				
8447712	3.96								
8447842	3.84								
Avg	4.13	Avg	4.86	Avg	3.62	Avg	2.41	Avg	2.72

15_MarthasVineyardS		16_NantucketN		17_NanucketS	
Gage	Range ft	Gage	Range ft	Gage	Range ft
8448725	3.14	8449130	3.57	MVCO	2.72
Avg	3.14	Avg	3.57	Avg	2.72

Note: Numbered gages represent NOAA stations. MVCO data is from Martha's Vineyard Coastal Observatory.

Table A-2. Data Sources for Tidal Restriction Data.

ID	Restricted Waterbody	Town	% GDTR	Data Source
1	Broad Cove	Hingham	80%	Woods Hole Group (2012a)
2	Home Meadow	Hingham	0%	Tidal Restriction Atlas
3	Rumney Marsh	Saugus	50%	Woods Hole Group (2014c)
4	Scituate Harbor	Scituate	100%	Tidal Restriction Atlas
5	Green Harbor River	Marshfield	8%	Division of Ecological Restoration
6	Long Creek/Crow River	Sandwich	0%	Tidal Restriction Atlas
7	Scorton Creek	Sandwich	72%	Tidal Restriction Atlas
8	Sesuit Creek	Dennis	85%	Mass Estuaries Project
9	Stony Brook	Brewster	33%	Woods Hole Group (2012b)
10	Freeman's Pond	Brewster	15%	Woods Hole Group (2011b)
11	Little Namskaket Creek	Orleans	85%	Division of Ecological Restoration
12	Fresh Brook	Welfleet	33%	Stantec (2011)
13	Mayo Creek	Welfleet	86%	Woods Hole Group (2011a)
14	Pamet River	Truro	50%	Cape Cod National Seashore
15	Pilgrim Lake	Truro	10%	Spaulding and Grilli (2005)
16	West End Marsh	Provincetown	11%	Cape Cod National Seashore
17	Hatches Harbor	Provincetown	55%	Cape Cod National Seashore
18	Herring River	Harwich	69%	Cape Cod National Seashore
19	Nauset Marsh	Eastham	52%	Cape Cod National Seashore
20	Frost Fish Creek	Chatham	15%	Mass Estuaries Project
21	Swan Pond River	Dennis	83%	Aubrey Consulting (1992)
22	Kelley's Bay and Follins Pond	Dennis	17%	Woods Hole Group (2002)
23	Rushy Marsh Pond	Barnstable	10%	Woods Hole Group (2014a)
24	Santuit River	Mashpee	84%	Mass Estuaries Project
25	Bournes Pond	Falmouth	82%	Mass Estuaries Project
26	Great Pond	Falmouth	95%	Mass Estuaries Project
27	Little Pond	Falmouth	45%	Mass Estuaries Project
28	Salt Pond	Falmouth	14%	Mass Estuaries Project
29	Centerville River	Barnstable	97%	Woods Hole Group (2004)
30	Mill Pond	Falmouth	29%	Woods Hole Group (2007)
31	Upper Agawam River	Wareham	76%	Mass Estuaries Project
32	Georges Pond	Dartmouth	13%	Woods Hole Group (2014b)
33	Upper W Branch (Westport River)	Westport	91%	Mass Estuaries Project
34	East Harbor (Westport River)	Westport	86%	Mass Estuaries Project
35	Upper E Branch (Westport River)	Westport	82%	Mass Estuaries Project

Table A-3. Model Input Parameters

Index Num	Name	SLR Zone	NWI Photo Date	DEM Date	Direction Offshore	Hist SLR Trend mm/yr	NAVD to MTL	Great Diurnal Tide Range (m)	Salt Elev (m MTL)	Marsh Eros (horz) (m/yr)	Swamp Eros (horz) (m/yr)	Tidal Flat Eros (horz) (m/yr)	Marsh Accretion Reg. Flood (mm/yr)	Marsh Accretion Irreg. Flood (mm/yr)	Marsh Accretion Tidal-Fresh (mm/yr)	Marsh Accretion Inland-Fresh (mm/yr)	Accretion Mangrove (mm/yr)	Accretion Tidal Swamp (mm/yr)	Accretion Swamp (mm/yr)	Beach Sed Eros Rate (mm/yr)	Freq OW
0	Great Marsh	Boston	2011	2011	East	2.8	-0.163	2.80	1.40	0	0	0.09	2.8	2.8	0	0	0	0	0	0	0
1	Northshore	Boston	2011	2011	South	2.8	-0.117	2.95	1.47	0	0	0.01	2.8	2.8	0	0	0	0	0	0	0
2	Boston	Boston	2011	2010	East	2.8	-0.182	3.12	1.56	0	0	0.00	2.8	2.8	0	0	0	0	0	0	0
3	Plymouth	Boston	2011	2011	East	2.8	-0.192	3.11	1.56	0	0	0.03	2.8	2.8	0	0	0	0	0	0	0
4	Cape Cod Bay	Boston	2011	2011	North	2.8	-0.185	3.19	1.59	0	0	0.10	2.8	2.8	0	0	0	0	0	0	0
5	Cape Cod Provincetown	Boston	2011	2011	North	2.8	-0.180	3.07	1.54	0	0	0.00	2.8	2.8	0	0	0	0	0	0	0
6	Cape Cod Monomoy	Boston	2011	2011	East	2.8	-0.139	1.95	0.98	0	0	0.00	2.8	2.8	0	0	0	0	0	0	0
7	Cape Cod Vineyard Sound E	Boston	2011	2011	South	2.8	-0.150	1.33	0.66	0	0	0.00	2.8	2.8	0	0	0	0	0	0	0
8	Cape Cod Vineyard Sound W	Boston	2011	2011	South	2.8	-0.126	0.91	0.46	0	0	0.06	2.8	2.8	0	0	0	0	0	0	0
9	Buzzards Bay E	Woods Hole	2011	2011	West	2.82	-0.061	1.11	0.55	0	0	0.05	2.82	2.82	0	0	0	0	0	0	0
10	Buzzards Bay W	Woods Hole	2011	2013	South	2.82	-0.032	1.26	0.63	0	0	0.08	2.82	2.82	0	0	0	0	0	0	0
11	Taunton River	Woods Hole	2011	2011	South	2.82	-0.034	1.48	0.74	0	0	0.00	2.82	2.82	0	0	0	0	0	0	0
12	Elizabeth Islands	Woods Hole	2011	2010	West	2.82	-0.048	1.10	0.55	0	0	0.07	2.82	2.82	0	0	0	0	0	0	0
13	Martha's Vineyard NE	Woods Hole	2011	2013	North	2.82	-0.155	0.73	0.37	0	0	0.10	2.82	2.82	0	0	0	0	0	0	0
14	Martha's Vineyard S	Woods Hole	2011	2013	South	2.82	-0.147	0.83	0.42	0	0	1.59	2.82	2.82	0	0	0	0	0	0	0
15	Martha's Vineyard NW	Woods Hole	2011	2013	North	2.82	-0.076	0.96	0.48	0	0	0.14	2.82	2.82	0	0	0	0	0	0	0
16	Nantucket N	Nantucket	2011	2013	North	3.55	-0.176	1.09	0.54	0	0	0.00	3.55	3.55	0	0	0	0	0	0	0
17	Nantucket S	Nantucket	2011	2013	South	3.55	-0.346	0.83	0.42	0	0	1.34	3.55	3.55	0	0	0	0	0	0	0

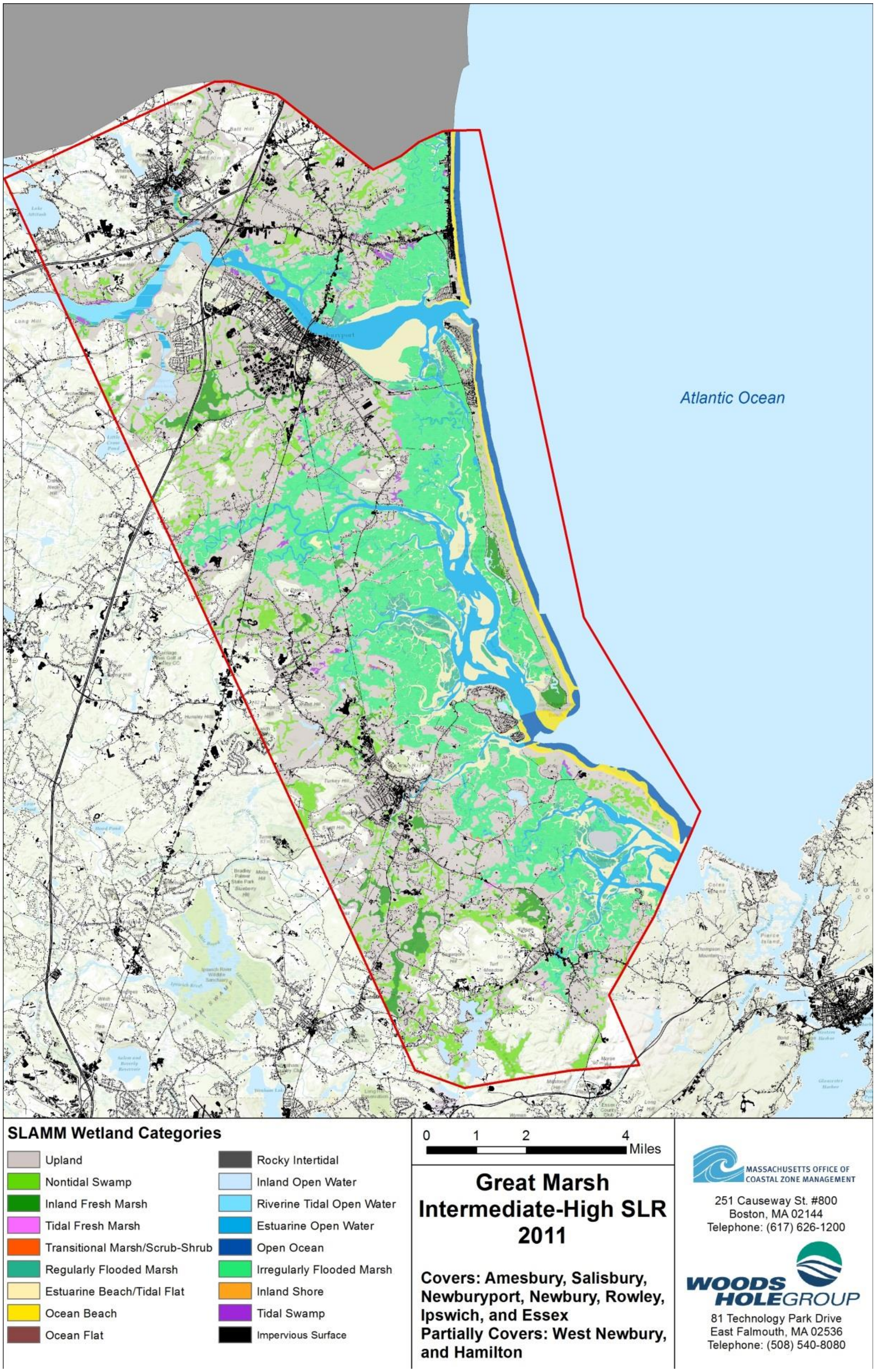
Table A-4. Statewide subset input parameters (part 1 of 2).

Subset Name	Model Panel	Index Num	Runs Where Waterbody is Restricted	GT%	GT (m)	Salt El (m)	Tidal Flat Eros (horz m/yr)	Discharge (m^3/s)
Merrimack River	Great Marsh	0						296.21
Parker River	Great Marsh	0						1.31
Ipswich River	Great Marsh	0						7
Erosion 1	Great Marsh	0					0.24	
Erosion 2	Great Marsh	0					0.52	
Erosion 3	North Shore	1					0.23	
Saugus River	Boston	2						1.04
Mystic River	Boston	2						1.46
Charles River	Boston	2						11.24
Neponset River	Boston	2						8.99
Town Brook	Boston	2						0.14
Monatiquot River	Boston	2						1.35
Whitmans Pond	Boston	2						0.18
Broad Cove	Boston	2	N/A	*80%*	2.49	1.25		
Home Meadow	Boston	2	LOW, INTLOW, INTHIGH, HIGH	*0%*	0.00	0.00		
Rumney Marsh	Boston	2	LOW, INTLOW, INTHIGH, HIGH	*50%*	1.56	0.78		
Indian Head River	Plymouth	3						2.03
Jones River	Plymouth	3						1.17
Scituate Harbor	Plymouth	3	LOW, INTLOW, INTHIGH, HIGH	*100%*	3.11	1.56		
Green Harbor River	Plymouth	3	LOW, INTLOW, INTHIGH, HIGH	*8%*	0.25	0.12		
Erosion 4	Plymouth	3					0.3	
Erosion 5	Plymouth	3					0.19	
Erosion 6	Plymouth	3					0.25	
Long Creek/Crow River	Cape Cod Bay	4	LOW, INTLOW, INTHIGH	*0%*	0.00	0.00		
Scorton Creek	Cape Cod Bay	4	LOW, INTLOW, INTHIGH, HIGH	--	2.31	1.16		
Sesuit Creek	Cape Cod Bay	4	LOW	*85%*	2.71	1.36		
Freeman's Pond	Cape Cod Bay	4	N/A	--	0.47	0.24		
Stony Brook	Cape Cod Bay	4	LOW, INTLOW	--	1.05	0.52		
Little Namskaket Creek-A	Cape Cod Bay	4	LOW, INTLOW, INTHIGH, HIGH	*85%*	2.71	1.36		
Erosion 7	Cape Cod Bay	4					1.02	
Erosion 8	Cape Cod Bay	4					1.09	
Erosion 9	Cape Cod Bay	4					0.45	
Little Namskaket Creek-B	Cape Cod Provincetown	5	LOW, INTLOW, INTHIGH, HIGH	*85%*	2.71	1.36		
Fresh Brook	Cape Cod Provincetown	5	LOW, INTLOW, INTHIGH, HIGH	--	1.00	0.50		
Mayo Creek	Cape Cod Provincetown	5	LOW	*86%*	1.68	0.84		
Pamet River	Cape Cod Provincetown	5	LOW, INTLOW, INTHIGH, HIGH	--	1.52	0.76		
Pilgrim Lake	Cape Cod Provincetown	5	LOW, INTLOW, INTHIGH, HIGH	--	0.31	0.16		
West End Marsh	Cape Cod Provincetown	5	LOW	--	2.41	1.21		
Hatches Harbor	Cape Cod Provincetown	5	LOW, INTLOW, INTHIGH, HIGH	*55%*	1.69	0.84		
Nauset Marsh-A	Cape Cod Provincetown	5	LOW	--	1.02	0.51		
Herring River	Cape Cod Provincetown	5	N/A	*69%*	2.12	1.06		
Erosion 10	Cape Cod Provincetown	5					0.55	
Erosion 11	Cape Cod Provincetown	5					0.63	
Erosion 12-A	Cape Cod Provincetown	5					0.95	

Table A-4. Statewide subset input parameters (part 2 of 2).

Subset Name	Model Panel	Index Num	Runs Where Waterbody is Restricted	*GT%*	GT (m)	Salt El (m)	Tidal Flat Eros (horz m/yr)	Discharge (m^3/s)
Nauset Marsh-B	Cape Cod Monomoy	6	LOW	--	1.02	0.51		
Frost Fish Creek-A	Cape Cod Monomoy	6	LOW, INTLOW	*15%*	0.29	0.15		
Erosion 12-B	Cape Cod Monomoy	6					0.95	
Erosion 13-A	Cape Cod Monomoy	6					2.52	
Erosion 14-A	Cape Cod Monomoy	6					1.16	
Herring River	Cape Cod VSE	7						0.29
Frost Fish Creek-B	Cape Cod VSE	7	LOW, INTLOW	*15%*	0.29	0.15		
Swan Pond River	Cape Cod VSE	7	LOW, INTLOW, INTHIGH	*83%*	1.10	0.55		
Kelley's Bay and Follins Pond	Cape Cod VSE	7	LOW, INTLOW, INTHIGH, HIGH	*17%*	0.23	0.11		
Erosion 13-B	Cape Cod VSE	7					2.52	
Erosion 14-B	Cape Cod VSE	7					1.16	
Quashnet River	Cape Cod VSE	8						0.58
Herring River	Cape Cod VSW	8	N/A	*100%*	0.91	0.46		
Rushy Marsh Pond	Cape Cod VSW	8	LOW	--	0.09	0.05		
Santuit River	Cape Cod VSW	8	LOW, INTLOW, INTHIGH, HIGH	*84%*	0.77	0.38		
Moonakiss River	Cape Cod VSW	8	N/A	*100%*	0.91	0.46		
Bournes Pond	Cape Cod VSW	8	LOW, INTLOW, INTHIGH, HIGH	*82%*	0.75	0.37		
Green Pond	Cape Cod VSW	8	N/A	*100%*	0.91	0.46		
Great Pond	Cape Cod VSW	8	LOW, INTLOW, INTHIGH, HIGH	*95%*	0.87	0.43		
Little Pond	Cape Cod VSW	8	LOW, INTLOW, INTHIGH	*45%*	0.41	0.21		
Salt Pond-A	Cape Cod VSW	8	LOW, INTLOW, INTHIGH, HIGH	*14%*	0.13	0.06		
Centerville River	Cape Cod VSW	8	LOW, INTLOW	*97%*	0.89	0.44		
Mill Pond-A	Cape Cod VSW	8	LOW	*17%*	0.23	0.11		
Erosion 15	Cape Cod VSW	8					0.42	
Salt Pond-B	Buzzards Bay E	9	LOW, INTLOW, INTHIGH, HIGH	*14%*	0.13	0.06		
Mill Pond-B	Buzzards Bay E	9	LOW	*29%*	0.32	0.16		
Paskamanset River	Buzzards Bay W	10						1.66
Mattapoisett River	Buzzards Bay W	10						2.74
Georges Pond	Buzzards Bay W	10	N/A	--	0.16	0.08		
Upper Agawam River	Buzzards Bay W	10	LOW, INTLOW, INTHIGH, HIGH	*76%*	0.96	0.48		
Westport River East Harbor	Buzzards Bay W	10	LOW, INTLOW, INTHIGH, HIGH	*86%*	1.08	0.54		
Upper West Branch (Westport River)	Buzzards Bay W	10	LOW, INTLOW, INTHIGH, HIGH	*91%*	1.15	0.57		
Upper East Branch (Westport River)	Buzzards Bay W	10	N/A	*82%*	1.03	0.52		
Taunton River	Taunton River	11						25.14
Erosion 16	Martha's Vineyard NE	13					0.61	
Erosion 18	Nantucket N	16					3.19	
Erosion 19	Nantucket N	16					0.54	
Erosion 20	Nantucket N	16					1.06	
Erosion 17	Nantucket S	17					0	

APPENDIX B. STATEWIDE RESULTS MAPS


Atlantic Ocean
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1 2 4 Miles
Great Marsh
Intermediate-High SLR
2011
Covers: Amesbury, Salisbury, Newburyport, Newbury, Rowley, Ipswich, and Essex
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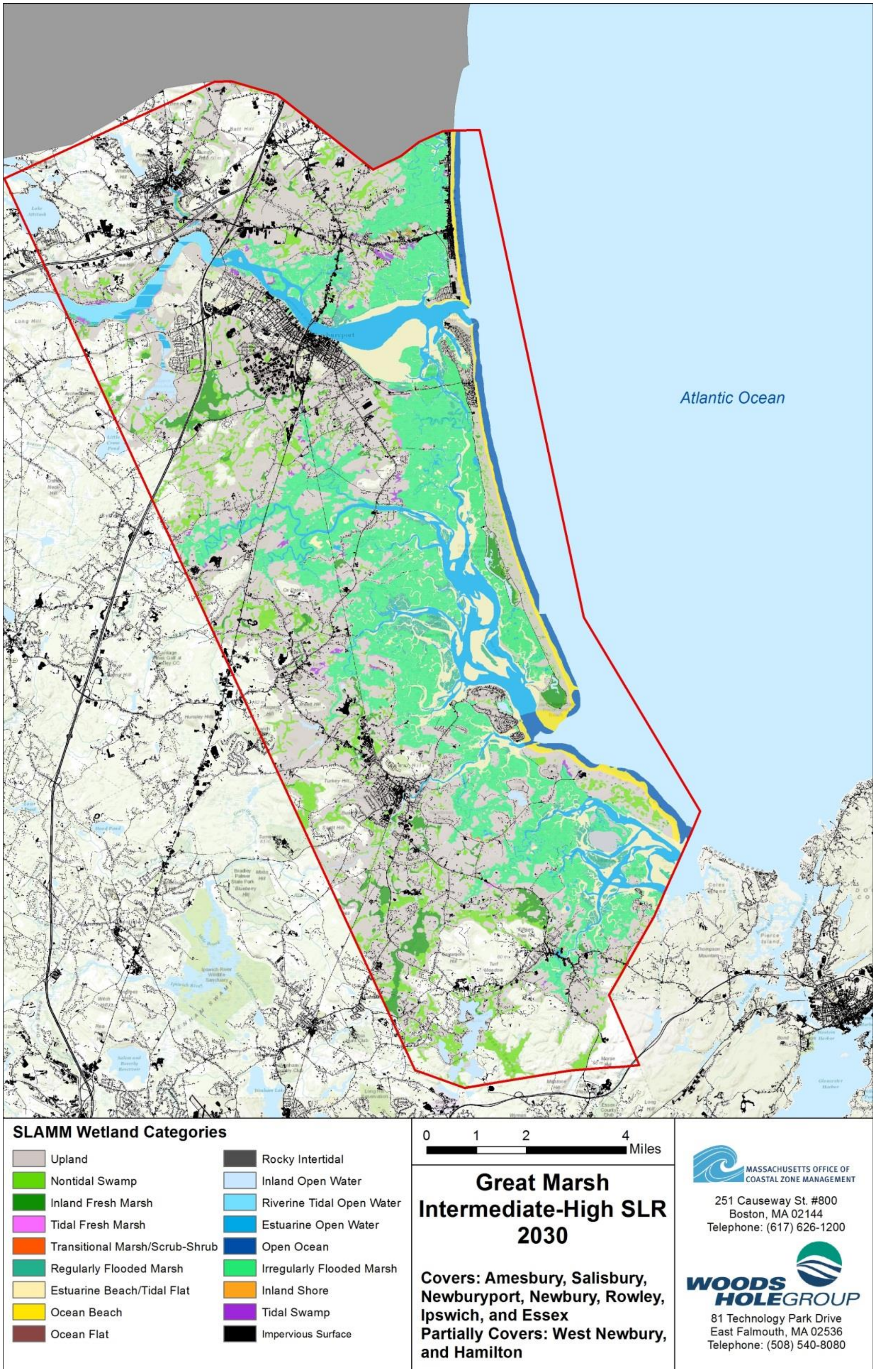
Atlantic Ocean
SLAMM Wetland Categories
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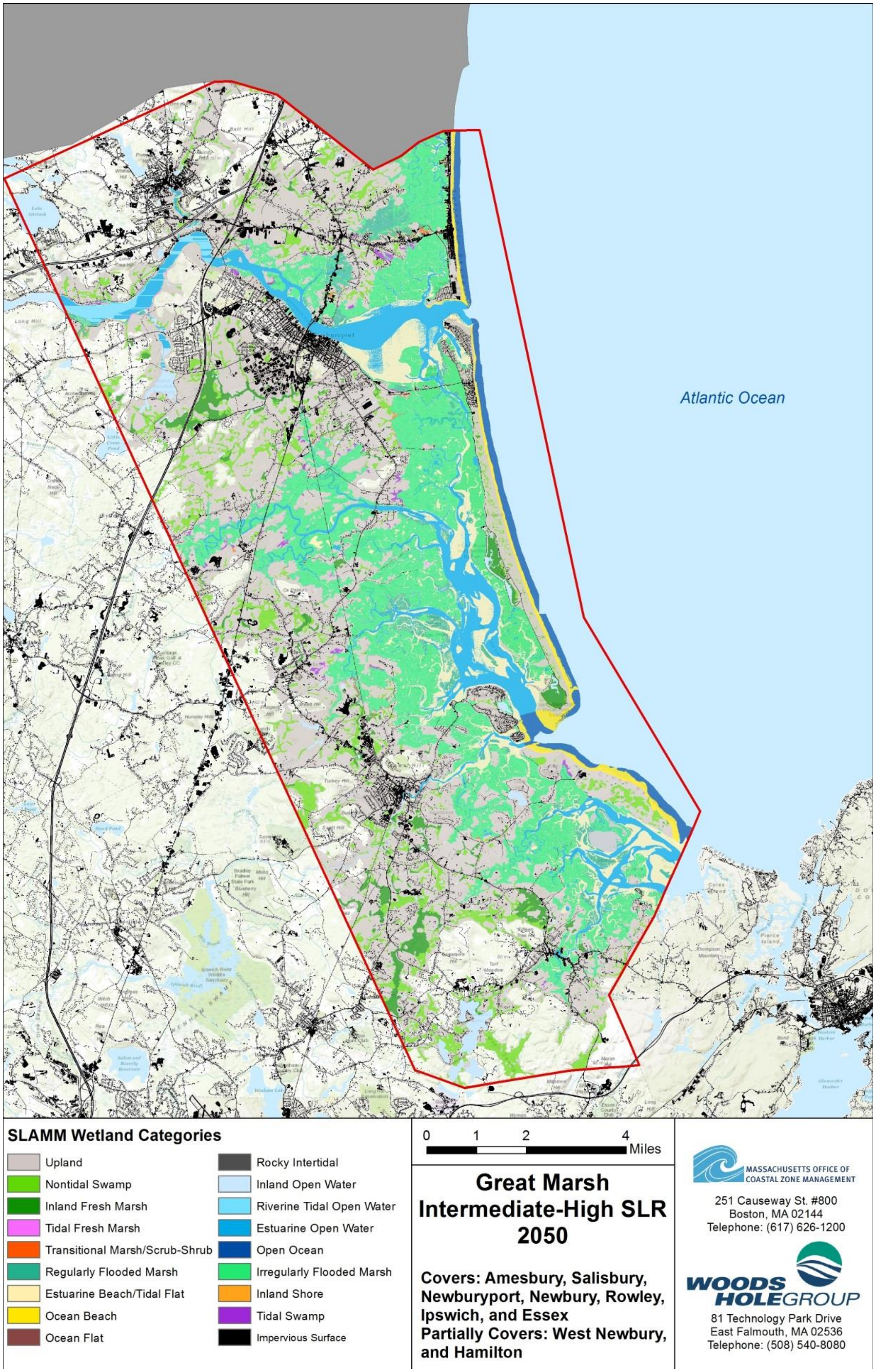
Atlantic Ocean
SLAMM Wetland Categories
Upland
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Open Ocean
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Tidal Swamp
Impervious Surface
0 1 2 4 Miles
Great Marsh
Intermediate-High SLR
2050
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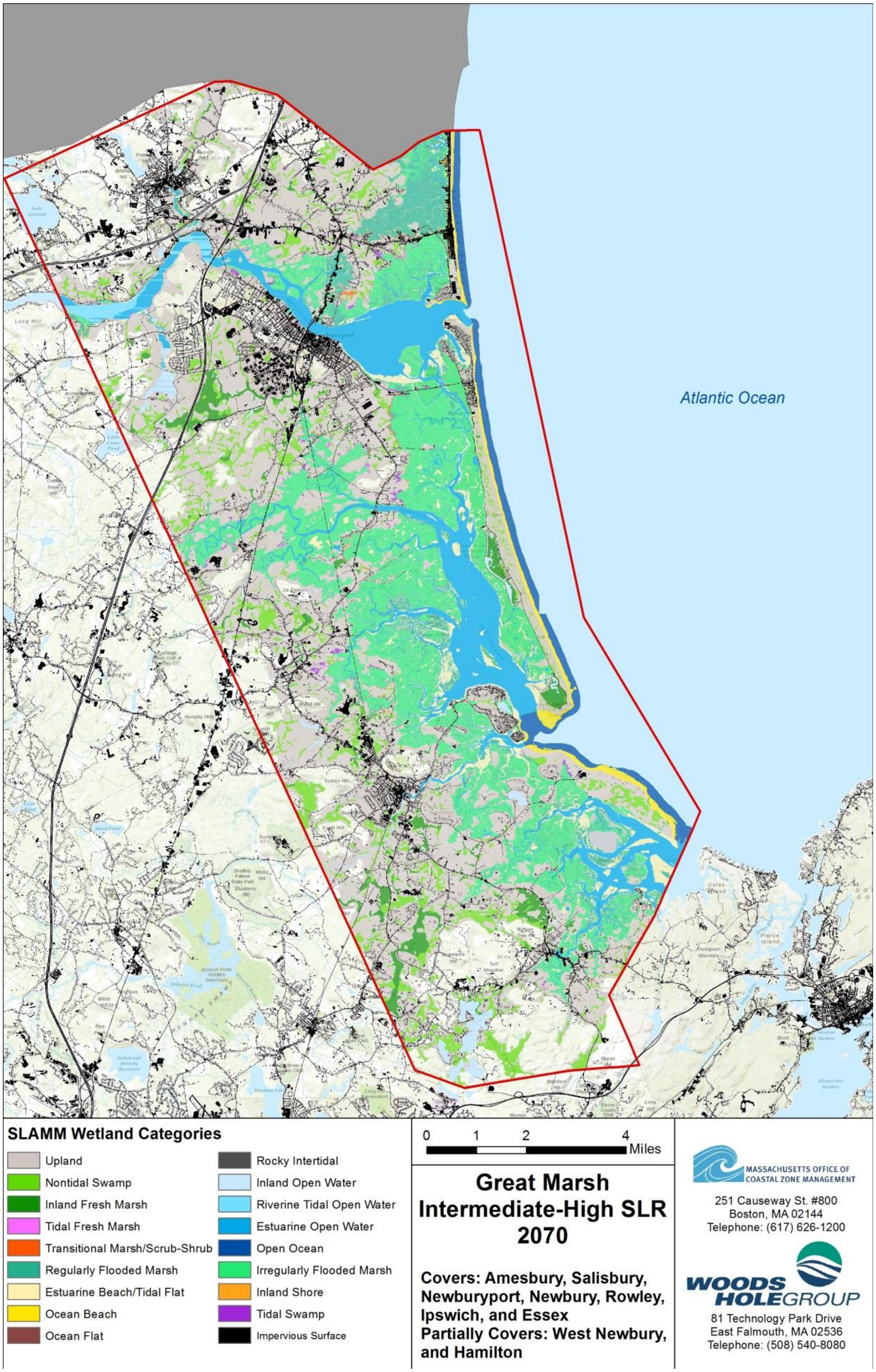
Atlantic Ocean
SLAMM Wetland Categories
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Tidal Swamp
Impervious Surface
0 1 2 4
Miles
Great Marsh
Intermediate-High SLR
2070
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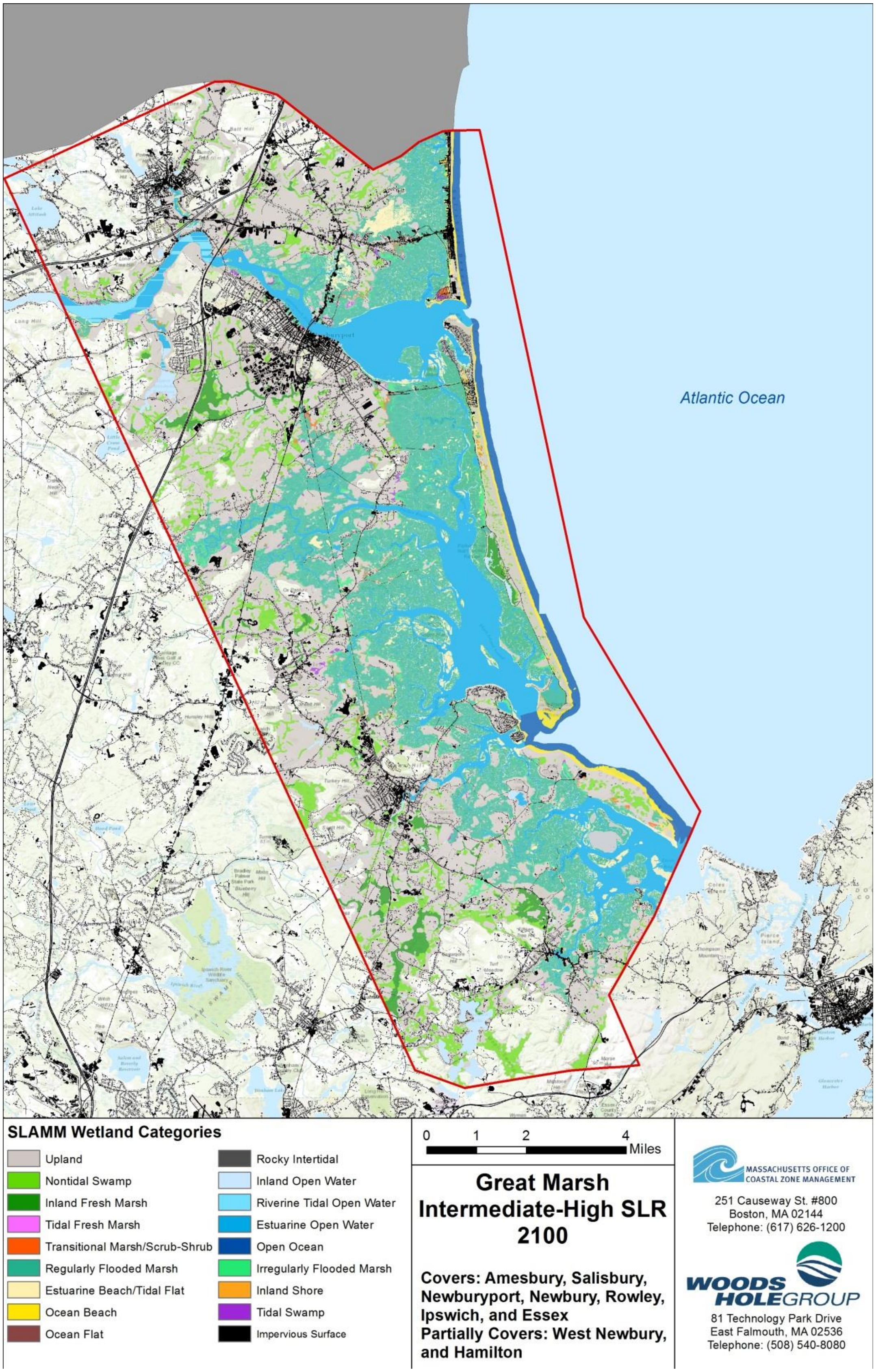
Atlantic Ocean
SLAMM Wetland Categories
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0 1 2 4
Miles
Great Marsh
Intermediate-High SLR
2100
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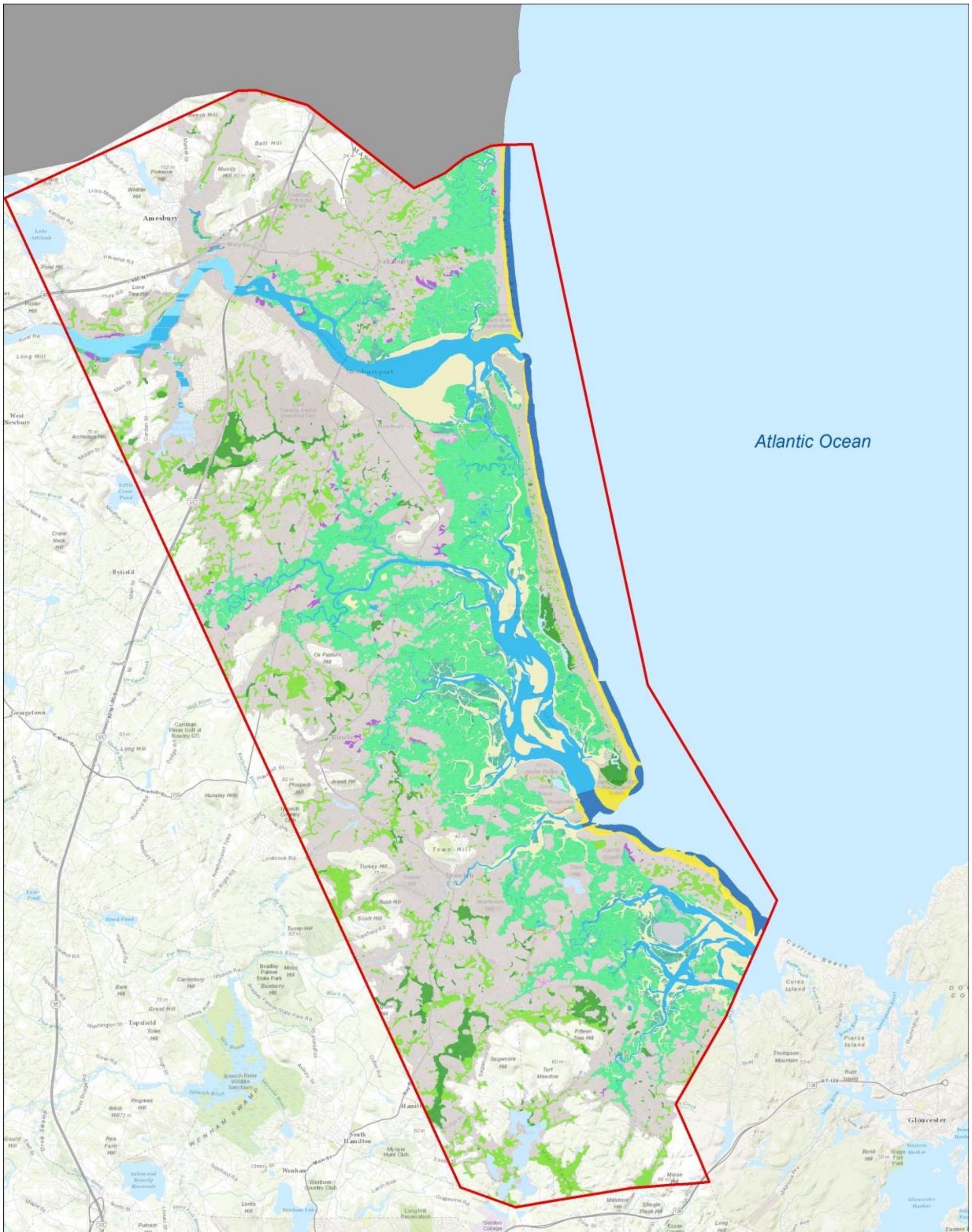

SLAMM Wetland Categories

- Upland
- Nontidal Swamp
- Inland Fresh Marsh
- Tidal Fresh Marsh
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- Estuarine Beach/Tidal Flat
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- Ocean Flat
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- Inland Shore
- Tidal Swamp

0 1 2 4 Miles

Great Marsh (MEM) Intermediate-High SLR 2011

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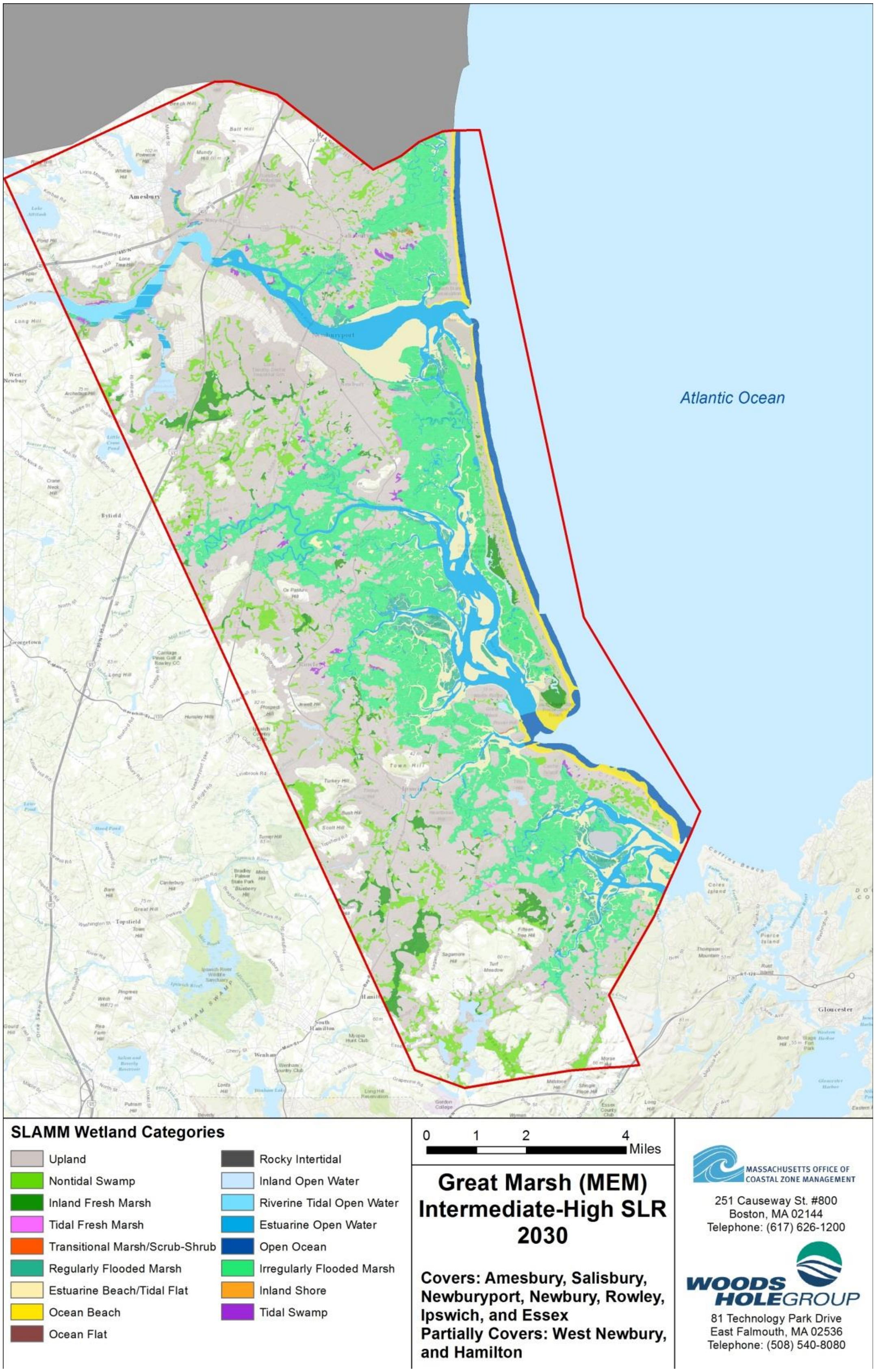
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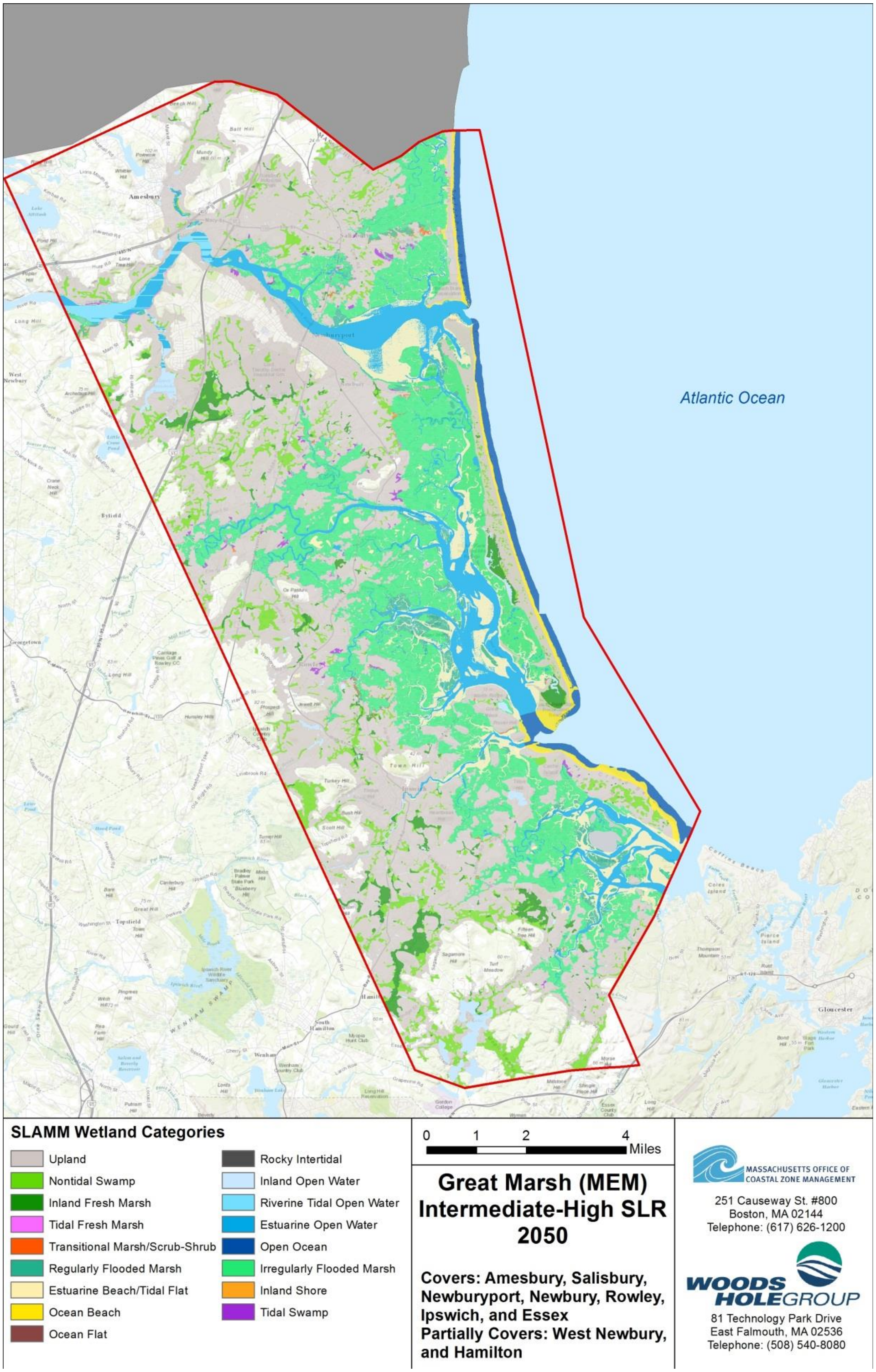
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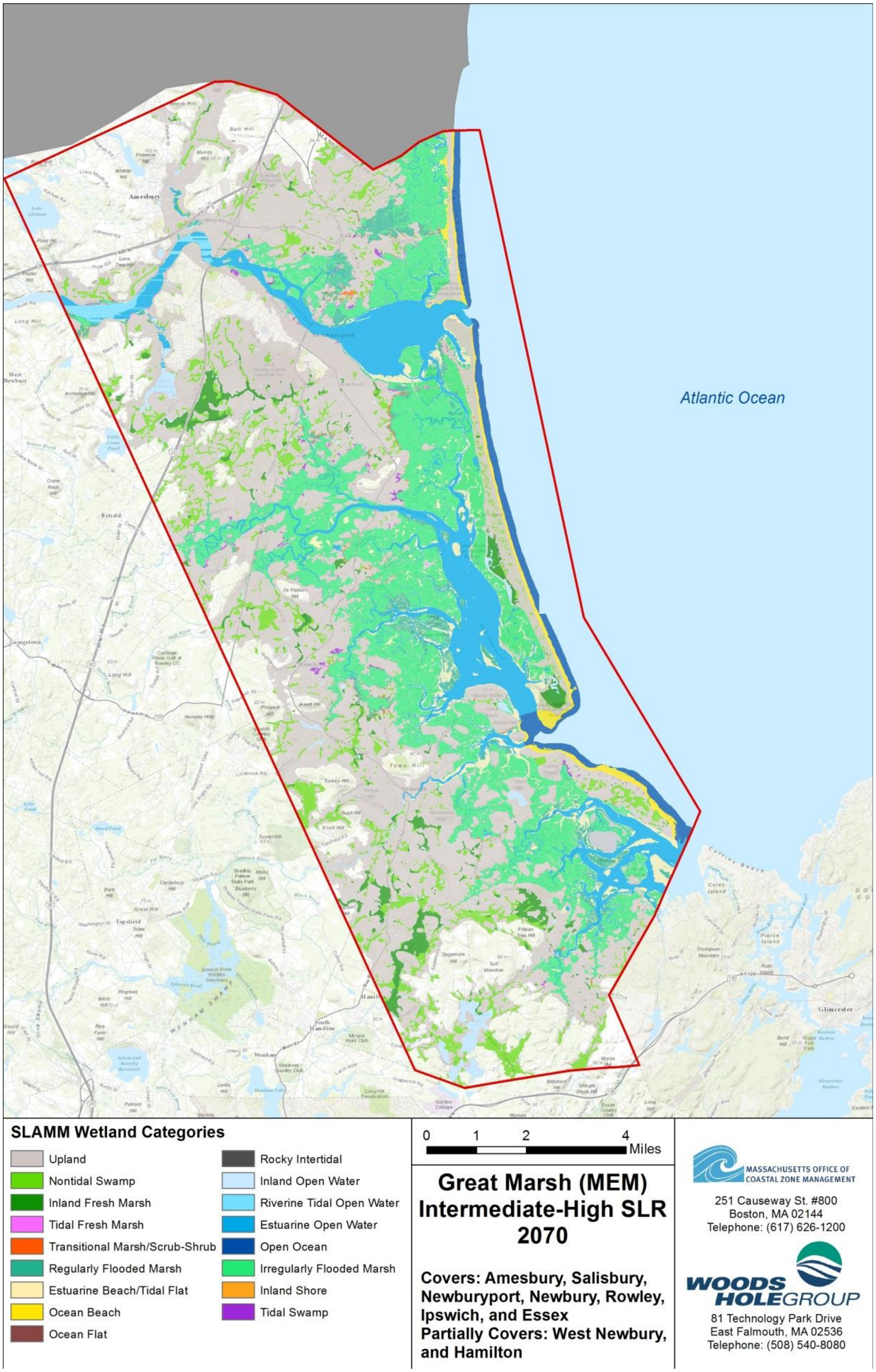
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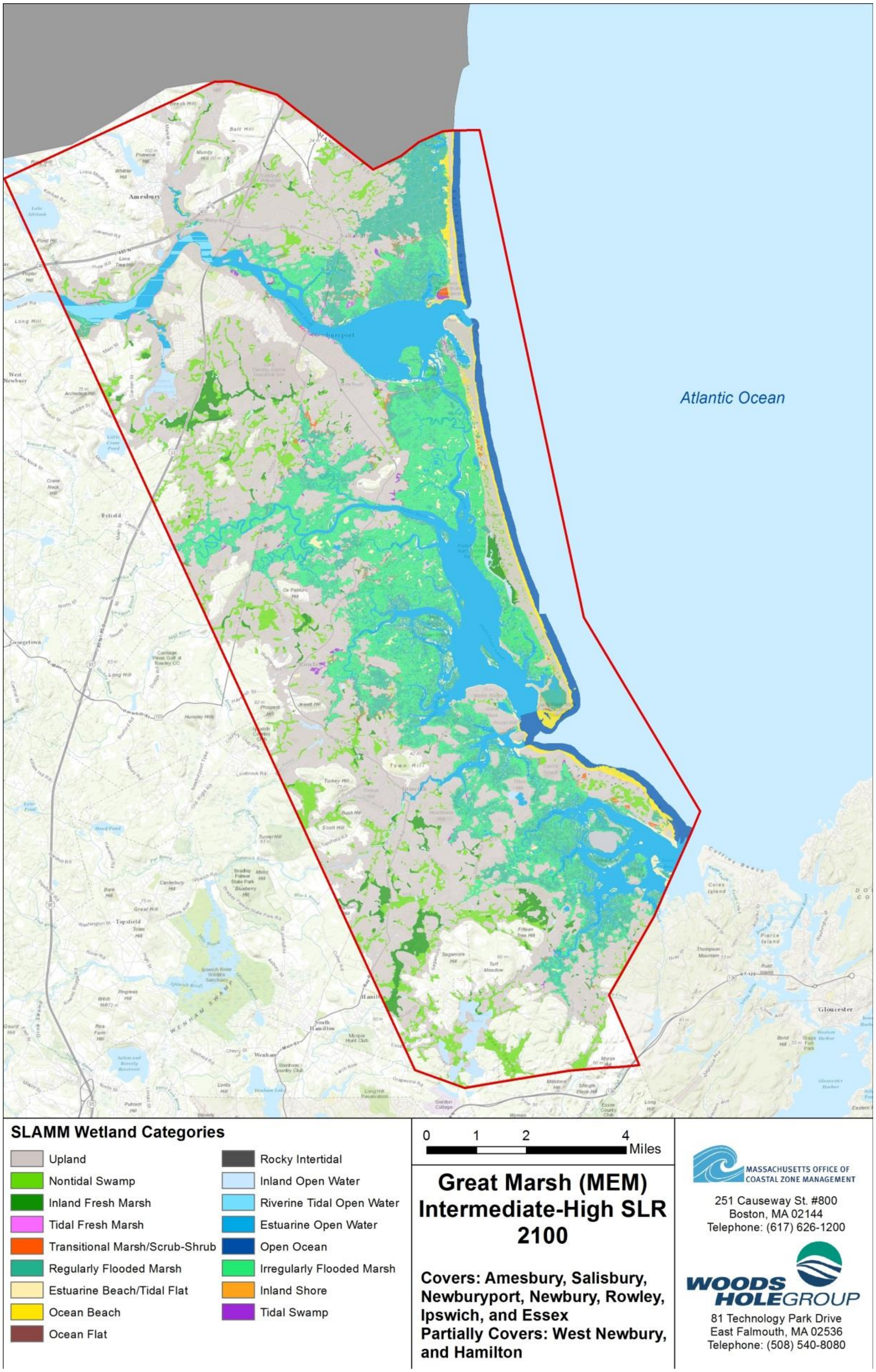
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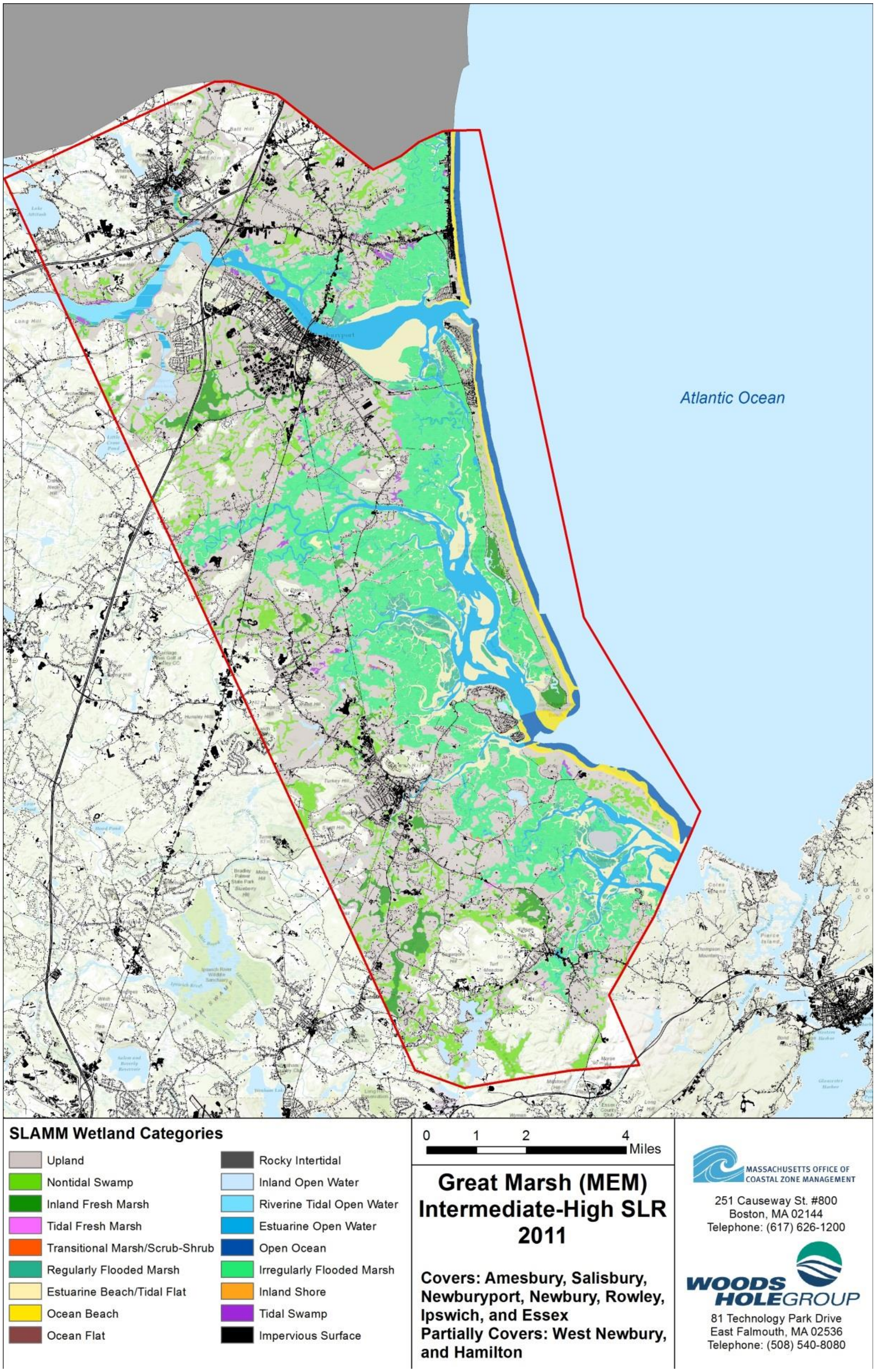
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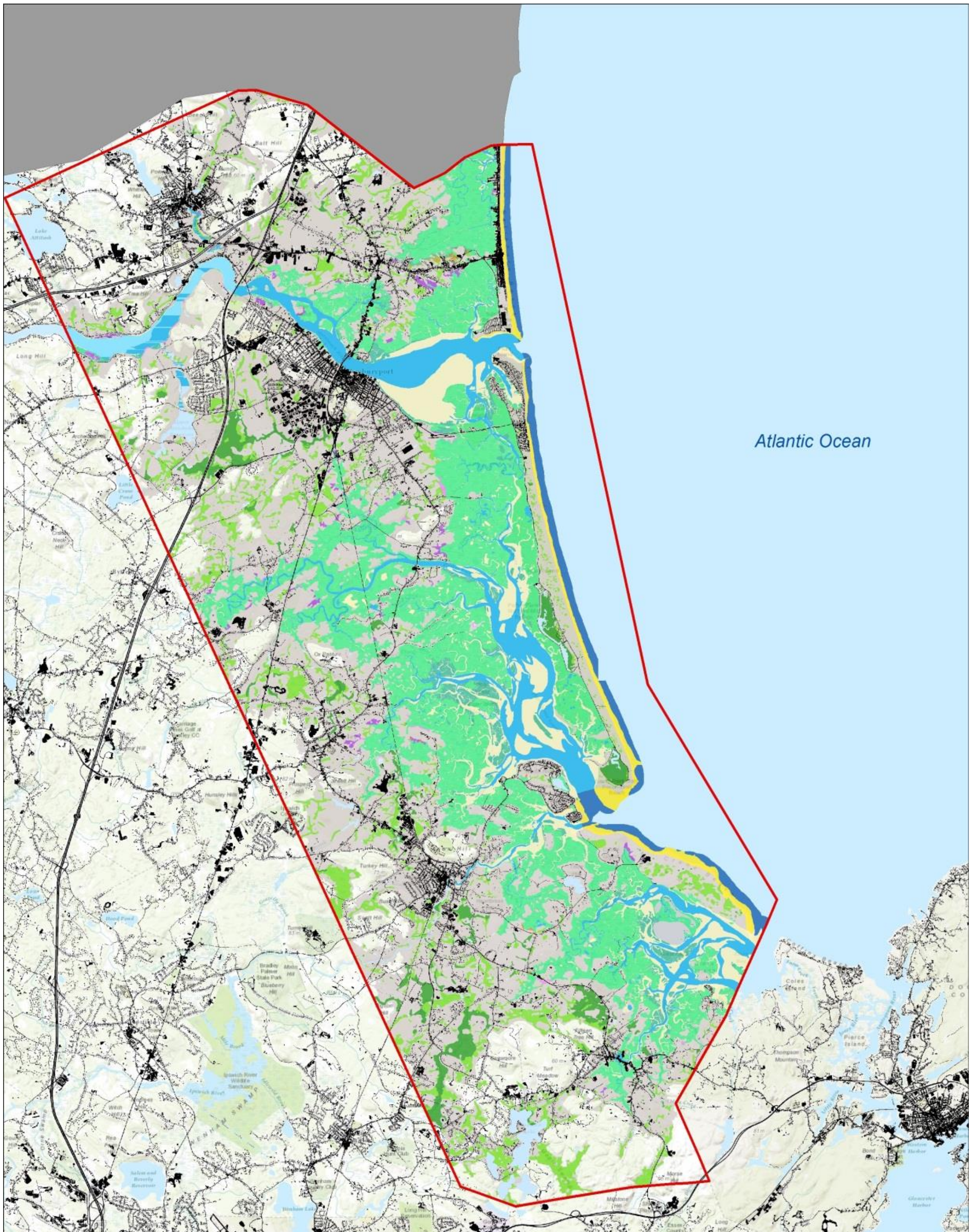
Boston, MA 02144
Telephone: (617) 626-1200
WOODS HOLE GROUP
81 Technology Park Drive
East Falmouth, MA 02536
Telephone: (508) 540-8080



SLAMM Wetland Categories

- Upland
- Nontidal Swamp
- Inland Fresh Marsh
- Tidal Fresh Marsh
- Transitional Marsh/Scrub-Shrub
- Regularly Flooded Marsh
- Estuarine Beach/Tidal Flat
- Ocean Beach
- Ocean Flat
- Rocky Intertidal
- Inland Open Water
- Riverine Tidal Open Water
- Estuarine Open Water
- Open Ocean
- Irregularly Flooded Marsh
- Inland Shore
- Tidal Swamp
- Impervious Surface

0 1 2 4 Miles

Great Marsh (MEM) Intermediate-High SLR 2030

Covers: Amesbury, Salisbury, Newburyport, Newbury, Rowley, Ipswich, and Essex
Partially Covers: West Newbury, and Hamilton

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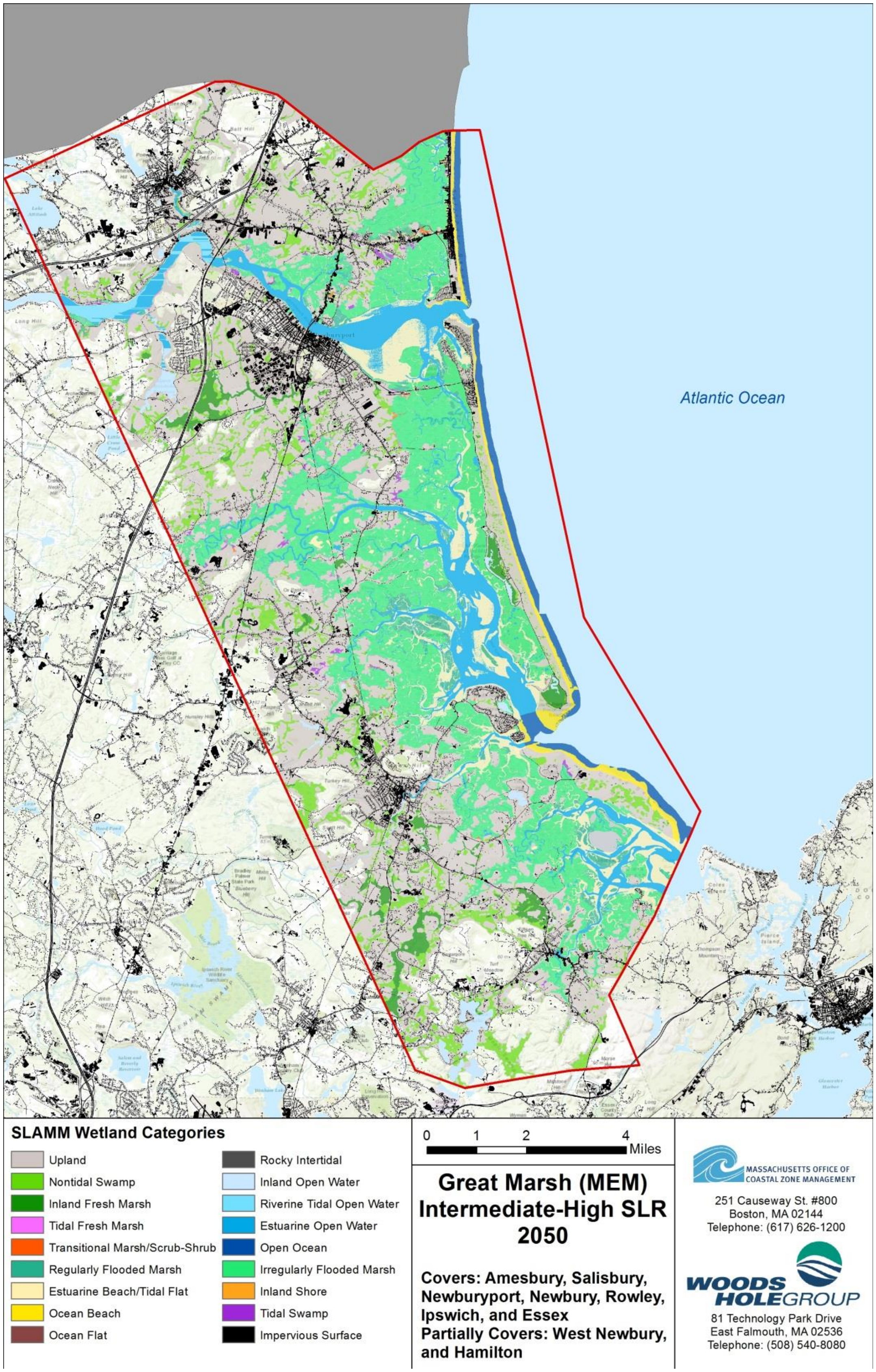
Atlantic Ocean
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1 2 4 Miles
Great Marsh (MEM)
Intermediate-High SLR
2050
Covers: Amesbury, Salisbury, Newburyport, Newbury, Rowley, Ipswich, and Essex
Partially Covers: West Newbury, and Hamilton
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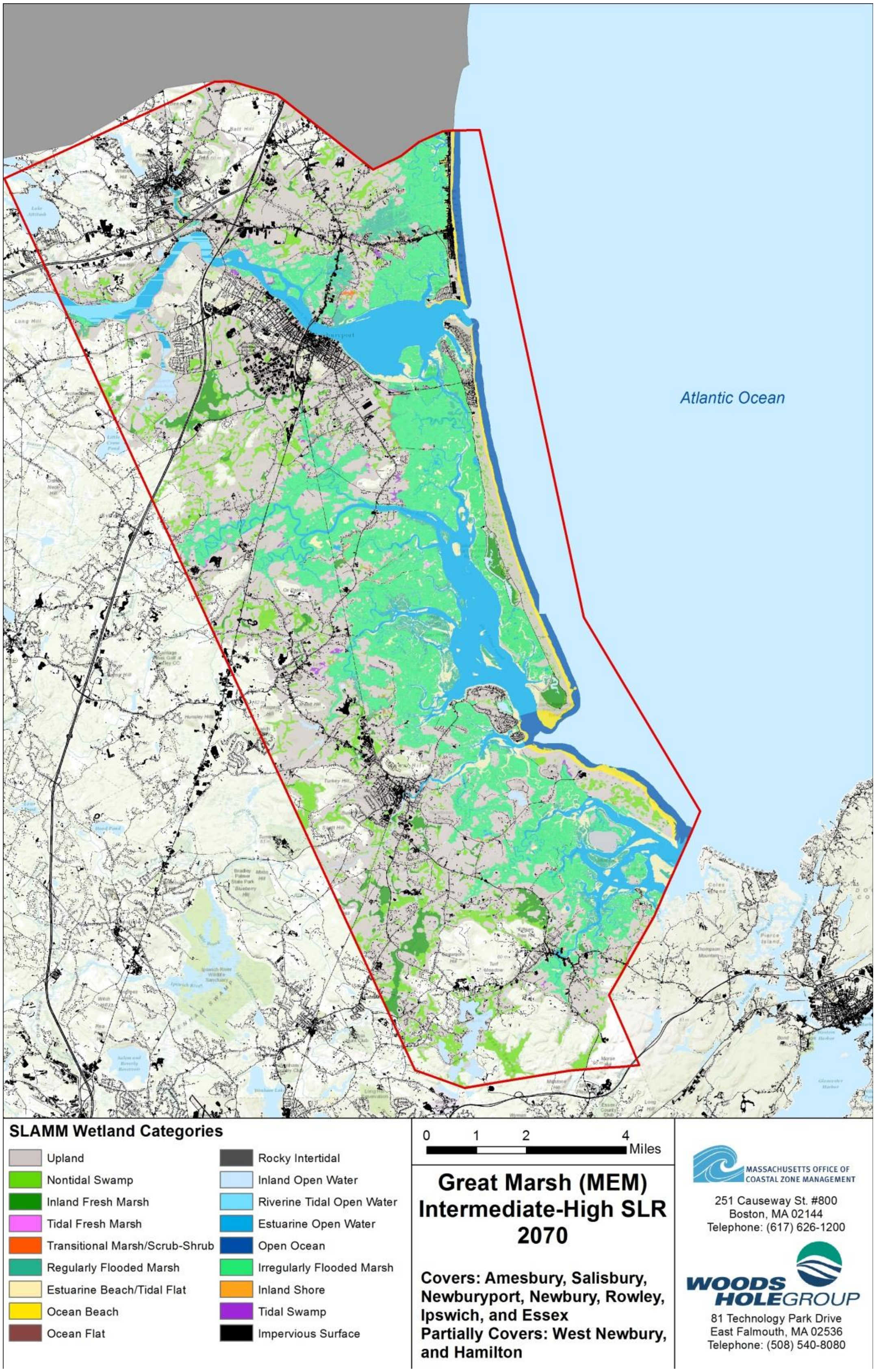
Atlantic Ocean
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1 2 4 Miles
Great Marsh (MEM)
Intermediate-High SLR
2070
Covers: Amesbury, Salisbury, Newburyport, Newbury, Rowley, Ipswich, and Essex
Partially Covers: West Newbury, and Hamilton
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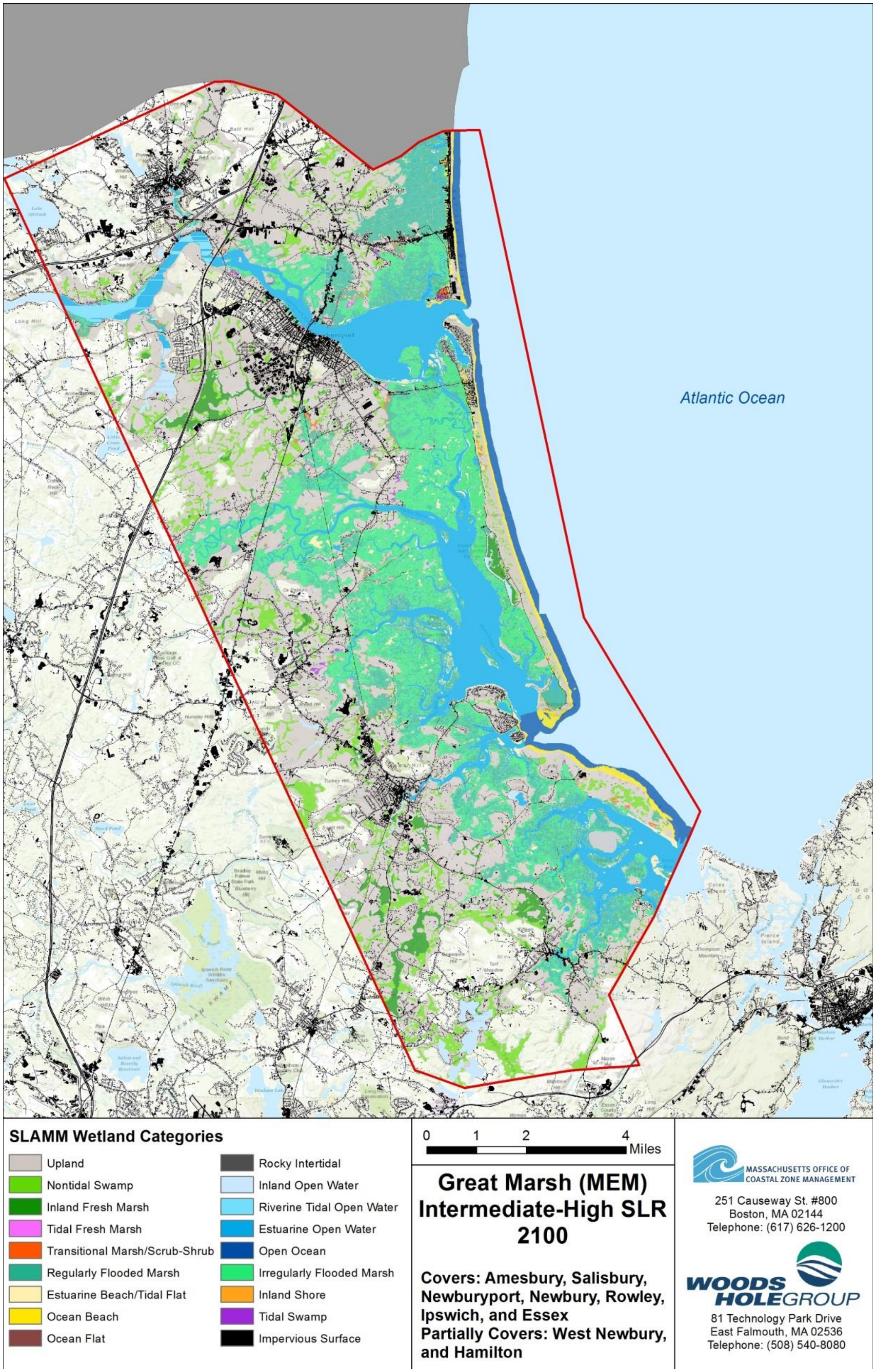
Atlantic Ocean
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1 2 4
Miles
Great Marsh (MEM)
Intermediate-High SLR
2100
Covers: Amesbury, Salisbury, Newburyport, Newbury, Rowley, Ipswich, and Essex
Partially Covers: West Newbury, and Hamilton
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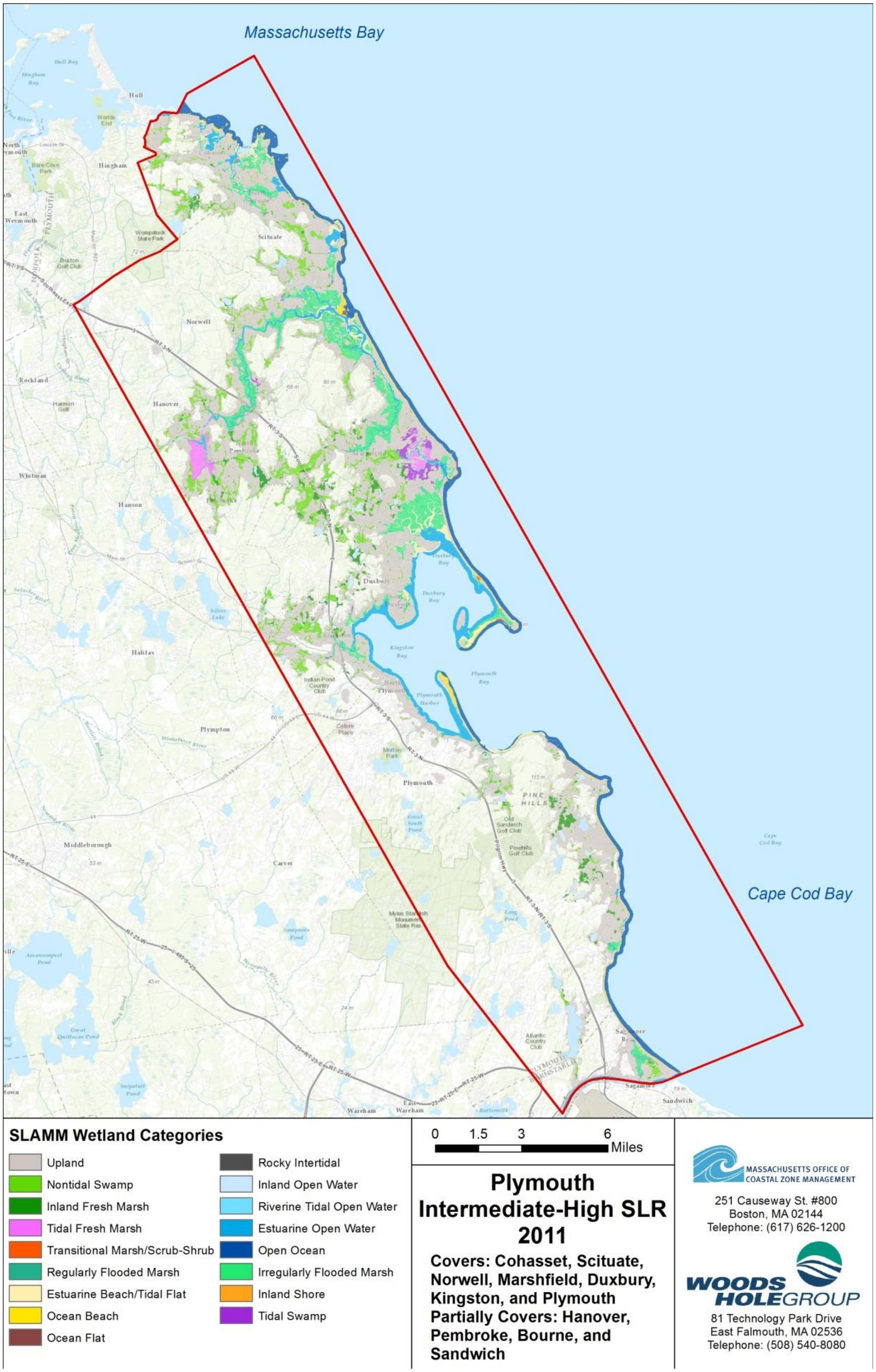
Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6
Miles
Plymouth
Intermediate-High SLR
2011
Covers: Cohasset, Scituate, Norwell, Marshfield, Duxbury, Kingston, and Plymouth
Partially Covers: Hanover, Pembroke, Bourne, and Sandwich
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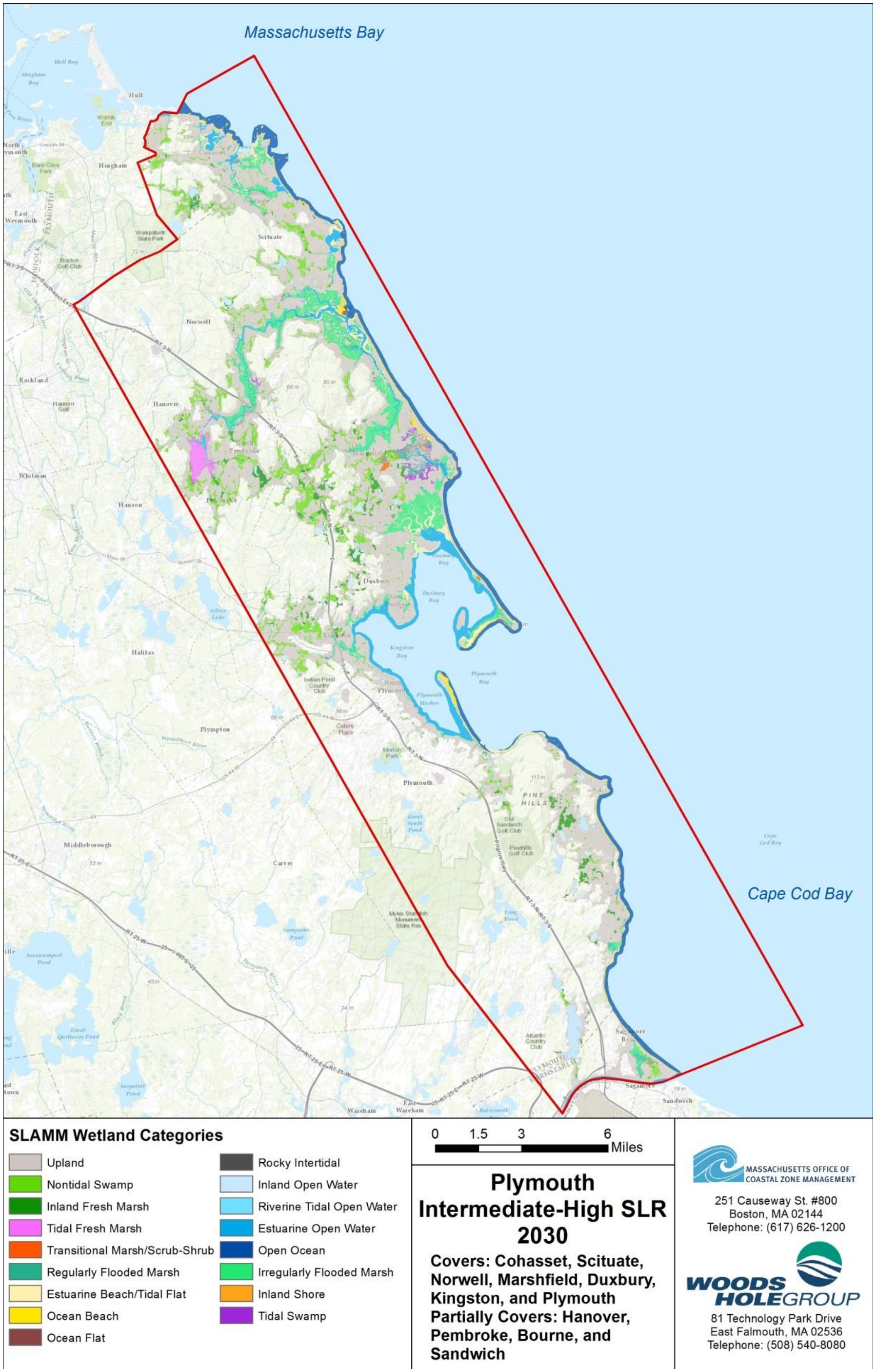
Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
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Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
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Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6
Miles
Plymouth
Intermediate-High SLR
2030
Covers: Cohasset, Scituate, Norwell, Marshfield, Duxbury, Kingston, and Plymouth
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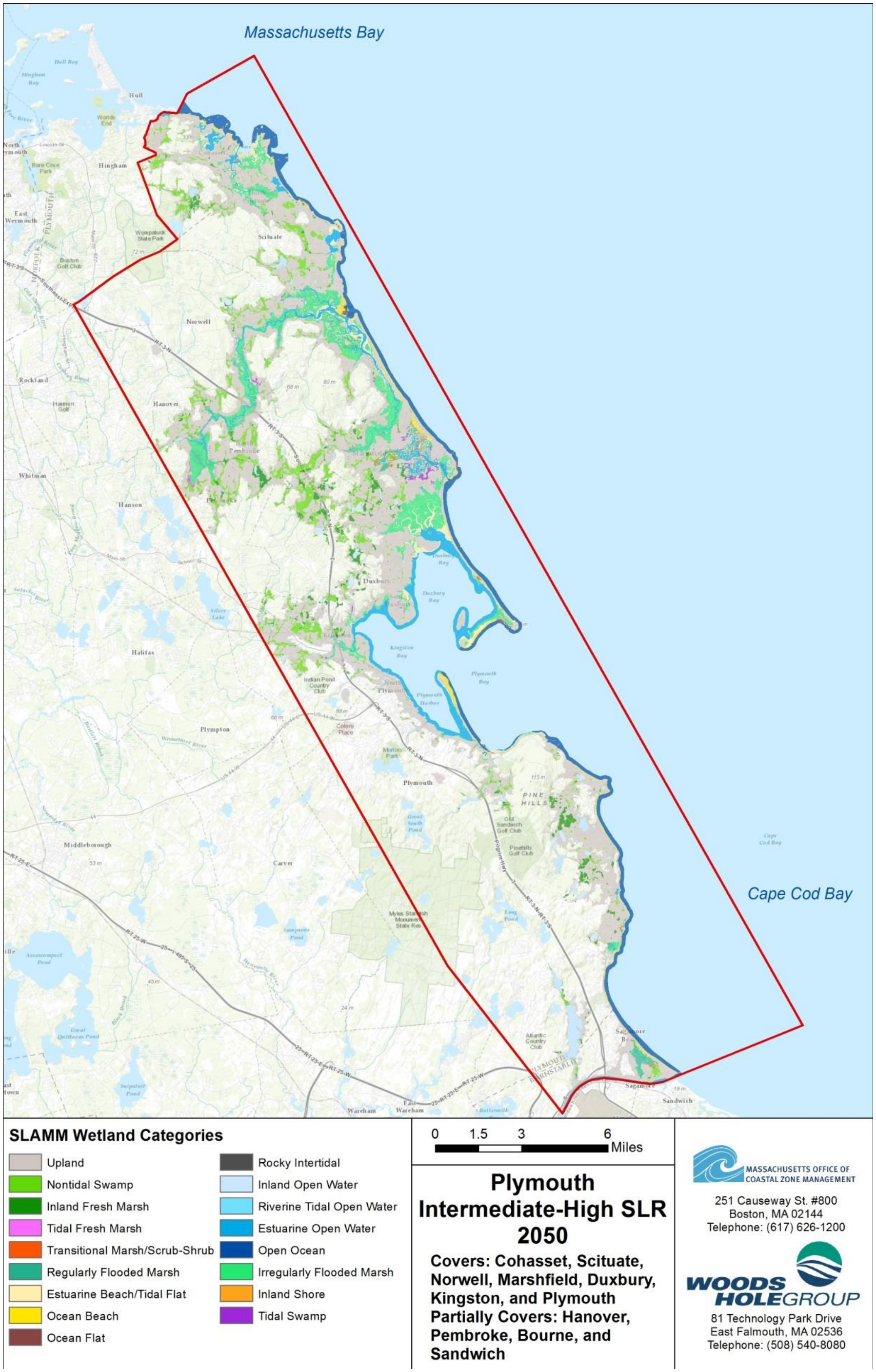
Massachusetts Bay
Cape Cod Bay
Hull
Hingham
Scituate
Norwell
Rockland
Hanover
Pembroke
Whitman
Hanson
Duxbury
Duxbury Bay
Kingston Bay
Plymouth Bay
Plymouth Harbor
Halifax
Plympton
Plymouth
Middleborough
Carver
Sandwich
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6
Miles
Plymouth
Intermediate-High SLR
2050
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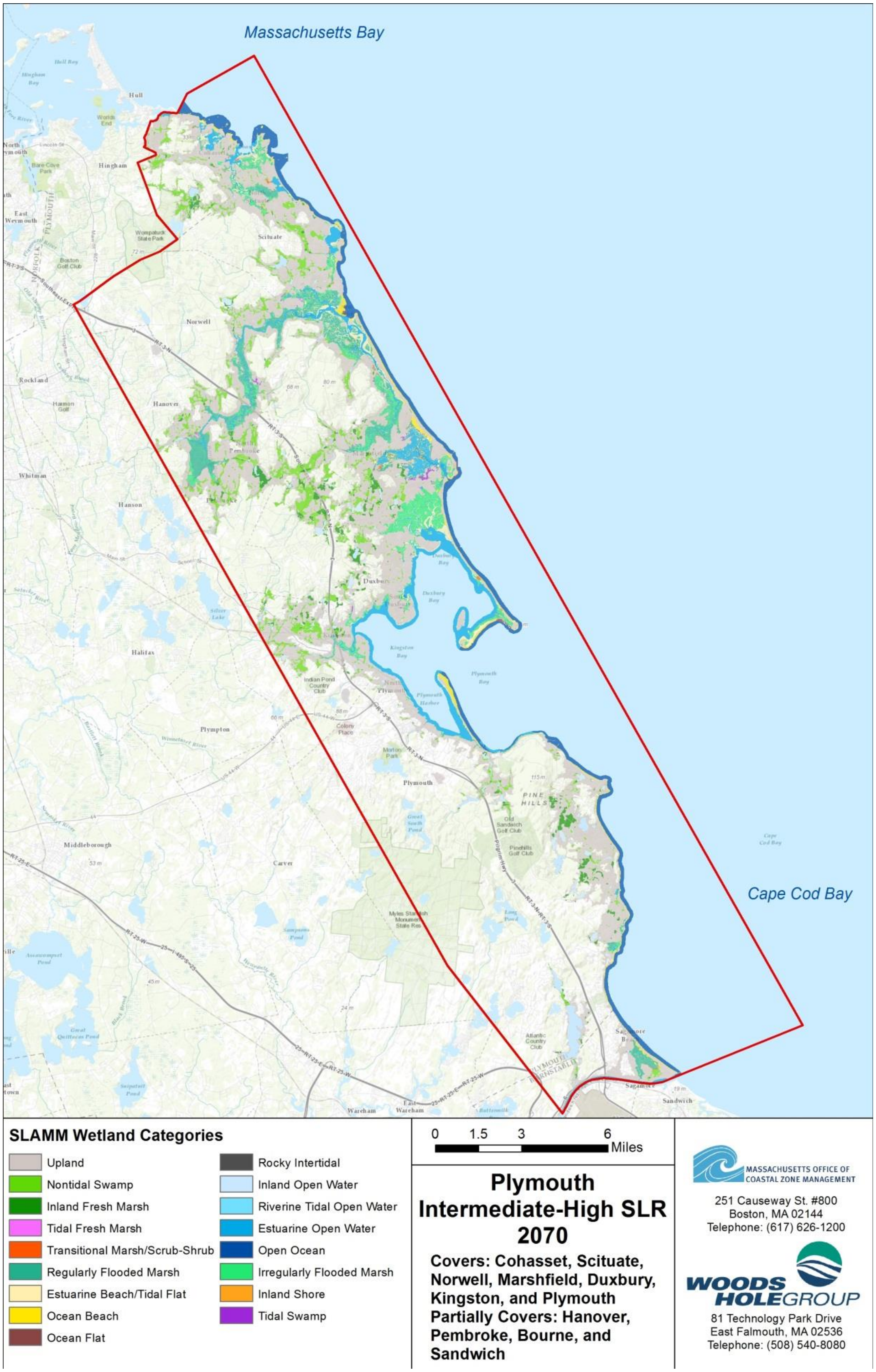
Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
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Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6
Miles
Plymouth
Intermediate-High SLR
2070
Covers: Cohasset, Scituate, Norwell, Marshfield, Duxbury, Kingston, and Plymouth
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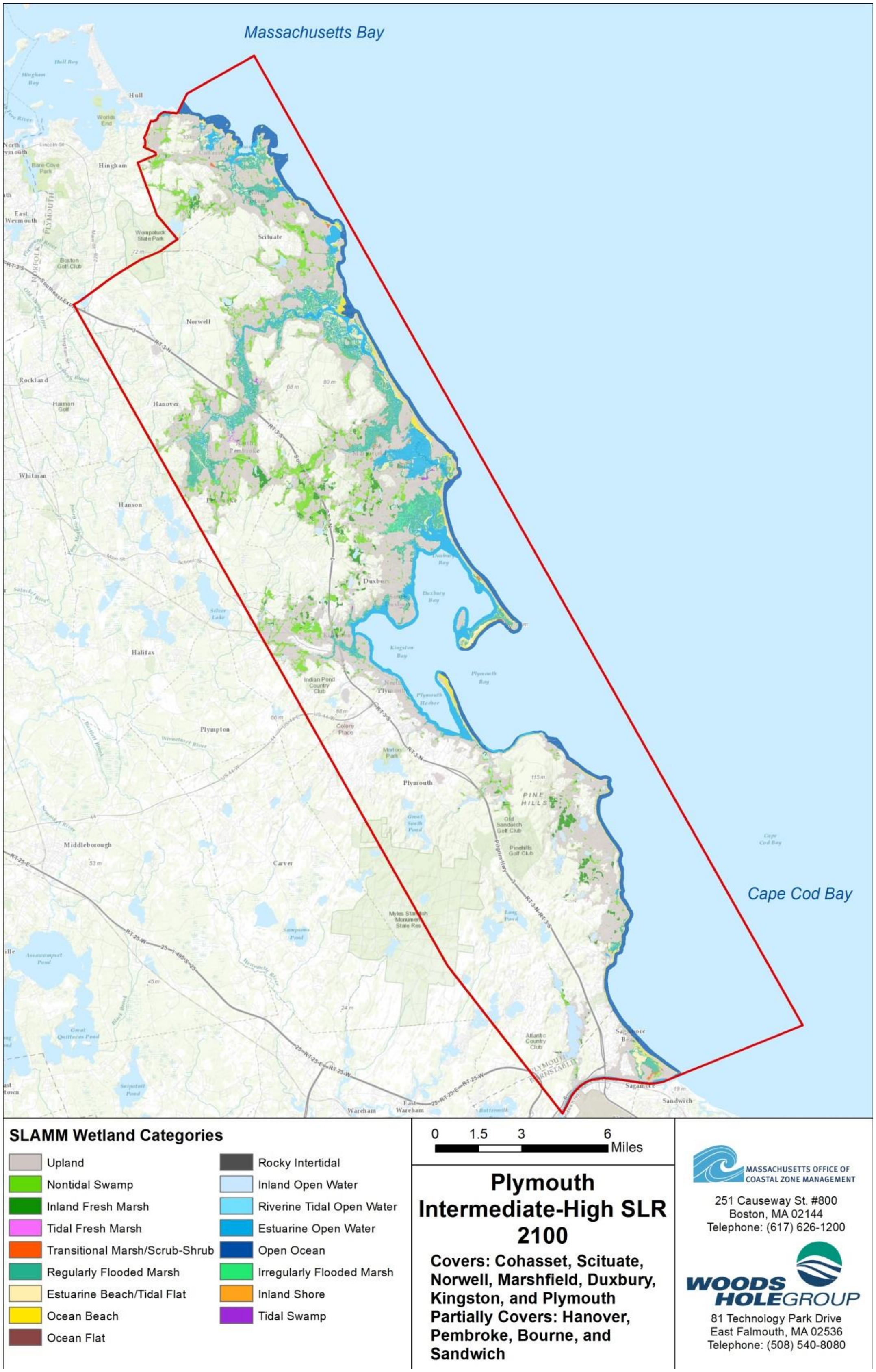
Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
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Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6 Miles
Plymouth
Intermediate-High SLR
2100
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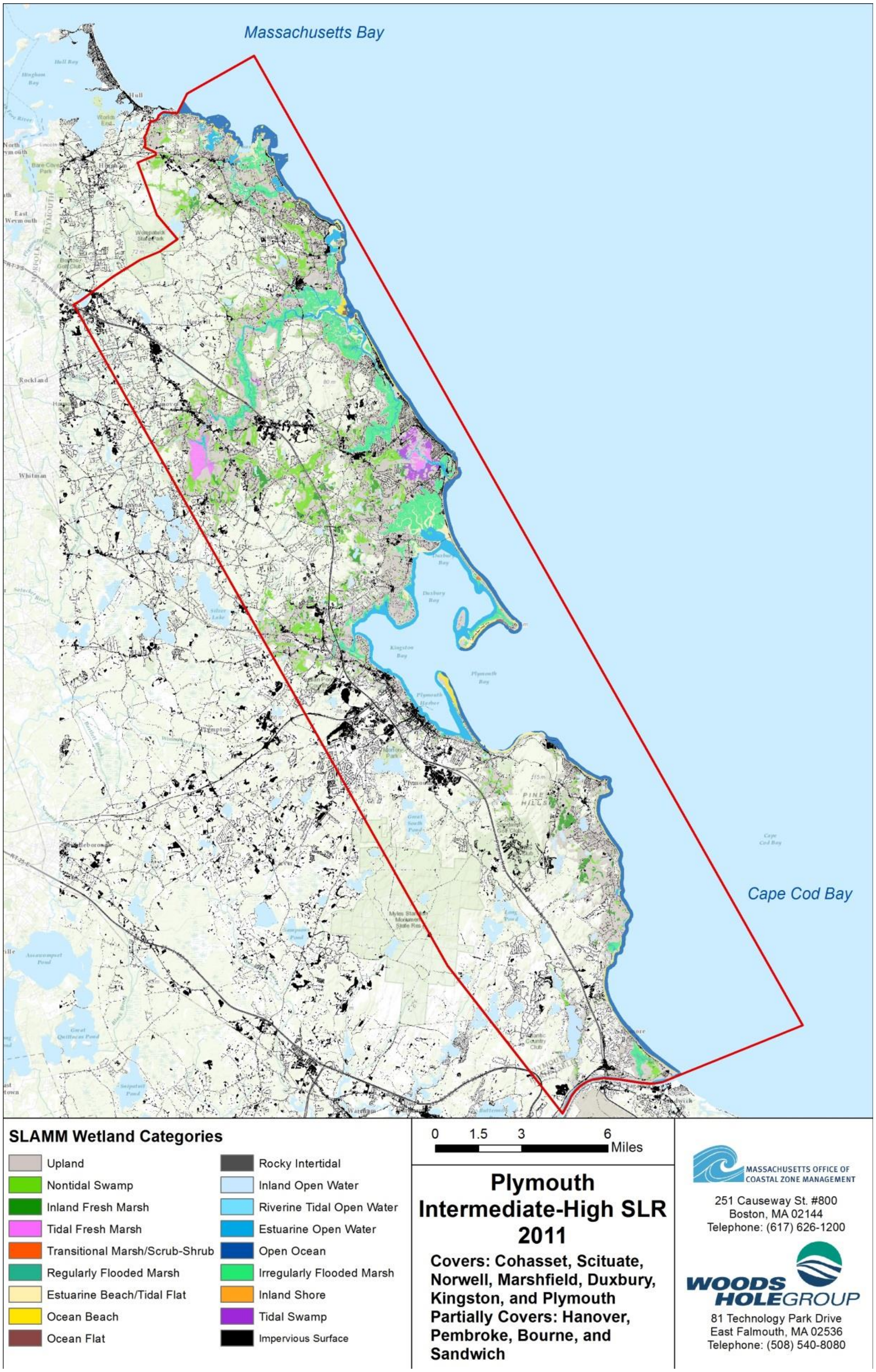

Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
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Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6 Miles
Plymouth
Intermediate-High SLR
2011
Covers: Cohasset, Scituate, Norwell, Marshfield, Duxbury, Kingston, and Plymouth
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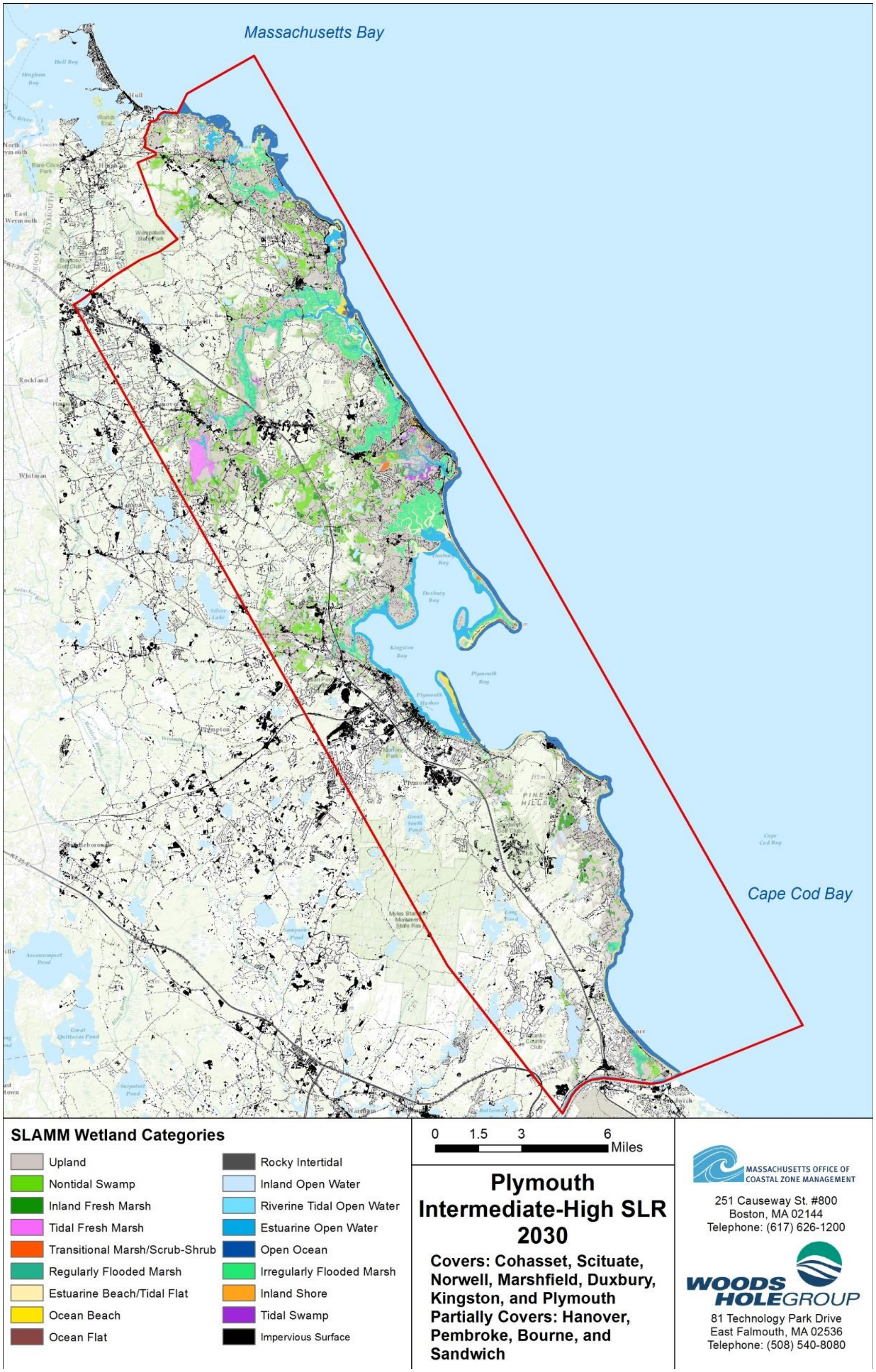
Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
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Regularly Flooded Marsh
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Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6 Miles
Plymouth
Intermediate-High SLR
2030
Covers: Cohasset, Scituate, Norwell, Marshfield, Duxbury, Kingston, and Plymouth
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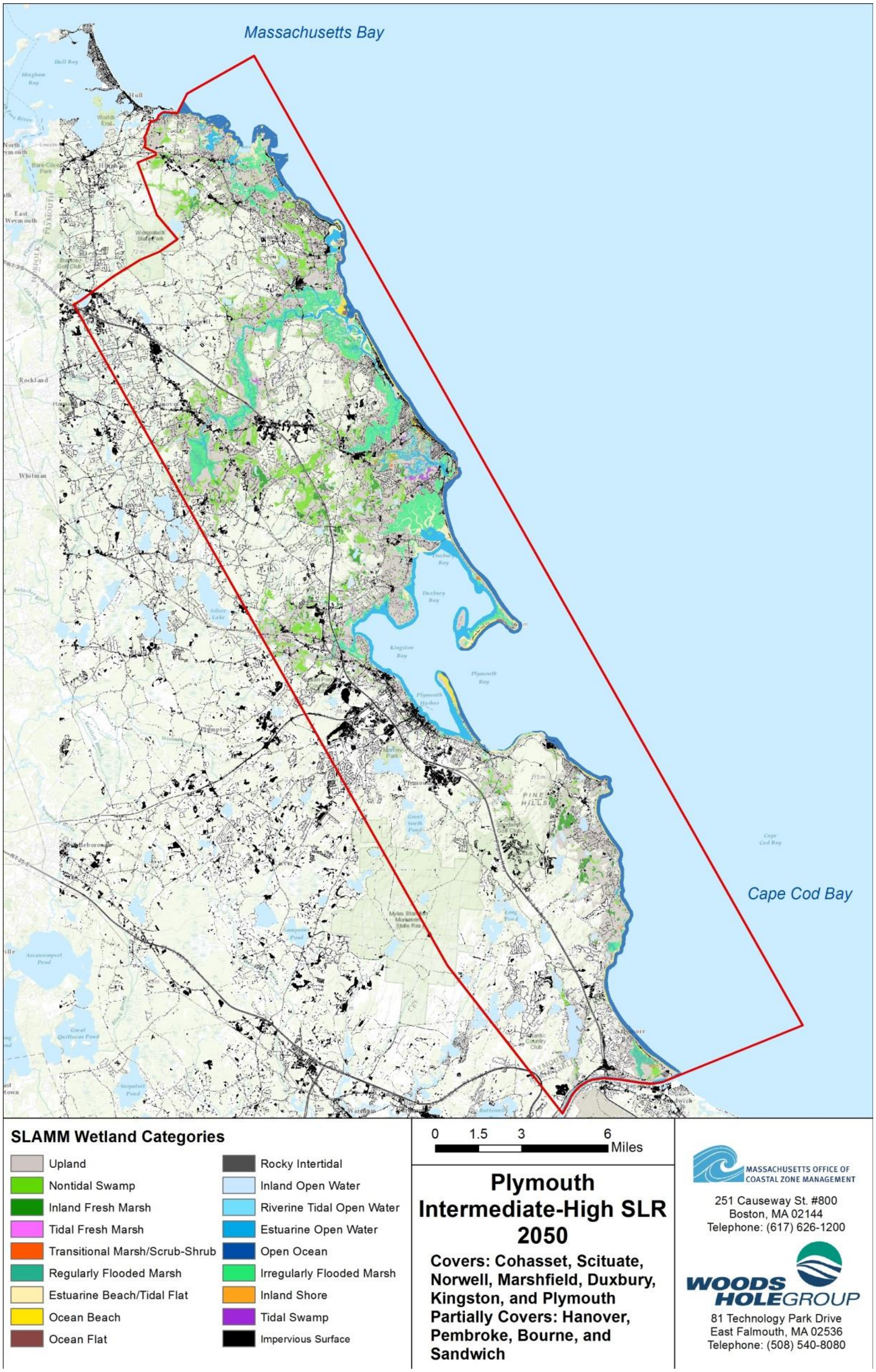
Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
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Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
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Rocky Intertidal
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Riverine Tidal Open Water
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Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6
Miles
Plymouth
Intermediate-High SLR
2050
Covers: Cohasset, Scituate, Norwell, Marshfield, Duxbury, Kingston, and Plymouth
Partially Covers: Hanover, Pembroke, Bourne, and Sandwich
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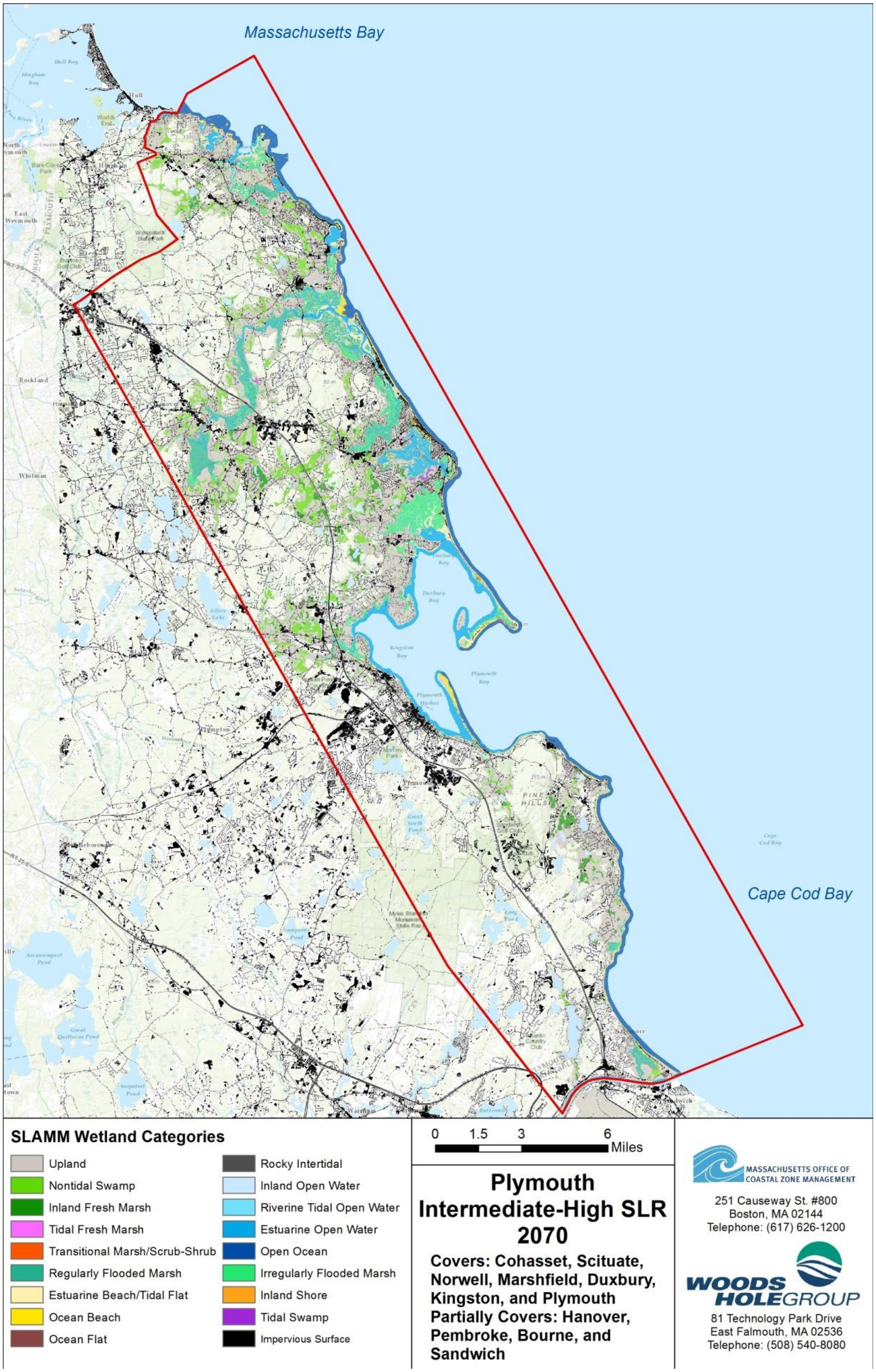
Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6 Miles
Plymouth
Intermediate-High SLR
2070
Covers: Cohasset, Scituate, Norwell, Marshfield, Duxbury, Kingston, and Plymouth
Partially Covers: Hanover, Pembroke, Bourne, and Sandwich
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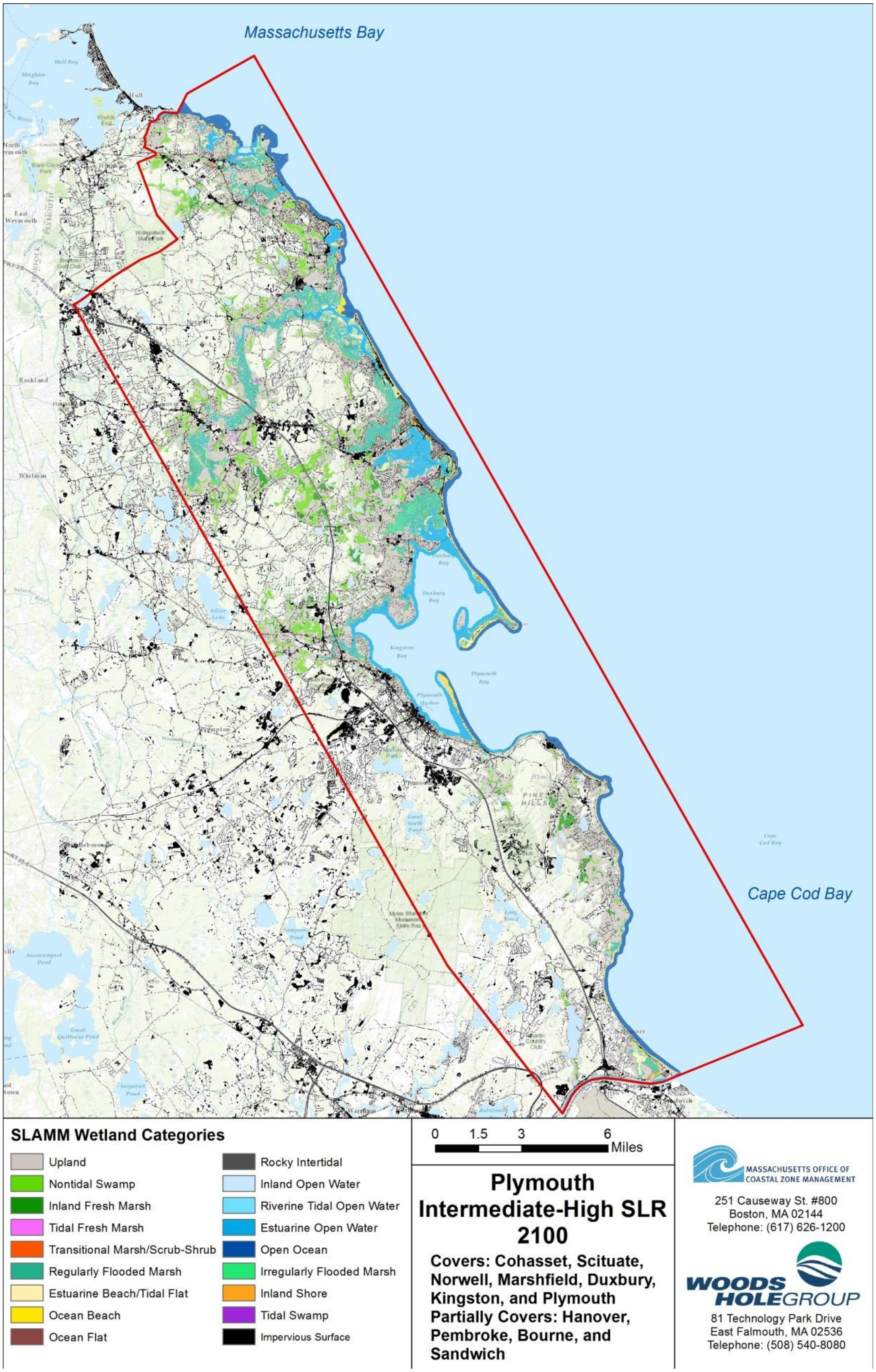
Massachusetts Bay
Cape Cod Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
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Ocean Beach
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Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6
Miles
Plymouth
Intermediate-High SLR
2100
Covers: Cohasset, Scituate, Norwell, Marshfield, Duxbury, Kingston, and Plymouth
Partially Covers: Hanover, Pembroke, Bourne, and Sandwich
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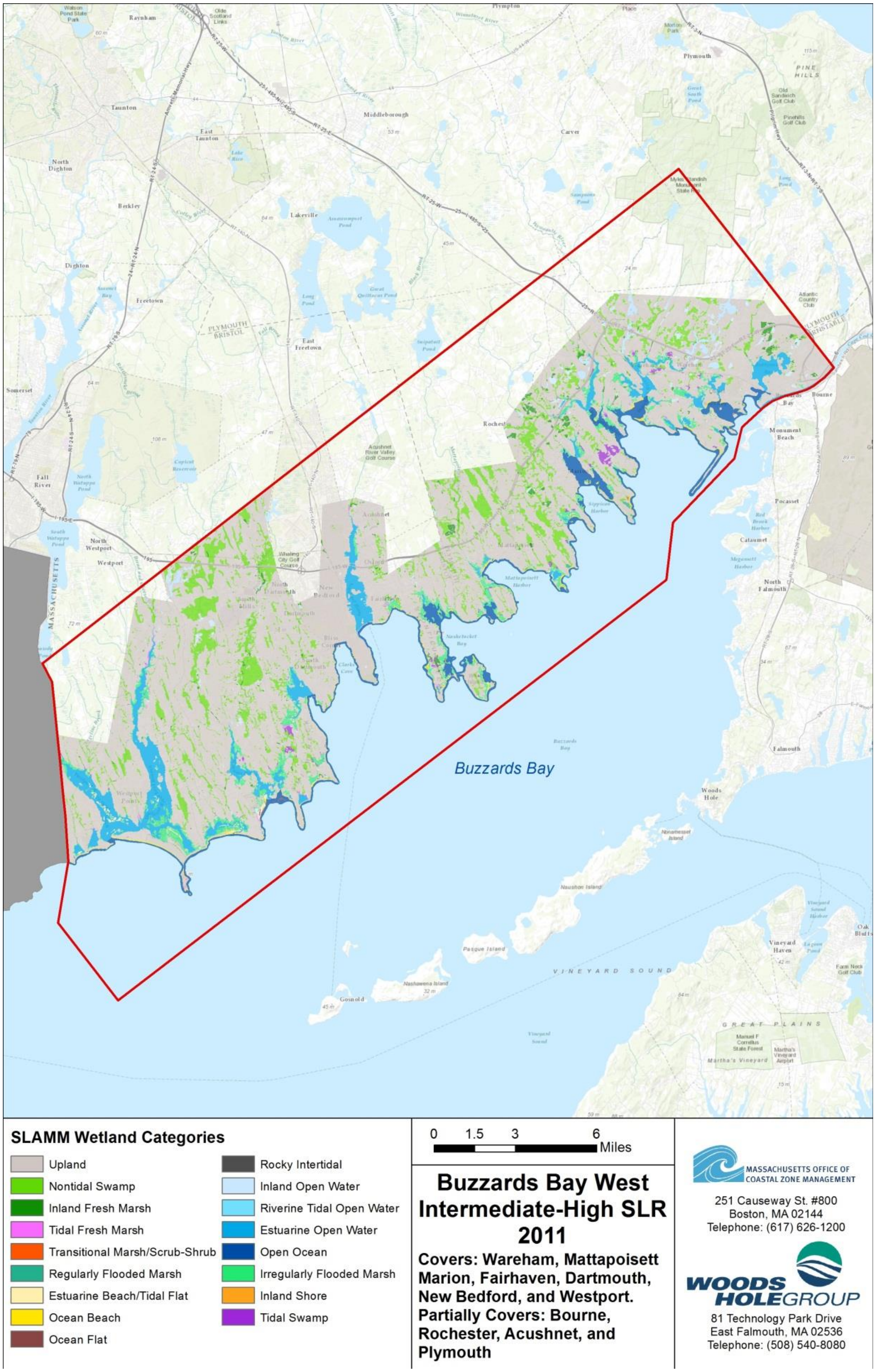
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6
Miles
Buzzards Bay West
Intermediate-High SLR
2011
Covers: Wareham, Mattapoisett
Marion, Fairhaven, Dartmouth,
New Bedford, and Westport.
Partially Covers: Bourne,
Rochester, Acushnet, and
Plymouth
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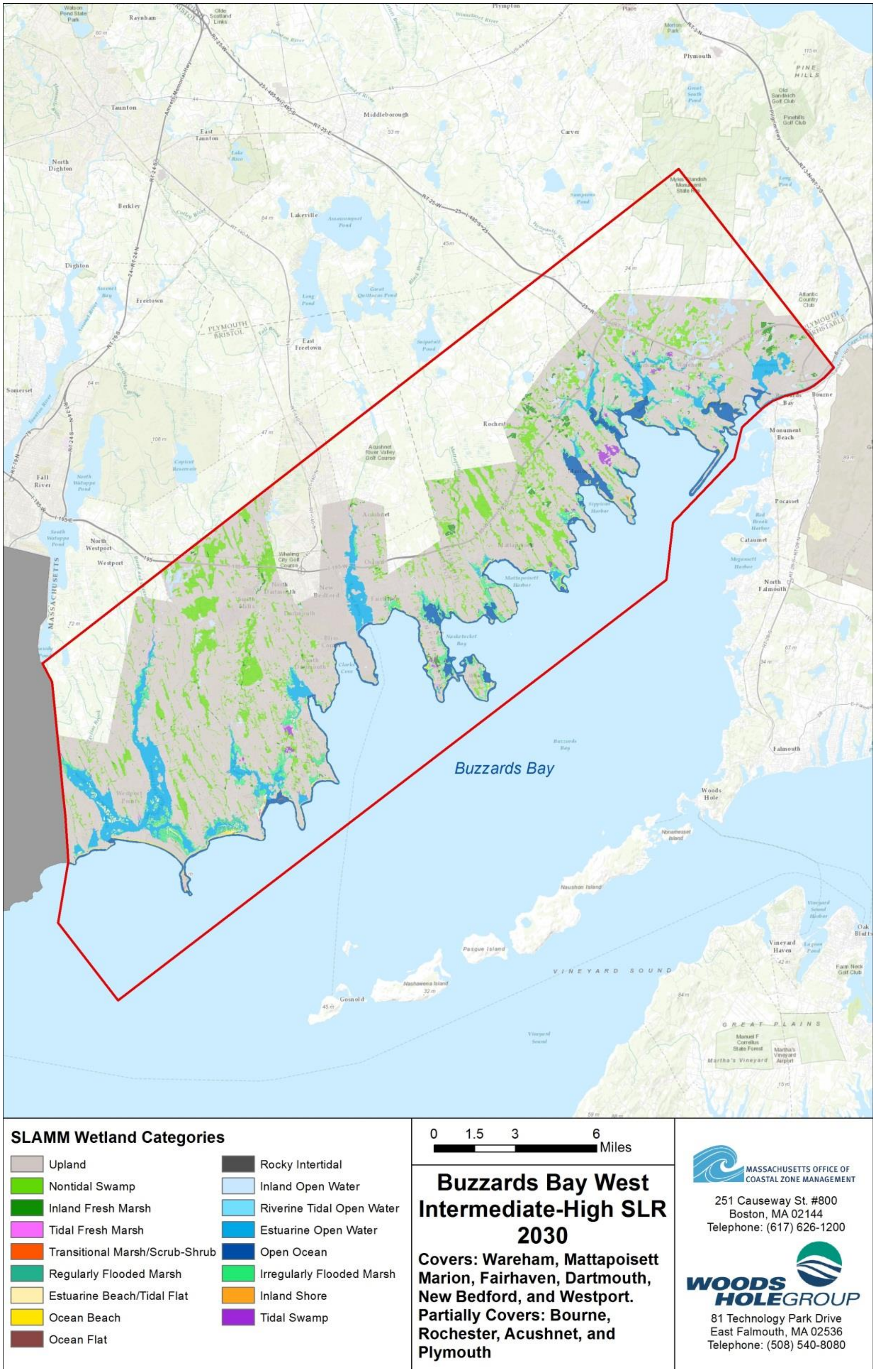
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6
Miles
Buzzards Bay West
Intermediate-High SLR
2030
Covers: Wareham, Mattapoisett Marion, Fairhaven, Dartmouth, New Bedford, and Westport. Partially Covers: Bourne, Rochester, Acushnet, and Plymouth
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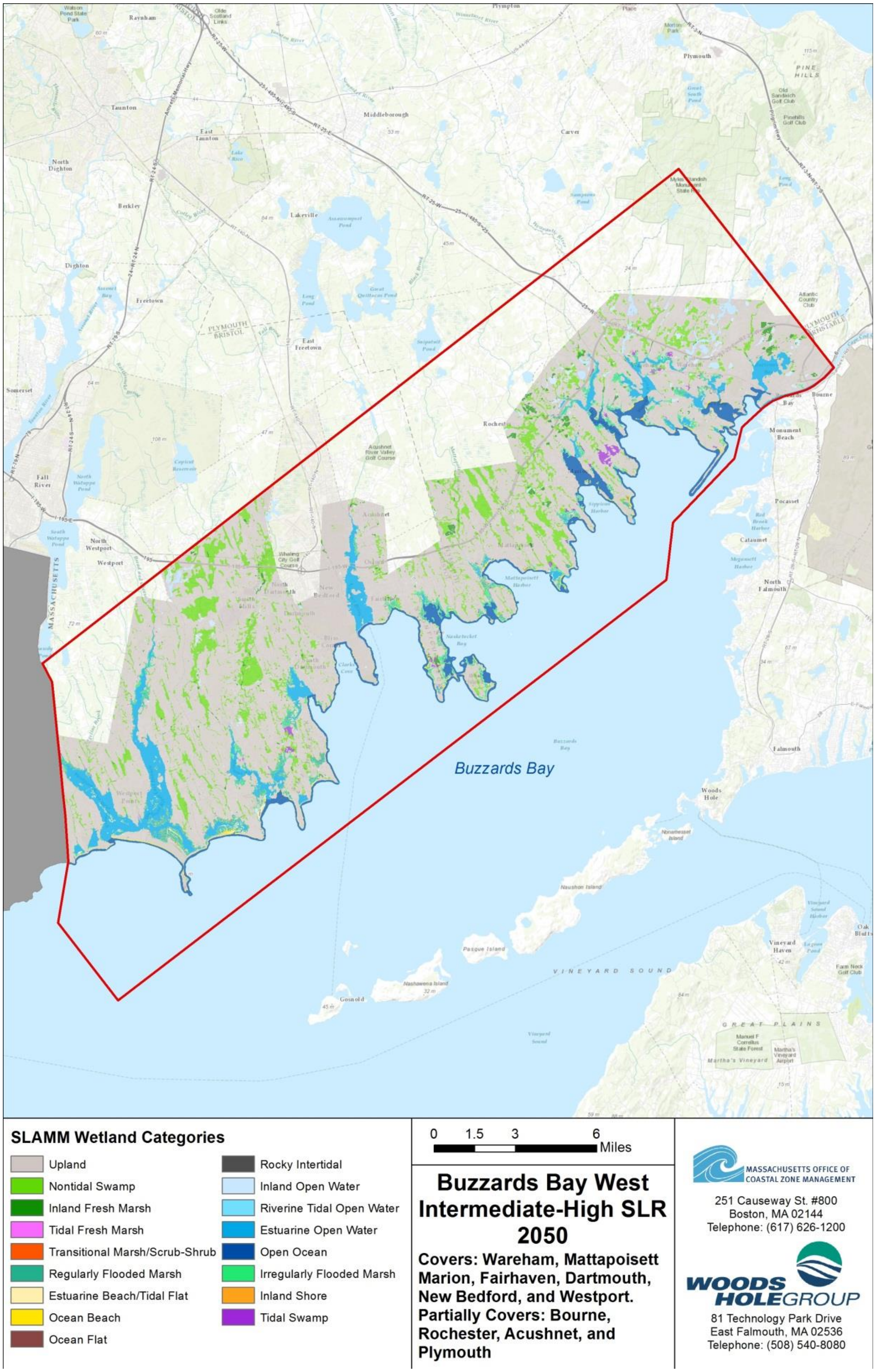
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6 Miles
Buzzards Bay West
Intermediate-High SLR
2050
Covers: Wareham, Mattapoisett Marion, Fairhaven, Dartmouth, New Bedford, and Westport. Partially Covers: Bourne, Rochester, Acushnet, and Plymouth
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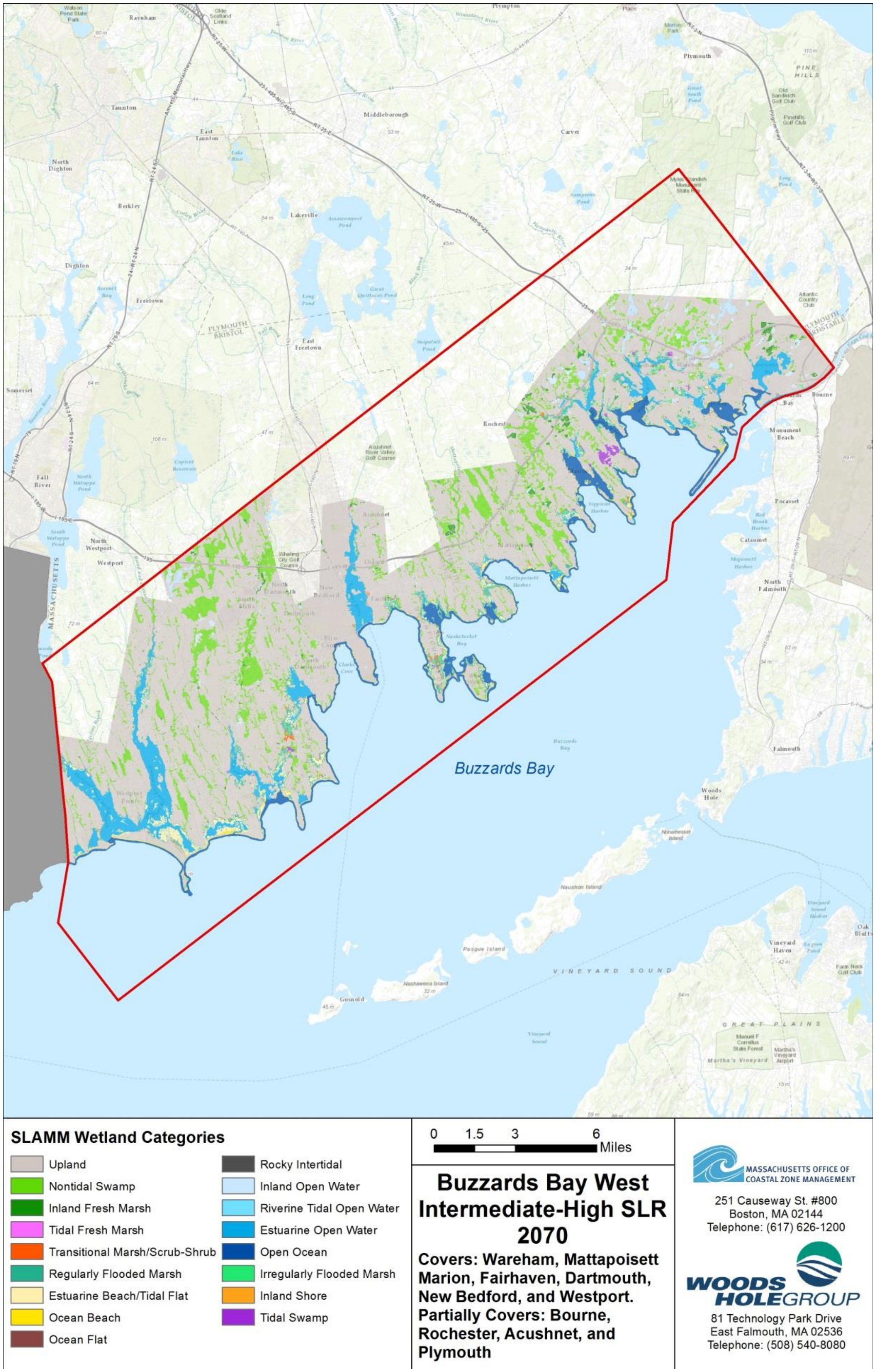
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
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Ocean Flat
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Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6
Miles
Buzzards Bay West
Intermediate-High SLR
2070
Covers: Wareham, Mattapoisett
Marion, Fairhaven, Dartmouth,
New Bedford, and Westport.
Partially Covers: Bourne,
Rochester, Acushnet, and
Plymouth
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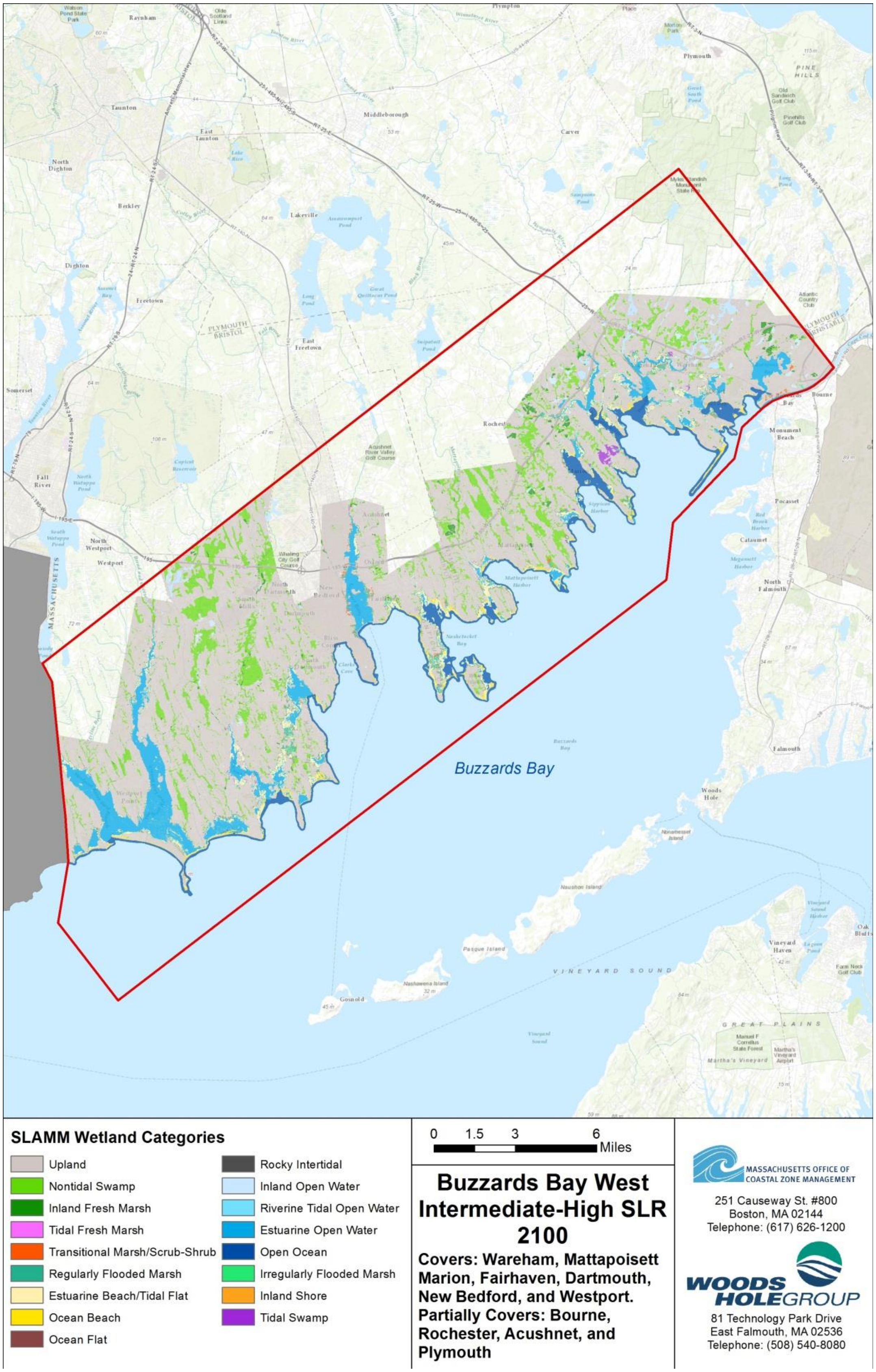
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
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Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
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Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
0 1.5 3 6 Miles
Buzzards Bay West Intermediate-High SLR 2100
Covers: Wareham, Mattapoisett Marion, Fairhaven, Dartmouth, New Bedford, and Westport. Partially Covers: Bourne, Rochester, Acushnet, and Plymouth
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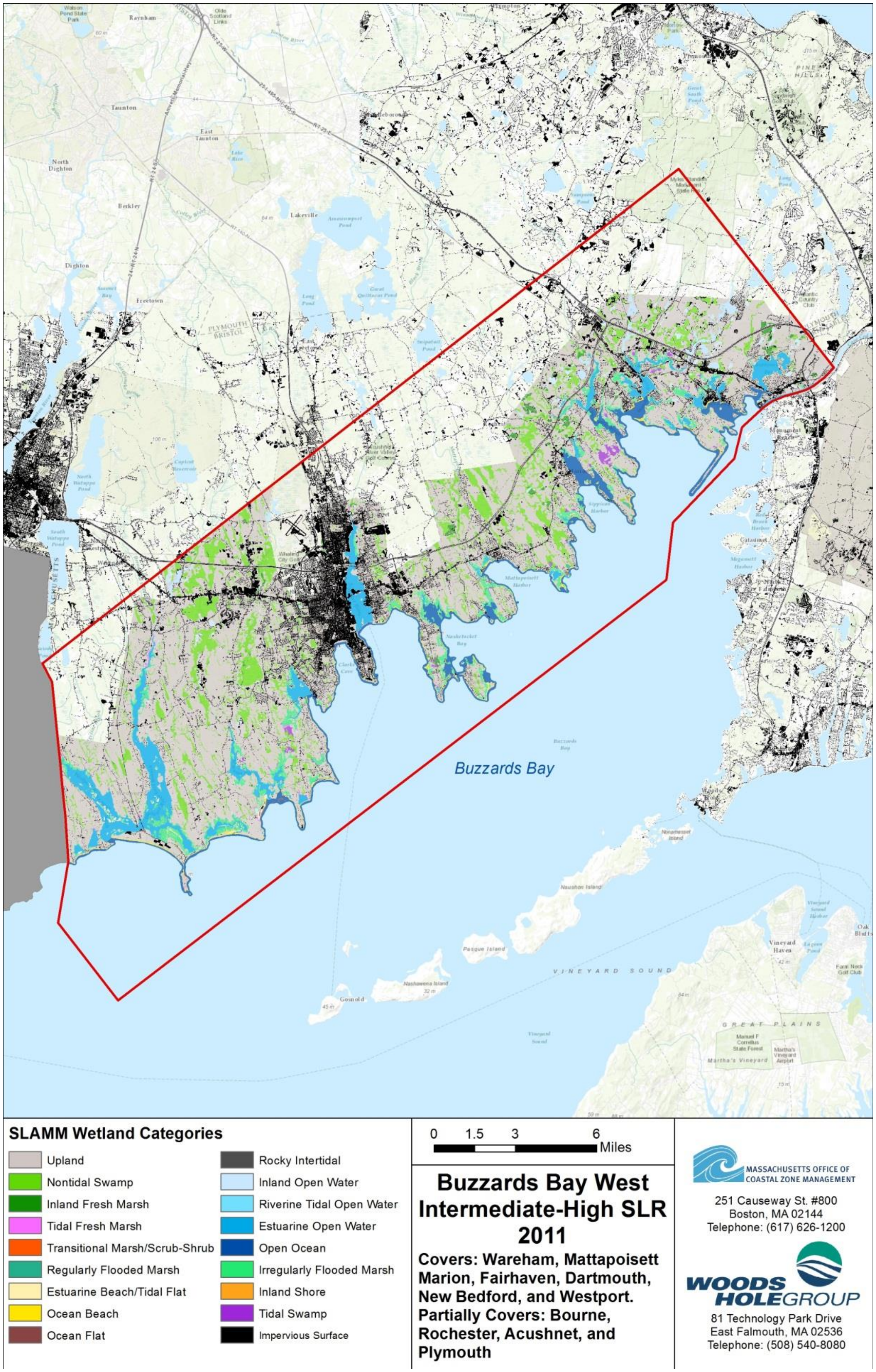
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
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Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6
Miles
Buzzards Bay West
Intermediate-High SLR
2011
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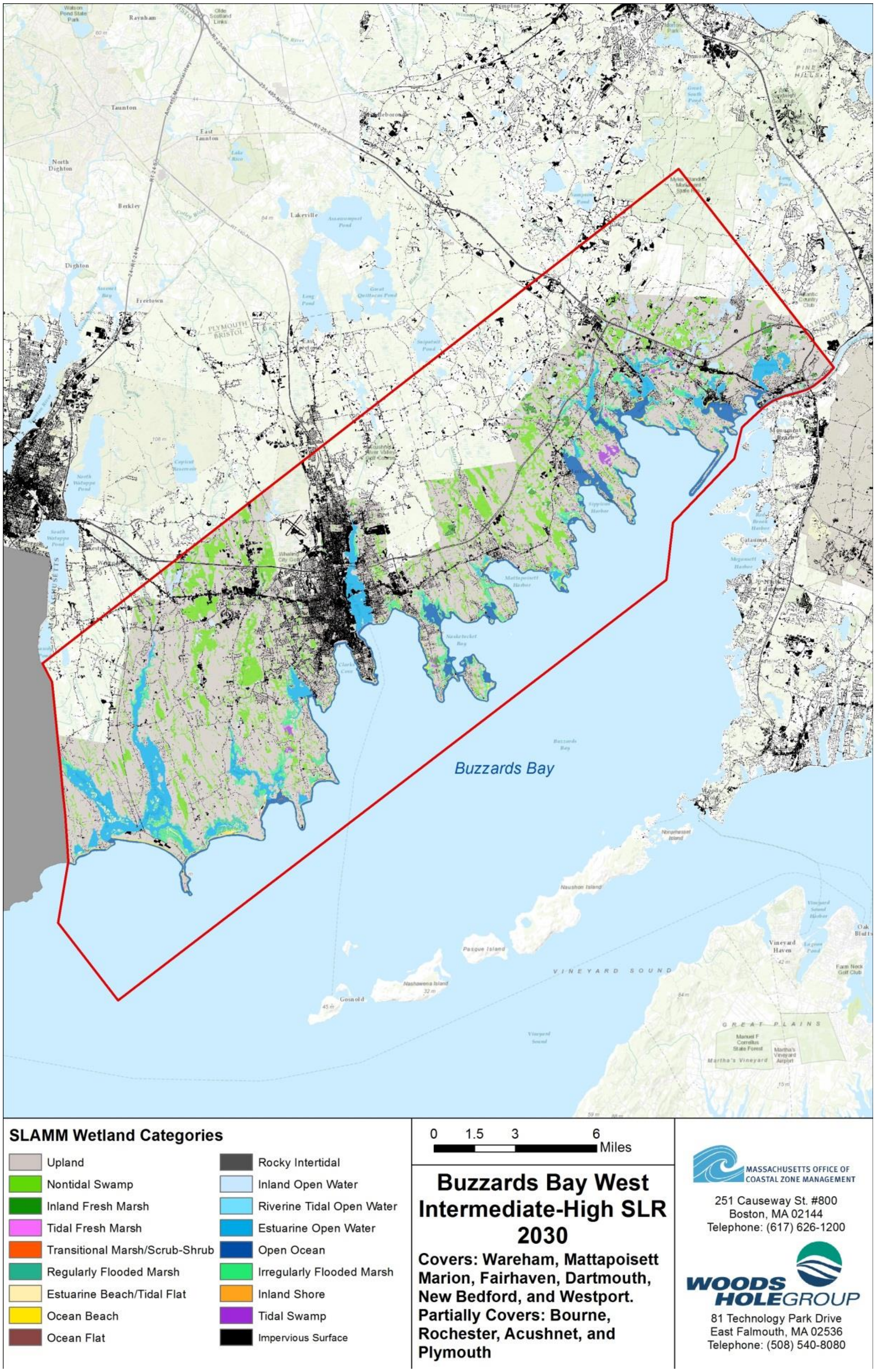
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6 Miles
Buzzards Bay West
Intermediate-High SLR
2030
Covers: Wareham, Mattapoisett Marion, Fairhaven, Dartmouth, New Bedford, and Westport. Partially Covers: Bourne, Rochester, Acushnet, and Plymouth
MASSACHUSETTS OFFICE OF COASTAL ZONE MANAGEMENT
251 Causeway St. #800
Boston, MA 02144
Telephone: (617) 626-1200
WOODS HOLE GROUP
81 Technology Park Drive
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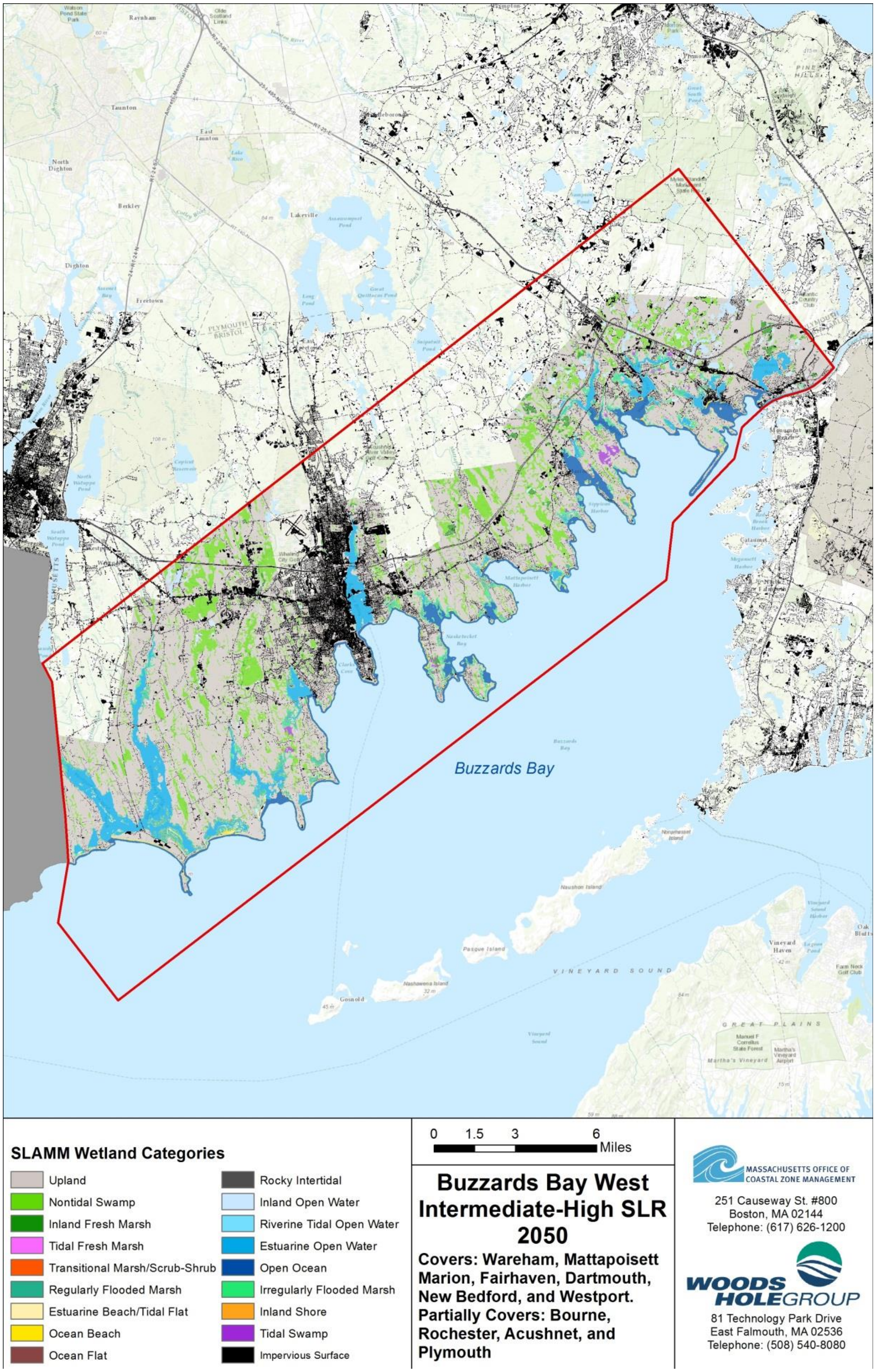
Telephone: (508) 540-8080


Buzzards Bay
Vineyard Sound
Nashawena Island
Pasque Island
Naushon Island
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6 Miles
Buzzards Bay West
Intermediate-High SLR
2050
Covers: Wareham, Mattapoisett
Marion, Fairhaven, Dartmouth,
New Bedford, and Westport.
Partially Covers: Bourne,
Rochester, Acushnet, and
Plymouth
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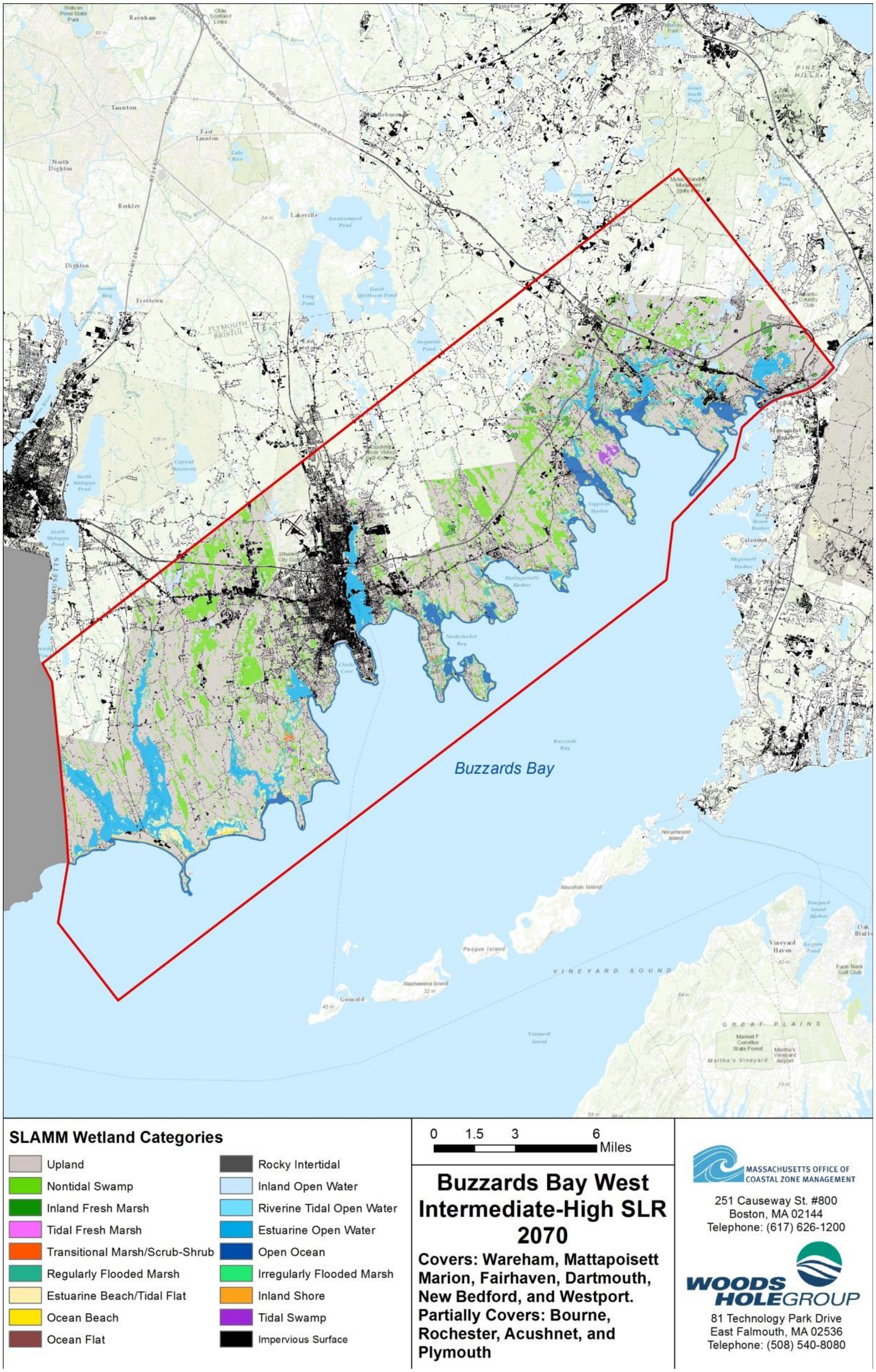
Buzzards Bay
Nashawena Island
Naushon Island
Pasque Island
VINEYARD SOUND
Vineyard Haven
GREAT PLAINS
Taunton
East Taunton
North Dighton
Berkley
Lakeville
Dighton
Freetown
Raynham
Mattapoisett Harbor
Nasketucket Bay
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6
Miles
Buzzards Bay West
Intermediate-High SLR
2070
Covers: Wareham, Mattapoisett
Marion, Fairhaven, Dartmouth,
New Bedford, and Westport.
Partially Covers: Bourne,
Rochester, Acushnet, and
Plymouth
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WOODS HOLE GROUP
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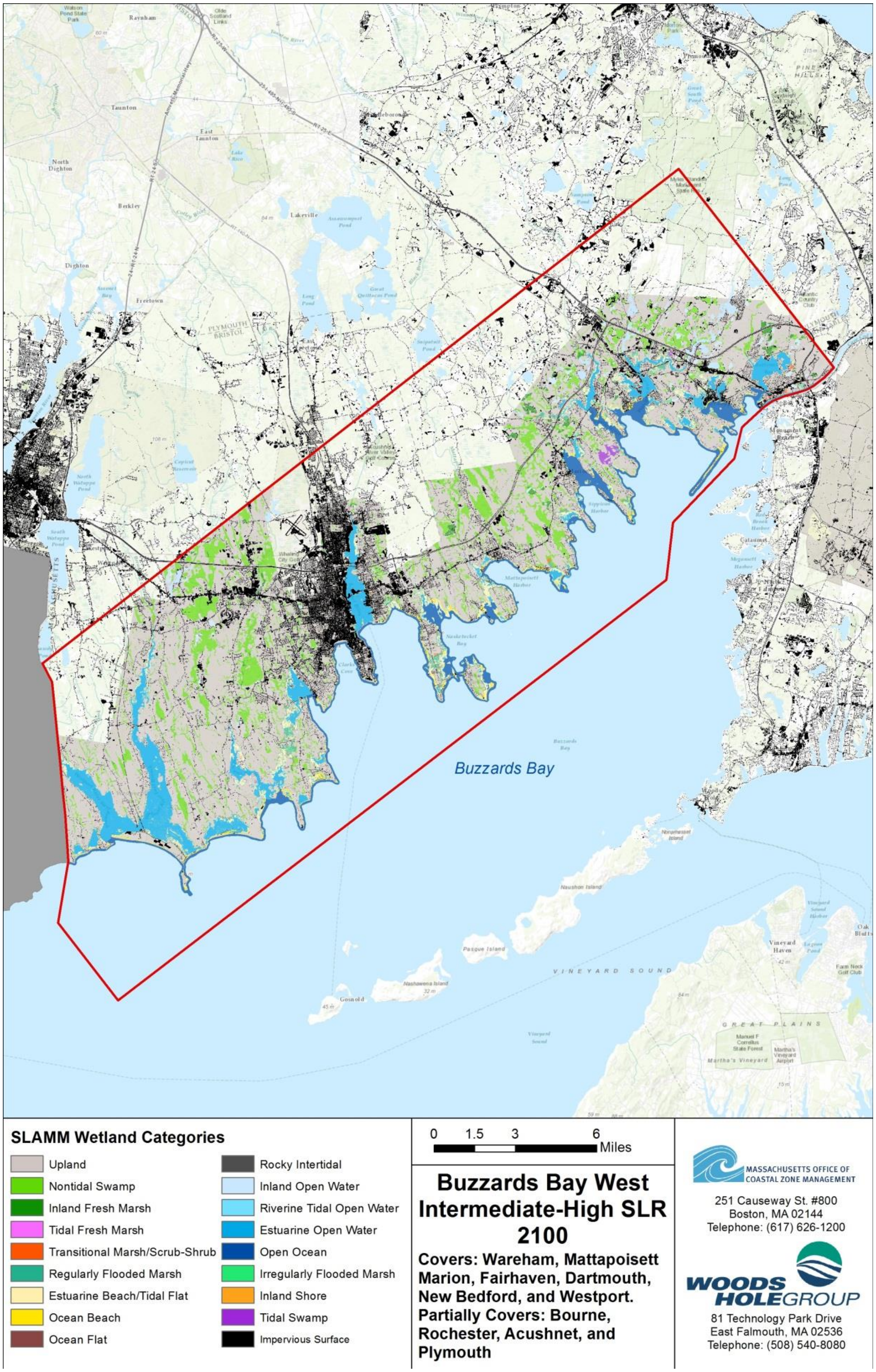
Buzzards Bay
SLAMM Wetland Categories
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach/Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Riverine Tidal Open Water
Estuarine Open Water
Open Ocean
Irregularly Flooded Marsh
Inland Shore
Tidal Swamp
Impervious Surface
0 1.5 3 6
Miles
Buzzards Bay West
Intermediate-High SLR
2100
Covers: Wareham, Mattapoisett Marion, Fairhaven, Dartmouth, New Bedford, and Westport. Partially Covers: Bourne, Rochester, Acushnet, and Plymouth
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Table B-1. Great Marsh (static accretion) wetland area changes under an intermediate-high SLR scenario

	Wetland Area in Hectares															
Date	Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Ocean Beach	Ocean Flat	Rocky Intertidal	Inland Open Water	Riverine Tidal	Estuarine Open Water	Open Ocean	Irreg.-Flooded Marsh
2011	15410.6	2102.6	737.1	32.6	23.1	736.8	1055.1	1141.7	469.0	5.0	1.6	413.9	184.9	2031.8	1035.9	6202.4
2030	15327.3	2094.1	734.4	33.9	66.0	793.0	1053.4	1174.8	461.5	5.0	1.6	413.2	184.8	2057.1	1046.9	6136.1
2040	15281.0	2087.0	727.2	38.2	57.9	890.3	1049.3	1195.5	456.5	5.0	1.6	412.1	126.9	2145.5	1055.3	6053.0
2050	15218.9	2078.9	720.6	42.4	65.7	1033.3	977.7	1144.2	440.6	5.0	1.6	411.4	126.1	2318.1	1077.3	5926.0
2060	15120.5	2067.0	715.4	42.9	90.5	1311.5	628.7	951.4	413.3	4.9	1.6	410.4	125.5	2929.5	1113.1	5662.9
2070	15005.3	2050.6	712.3	49.6	100.0	1841.8	445.8	863.7	390.0	4.8	1.6	409.4	124.8	3283.8	1146.3	5163.9
2080	14872.0	2033.5	698.5	51.8	117.3	2985.2	302.9	814.6	381.1	4.7	1.6	399.5	124.0	3590.3	1168.9	4048.0
2090	14707.9	2003.3	650.2	58.1	184.2	5113.4	207.6	829.1	380.5	4.4	1.6	382.5	121.9	3855.8	1190.0	1909.4
2100	14511.2	1969.7	644.6	58.5	165.6	6292.0	160.8	975.4	379.8	4.3	1.6	379.0	120.4	4039.9	1213.1	683.1

Table B-2. Great Marsh (MEM accretion) wetland area changes under an intermediate-high SLR scenario

	Wetland Area in Hectares															
Date	Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Ocean Beach	Ocean Flat	Rocky Intertidal	Inland Open Water	Riverine Tidal	Estuarine Open Water	Open Ocean	Irreg.-Flooded Marsh
2011	15410.6	2102.6	737.1	32.6	23.1	736.8	1055.1	1141.7	469.0	5.0	1.6	413.9	184.9	2031.8	1035.9	6202.4
2030	15328.4	2094.1	734.4	33.7	65.8	771.1	1053.4	1126.8	461.5	5.0	1.6	413.2	184.8	2055.5	1046.9	6207.4
2040	15282.6	2087.2	727.2	37.5	57.6	817.9	1049.3	1121.2	456.4	5.0	1.6	412.1	126.9	2142.7	1055.3	6202.1
2050	15219.9	2079.0	720.8	42.2	65.9	863.0	977.7	1043.3	440.6	5.0	1.6	411.4	126.1	2312.8	1077.3	6200.6
2060	15121.9	2067.2	715.4	43.3	90.4	954.0	628.7	823.6	413.3	4.9	1.6	410.4	125.5	2917.8	1113.1	6157.8
2070	15006.2	2050.6	712.3	49.6	101.2	1137.1	445.7	695.1	390.0	4.8	1.6	409.8	124.8	3268.8	1146.3	6049.5
2080	14872.4	2033.8	698.5	52.0	118.1	1433.2	302.8	583.6	381.1	4.7	1.6	399.5	124.0	3573.3	1168.9	5846.3
2090	14708.0	2003.3	650.3	58.2	185.5	2030.1	207.5	481.5	380.6	4.4	1.6	391.6	121.9	3825.5	1190.0	5360.0
2100	14511.2	1969.7	644.6	58.4	166.7	3512.3	160.6	402.9	379.9	4.3	1.6	379.0	120.4	4013.1	1213.1	4060.8

Table B-3. Plymouth wetland area changes under an intermediate-high SLR scenario

	Wetland Area in Hectares															
Date	Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Ocean Beach	Ocean Flat	Rocky Intertidal	Inland Open Water	Riverine Tidal	Estuarine Open Water	Open Ocean	Irreg.-Flooded Marsh
2011	15930.7	2781.8	711.2	324.6	11.8	209.9	533.8	117.2	342.9	28.0	0.0	865.8	9.7	1678.3	1716.6	2205.3
2030	15816.0	2740.7	699.5	281.3	75.6	337.4	536.6	144.2	349.1	28.0	0.0	863.6	0.9	1699.9	1745.0	2200.4
2040	15750.6	2708.7	695.3	44.6	71.9	434.4	537.1	232.2	351.0	28.0	0.0	862.9	0.6	1721.9	1752.2	2347.8
2050	15678.0	2676.8	692.7	43.1	76.2	595.6	536.8	233.4	356.7	27.9	0.0	856.4	0.4	1823.5	1760.3	2203.0
2060	15579.2	2651.4	688.5	33.6	82.4	949.9	498.5	230.0	366.4	26.6	0.0	853.2	0.4	1969.9	1771.9	1867.1
2070	15462.4	2632.1	683.6	37.0	83.0	1463.3	446.7	233.6	383.4	21.3	0.0	852.2	0.3	2109.8	1789.8	1383.3
2080	15323.8	2607.9	673.9	34.8	109.3	1916.9	369.8	272.6	405.2	17.8	0.0	849.4	0.3	2255.7	1804.6	948.1
2090	15169.4	2580.8	658.9	35.2	110.7	2274.6	318.7	333.4	431.4	13.6	0.0	844.8	0.2	2373.5	1820.9	623.4
2100	15017.1	2558.7	651.5	42.9	114.7	2501.5	285.8	481.3	457.1	10.6	0.0	838.4	0.2	2463.7	1837.7	344.5

Table B-4. Buzzards Bay West wetland area changes under an intermediate-high SLR scenario

	Wetland Area in Hectares															
Date	Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Ocean Beach	Ocean Flat	Rocky Intertidal	Inland Open Water	Riverine Tidal	Estuarine Open Water	Open Ocean	Irreg.-Flooded Marsh
2011	36520.0	5377.6	448.4	66.9	5.1	143.6	173.3	123.6	388.7	48.7	1.5	731.3	0.0	3283.9	2709.9	1682.9
2030	36486.2	5375.5	446.4	56.3	22.2	257.0	166.2	216.1	383.2	35.9	1.4	731.0	0.0	3227.3	2738.0	1566.2
2040	36439.3	5370.8	440.9	42.2	44.2	505.6	150.2	180.3	377.3	24.5	1.3	730.8	0.0	3338.7	2767.8	1298.4
2050	36365.0	5362.7	431.2	33.5	68.2	900.2	133.7	211.2	373.5	16.3	1.2	730.5	0.0	3394.8	2798.6	899.7
2060	36204.7	5347.5	418.5	24.8	133.2	1170.9	122.1	426.4	388.4	10.2	1.0	725.0	0.0	3458.5	2836.7	473.8
2070	35991.9	5312.2	407.8	21.9	181.1	1010.0	117.0	871.7	423.4	6.6	0.8	724.1	0.0	3518.3	2870.6	308.7
2080	35745.2	5283.3	395.4	20.4	191.5	776.0	112.6	1355.5	479.4	4.3	0.6	721.1	0.0	3592.5	2901.8	206.5
2090	35464.5	5245.7	389.0	17.9	220.5	754.8	84.4	1505.7	538.4	2.9	0.5	719.8	0.0	3789.7	2935.9	133.7
2100	35169.8	5215.3	386.0	16.7	222.5	755.3	79.4	1428.0	590.7	1.9	0.4	718.2	0.0	4160.6	2975.9	93.8

APPENDIX C. STATEWIDE RESULTS WETLAND AREA CHANGES

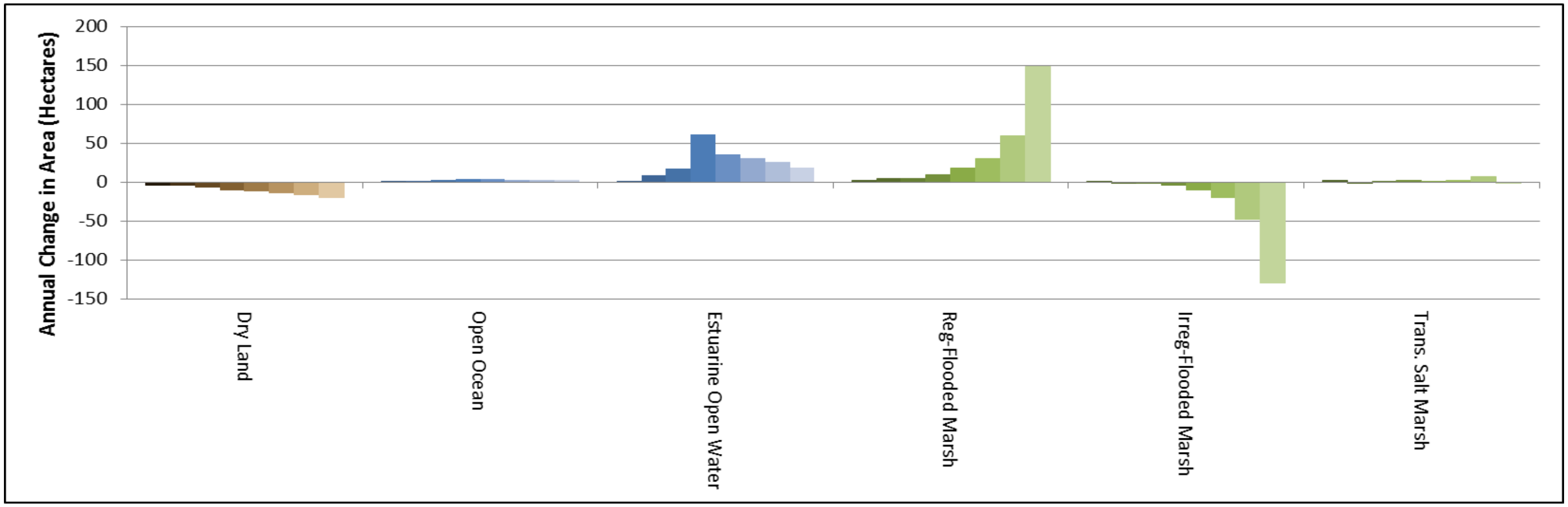

Figure C-1. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Great Marsh (00) panel (with time-variable accretion).

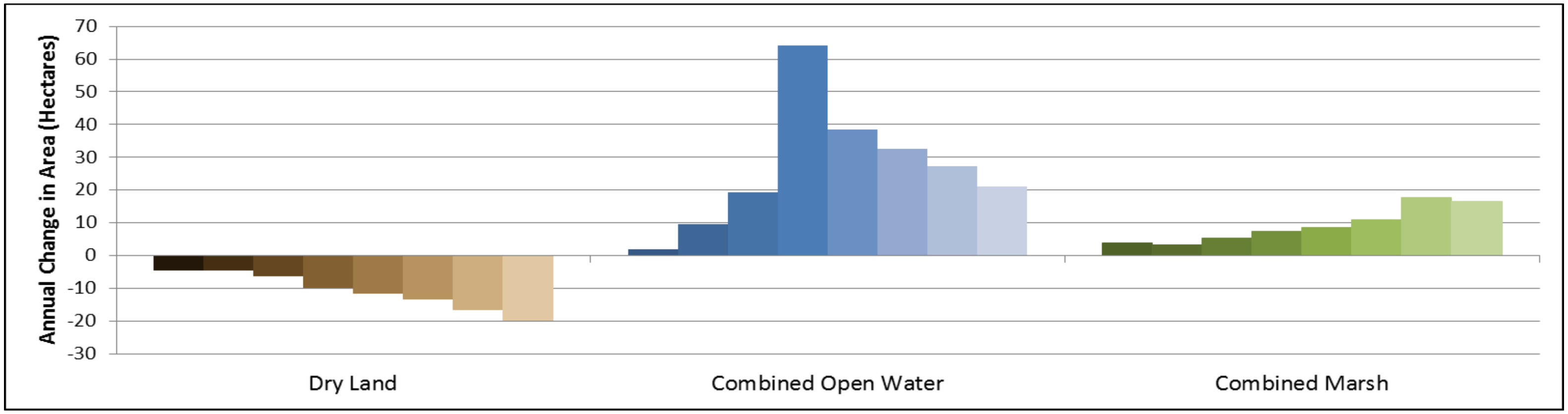

Figure C-2. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Great Marsh (00) panel (with time-variable accretion).

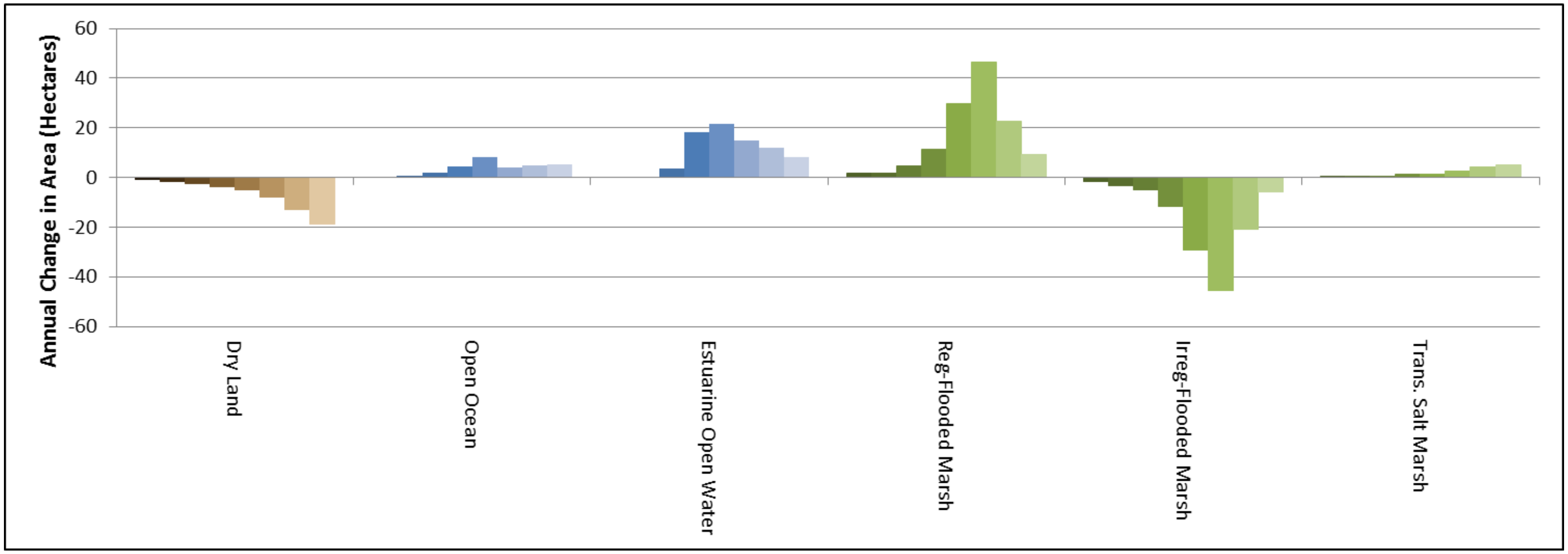

Figure C-3. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the North Shore (01) panel.

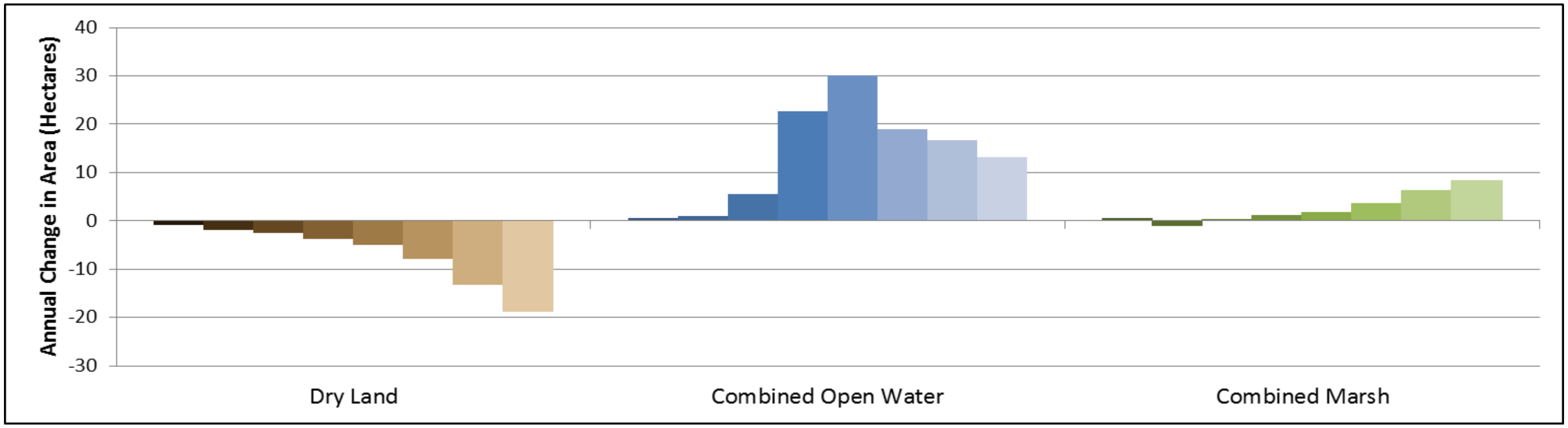

Figure C-4. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the North Shore (01) panel.

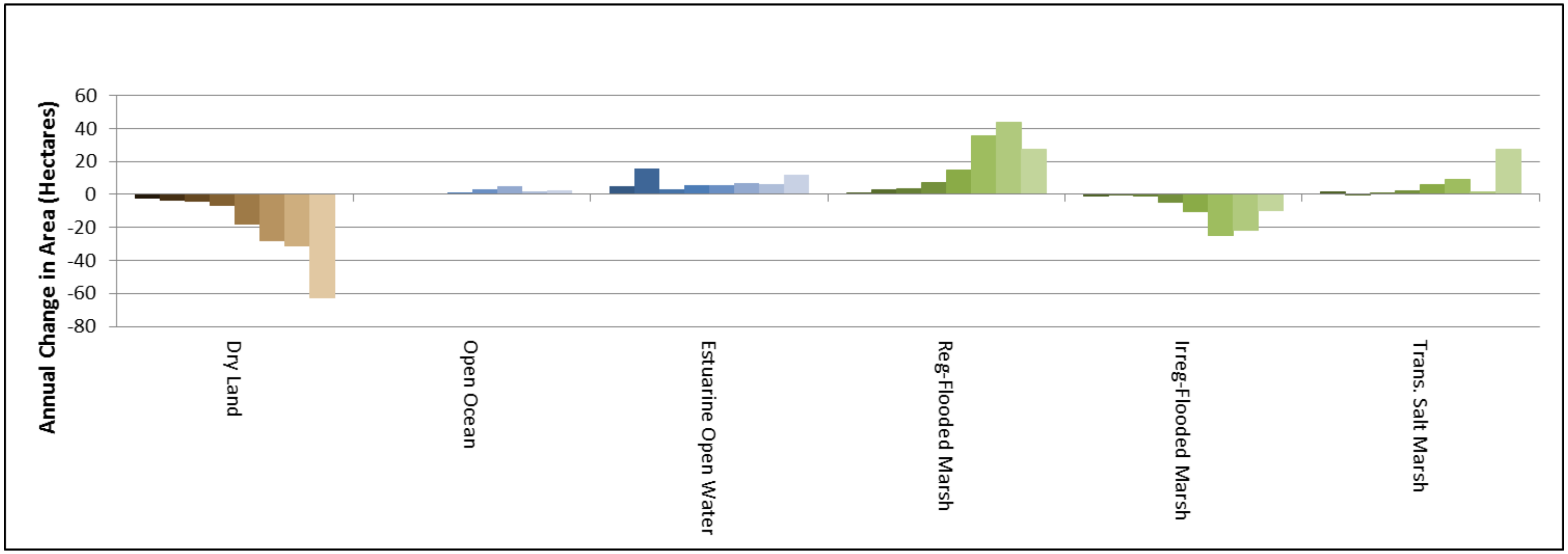

Figure C-5. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Boston (02) panel.

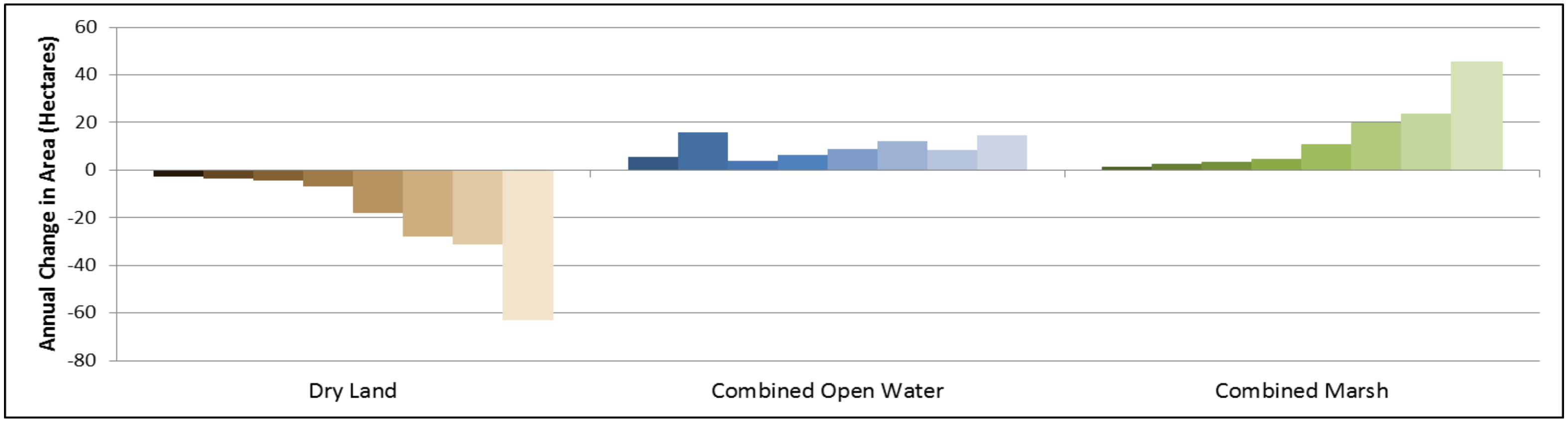

Figure C-6. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Boston (02) panel.

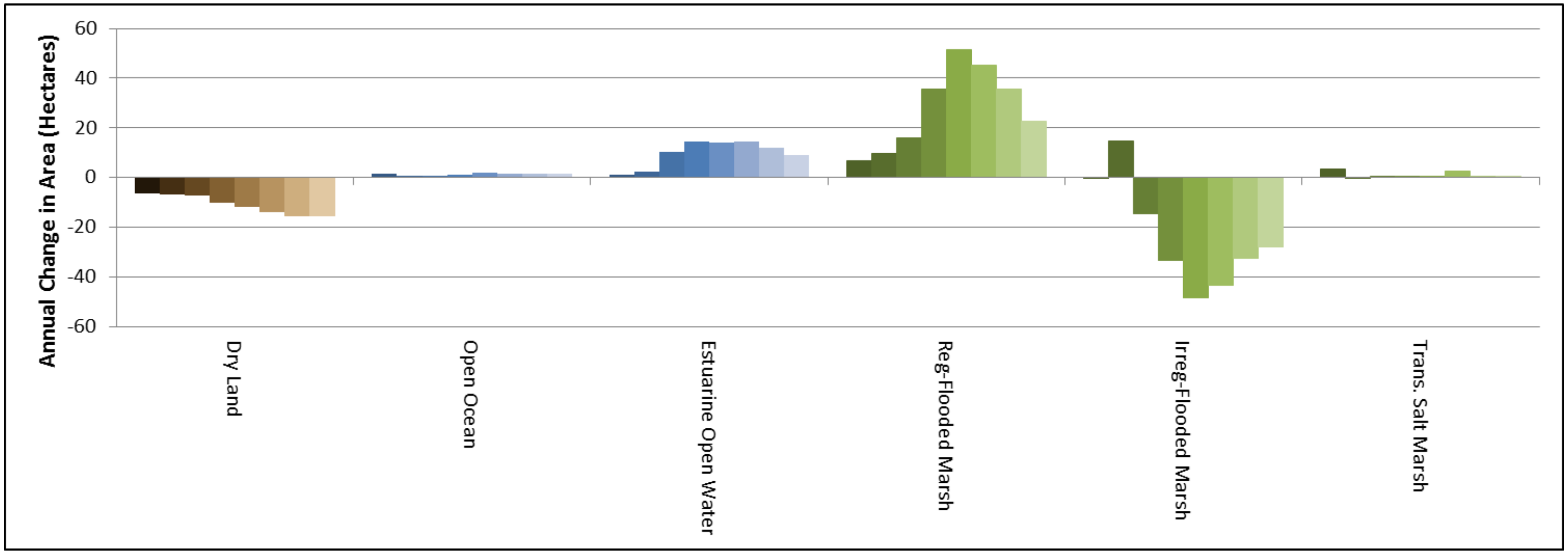

Figure C-7. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Plymouth (03) panel.

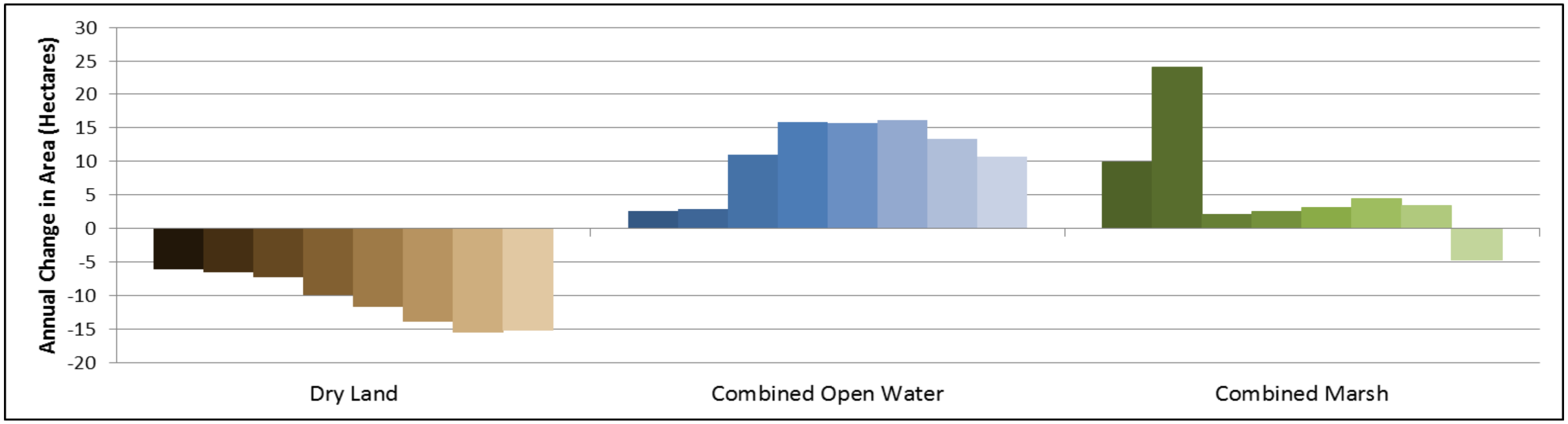

Figure C-8. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Plymouth (03) panel.

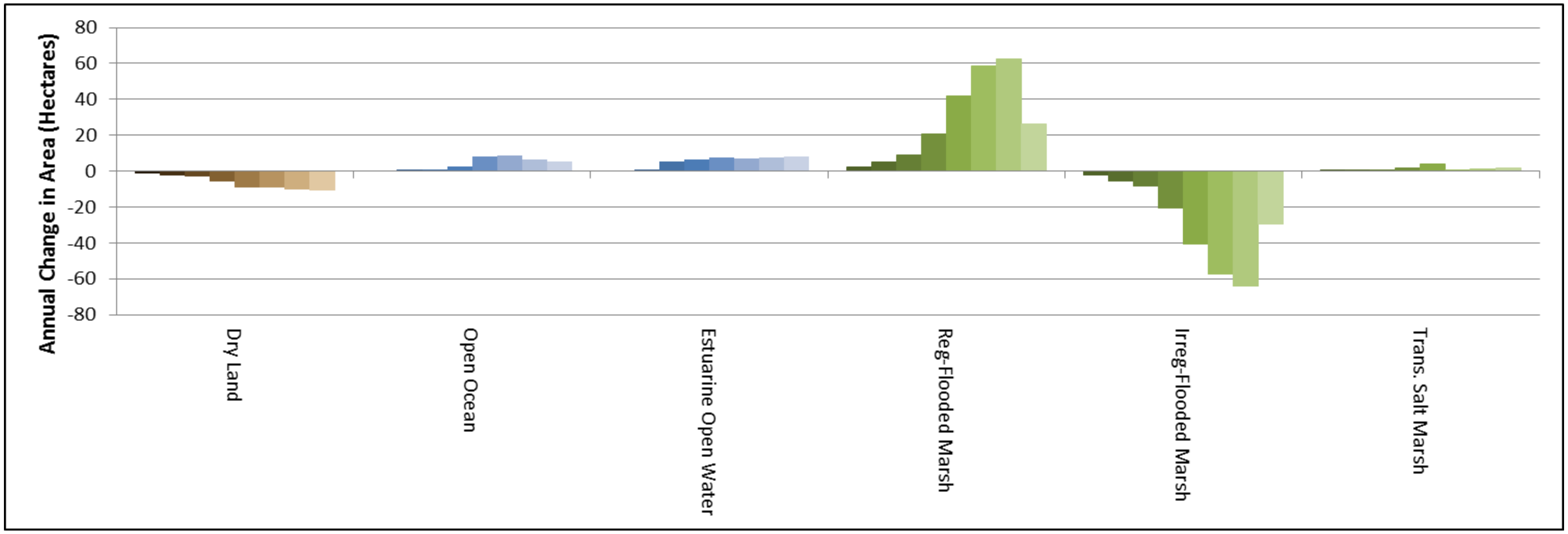

Figure C-9. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Bay (04) panel.

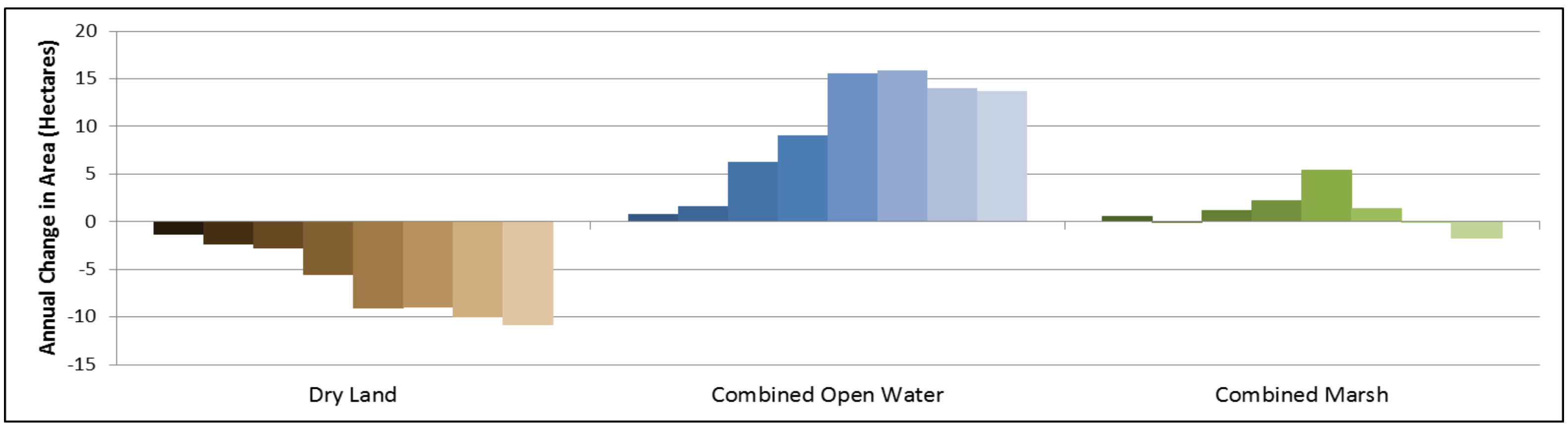

Figure C-10. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Bay (04) panel.

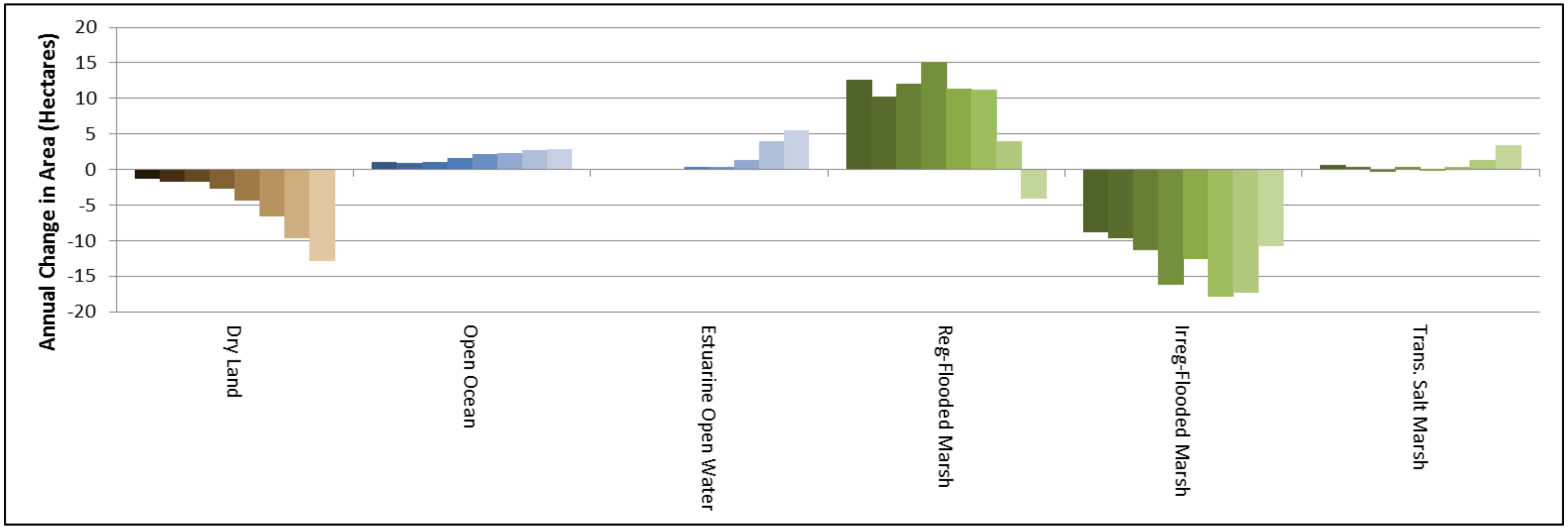

Figure C-11. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Provincetown (05) panel.

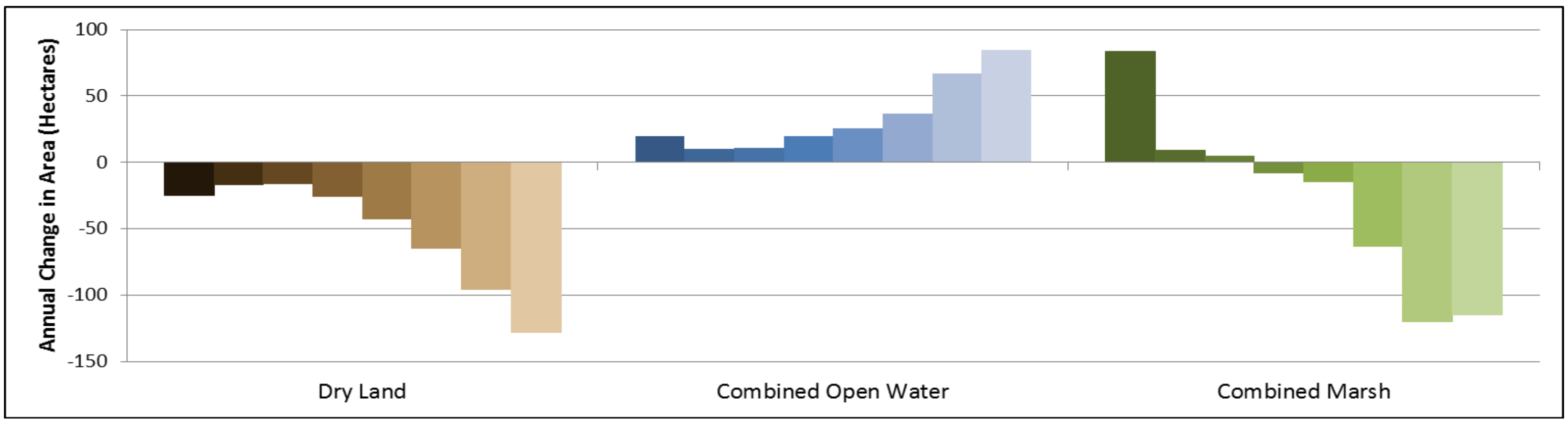

Figure C-12. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Provincetown (05) panel.

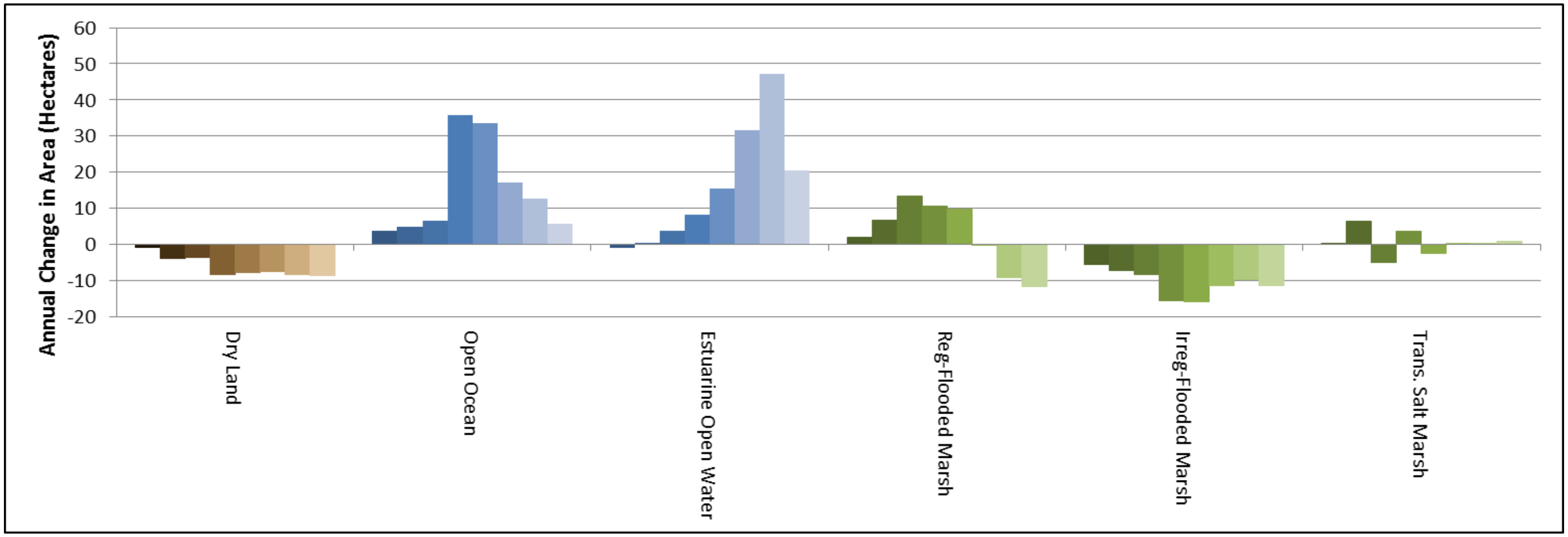

Figure C-13. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Monomoy (06) panel.

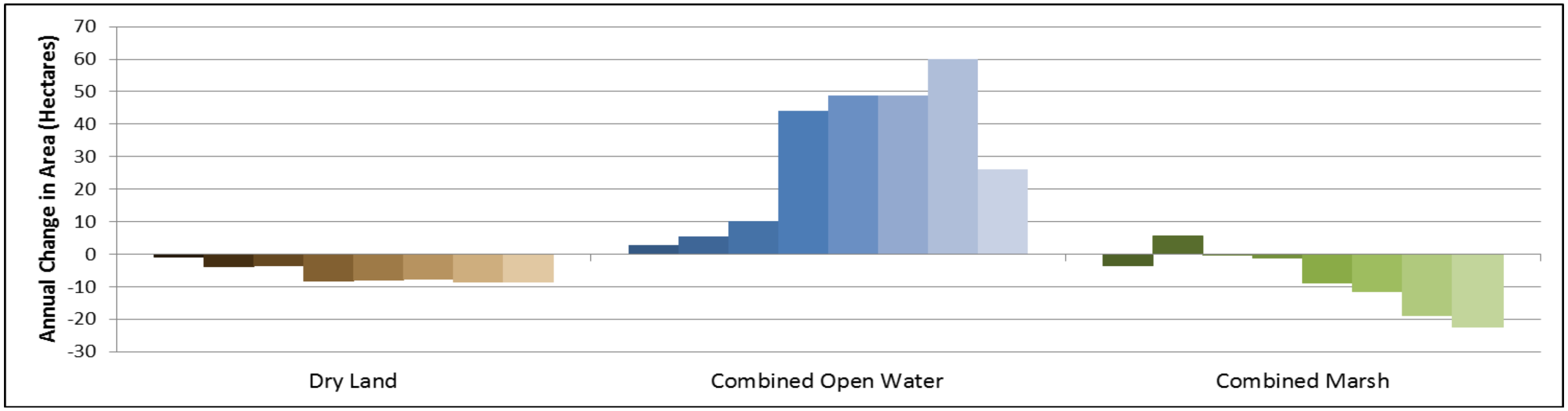

Figure C-14. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Monomoy (06) panel.

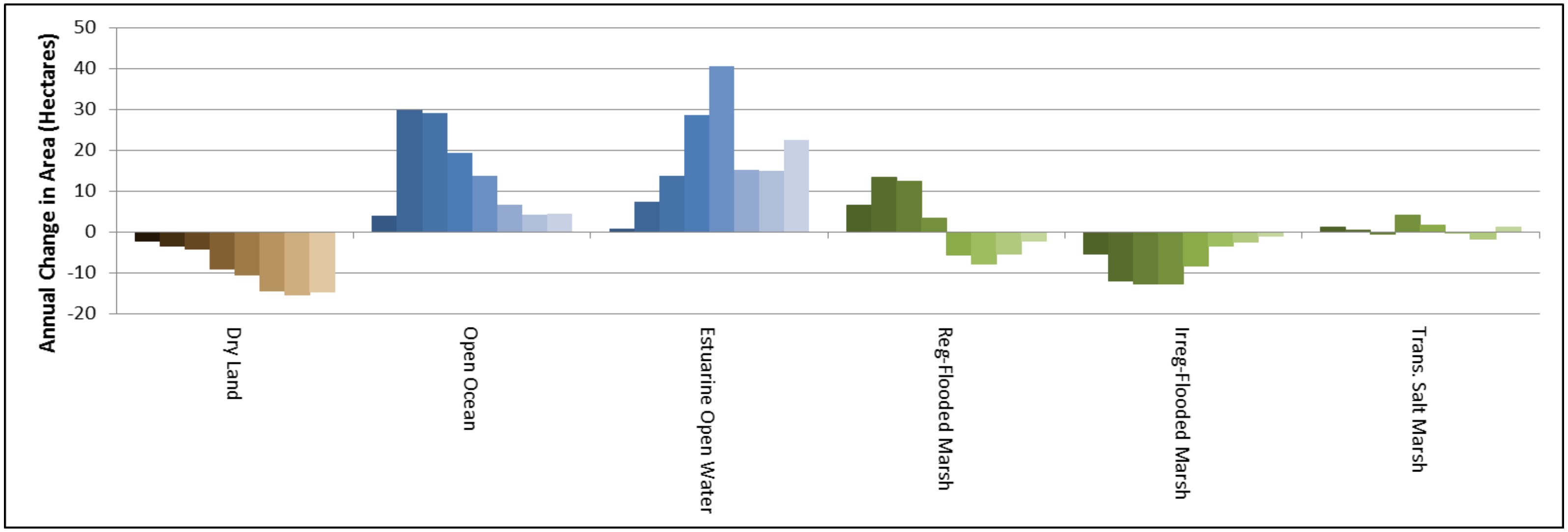

Figure C-15. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Vineyard Sound East (07) panel.

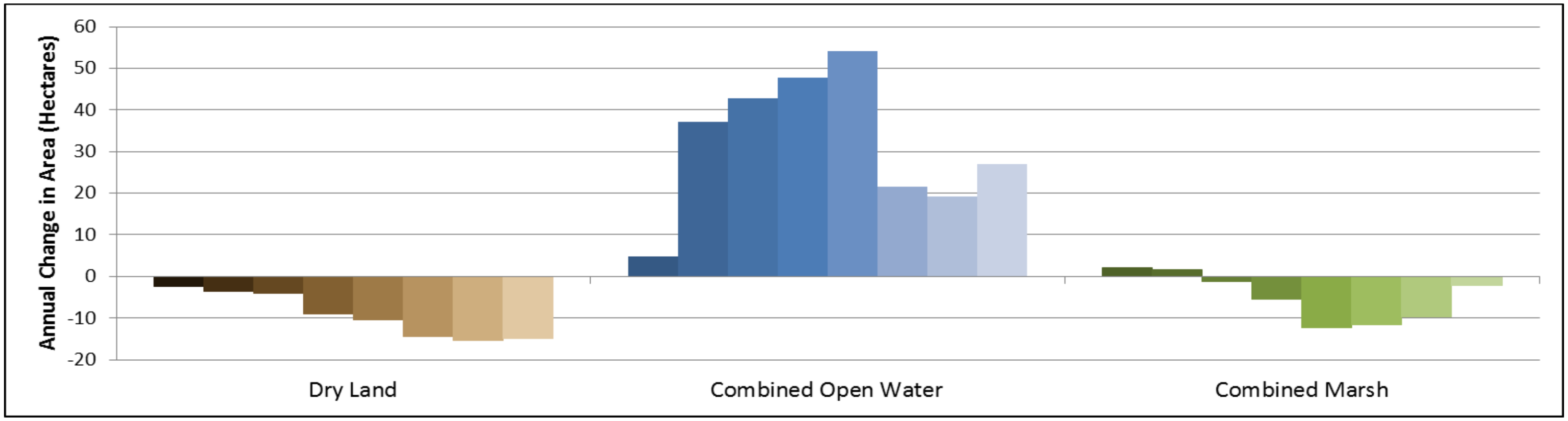

Figure C-16. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Cape Cod Vineyard Sound East (07) panel.

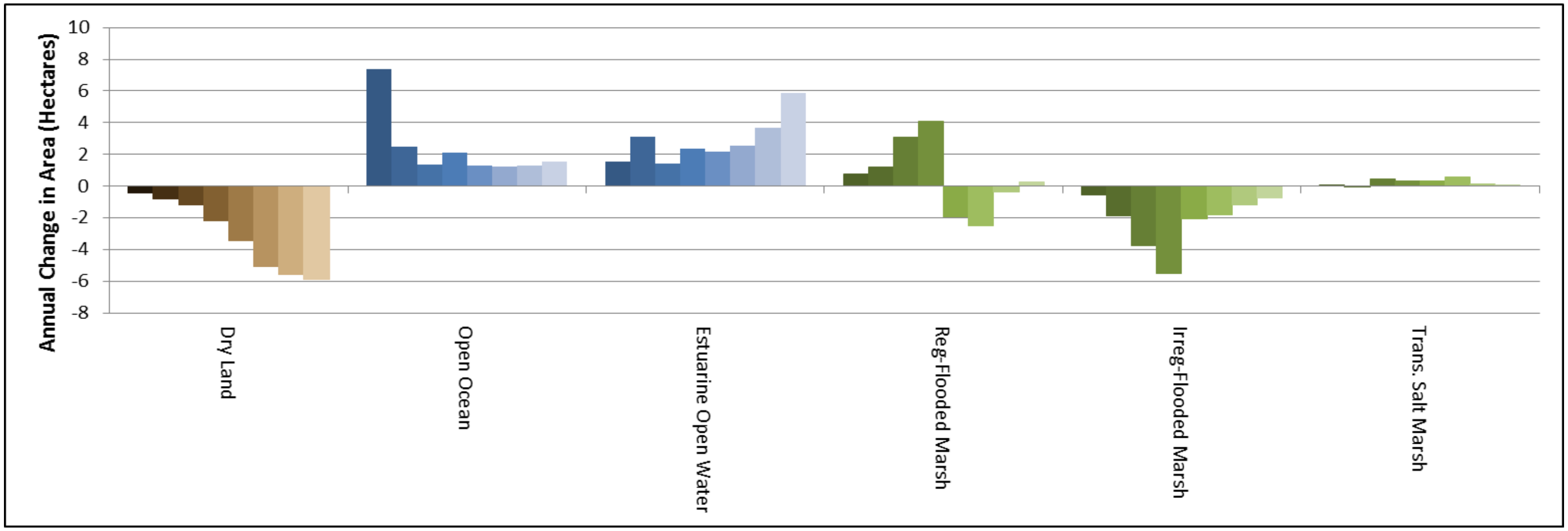

Figure C-17. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Buzzards Bay East (09) panel.

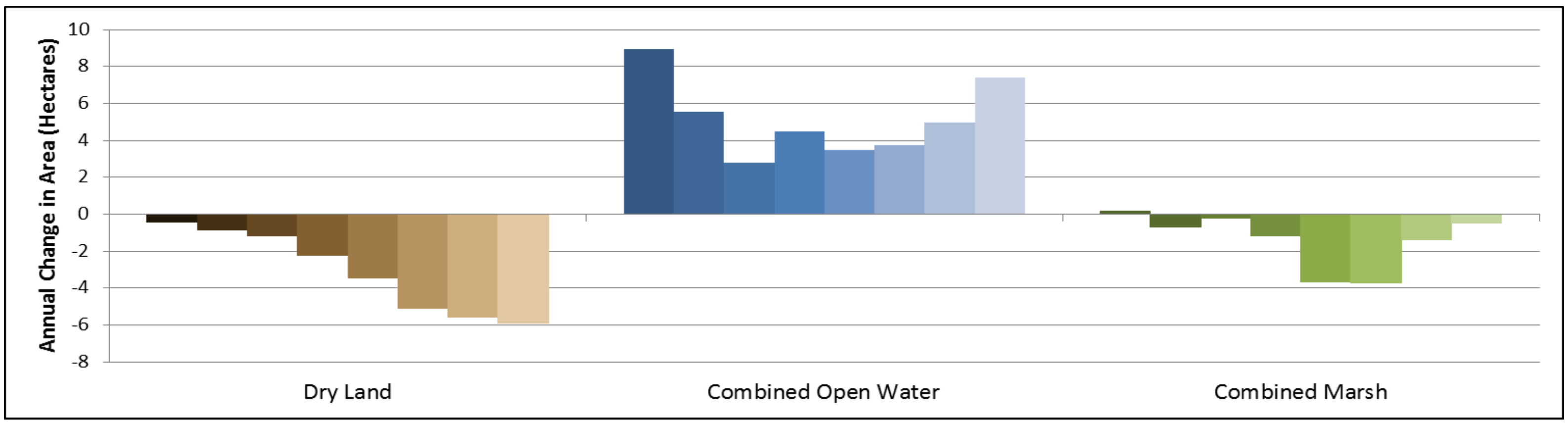

Figure C-18. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Buzzards Bay East (09) panel.

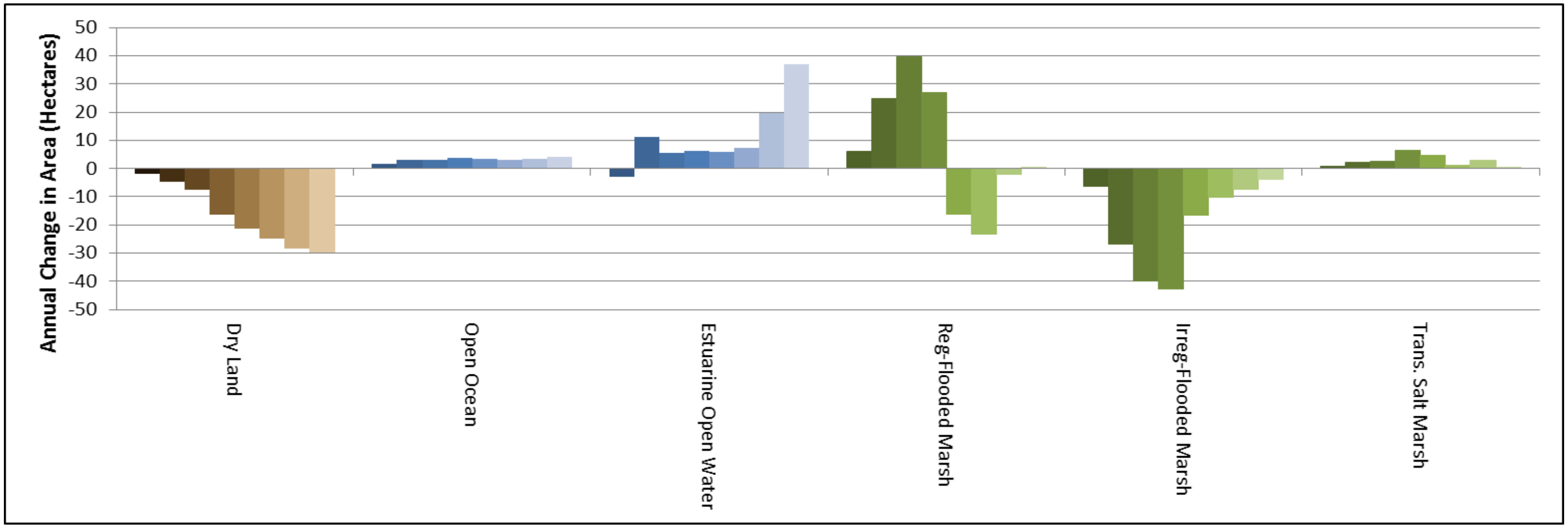

Figure C-19. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Buzzards Bay West (10) panel.

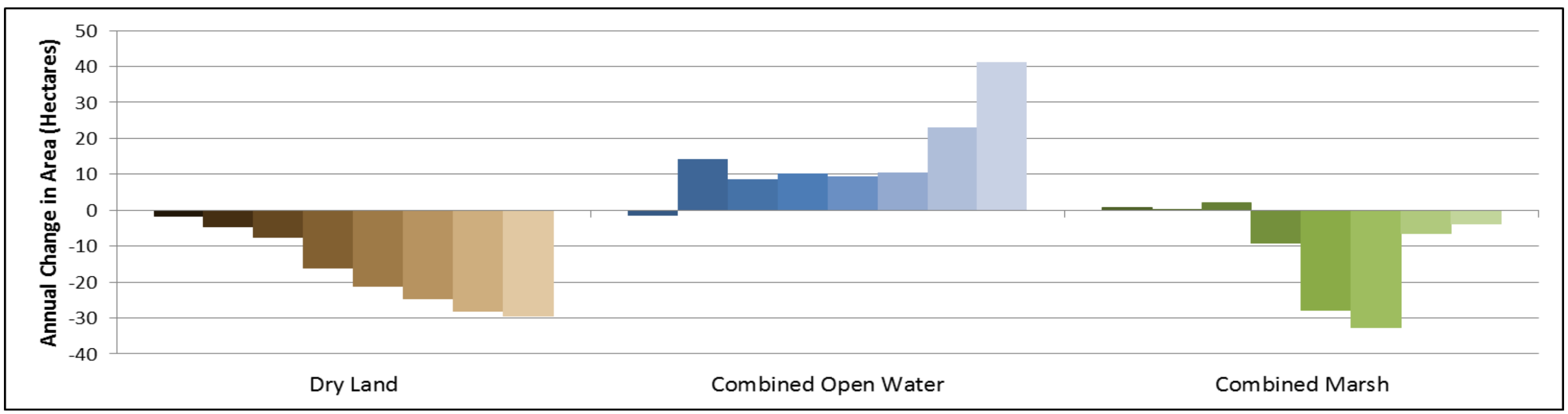

Figure C-20. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Buzzards Bay West (10) panel.

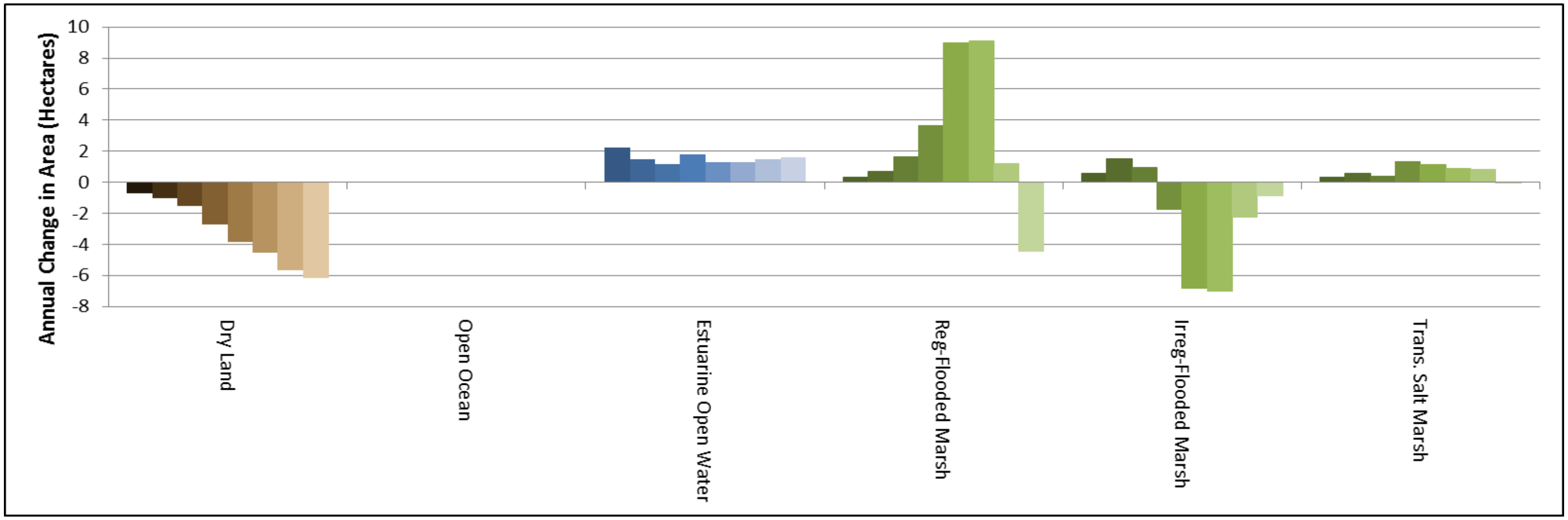

Figure C-21. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Taunton River (11) panel.

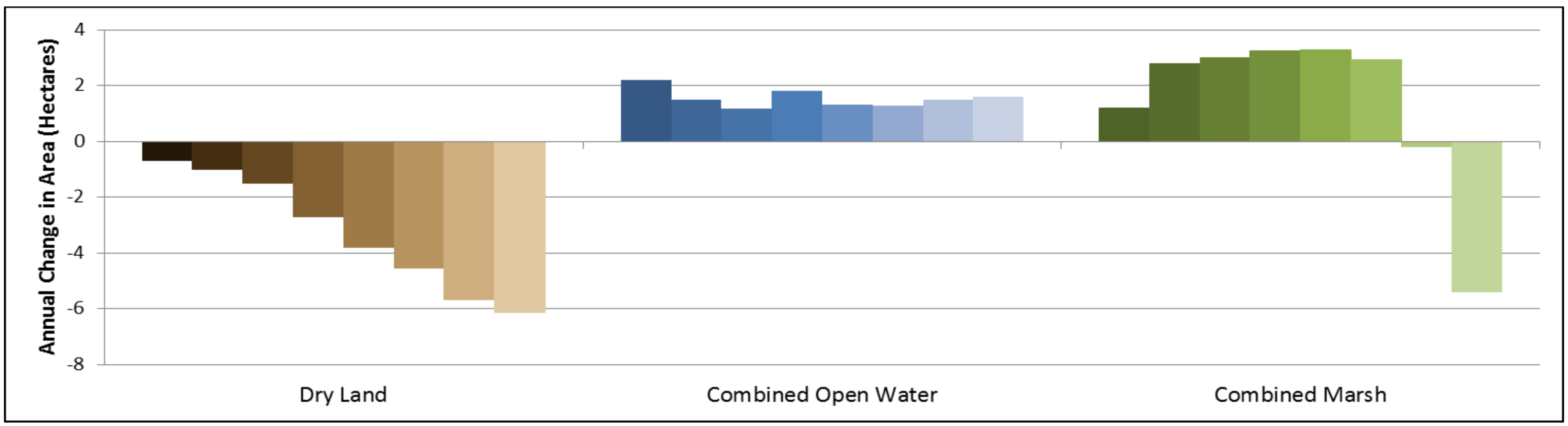

Figure C-22. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Taunton River (11) panel.

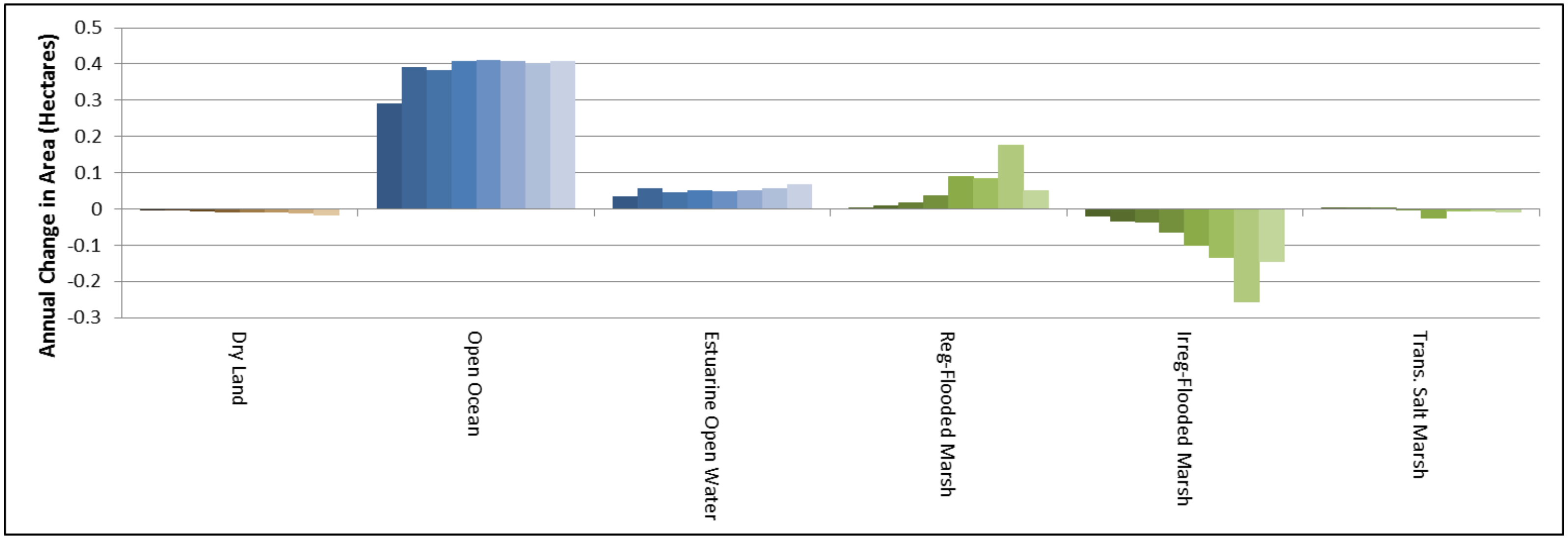

Figure C-23. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Elizabeth Islands (12) panel.

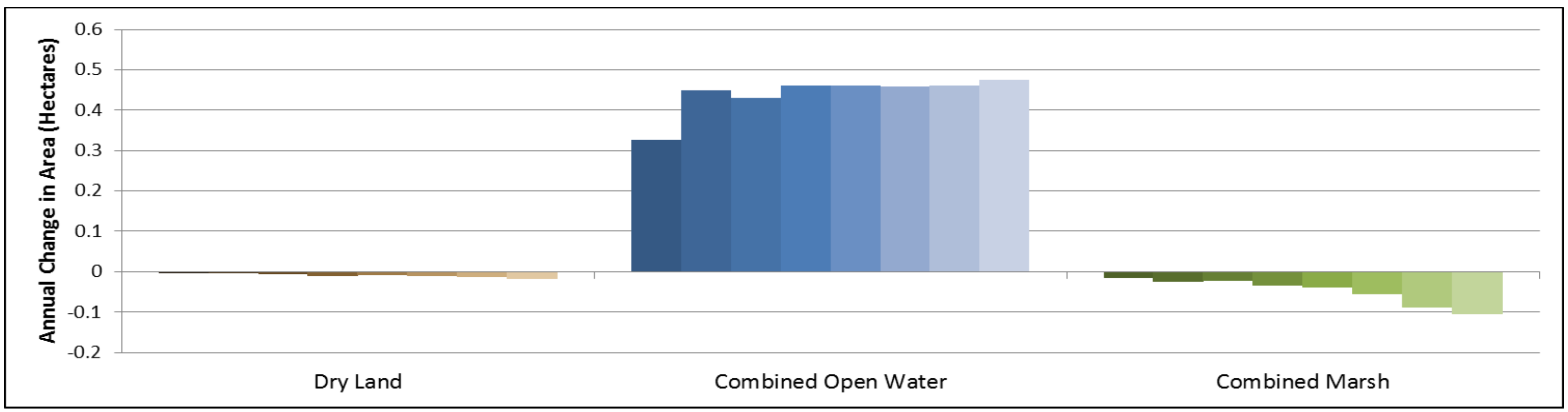

Figure C-24. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Elizabeth Islands (12) panel.

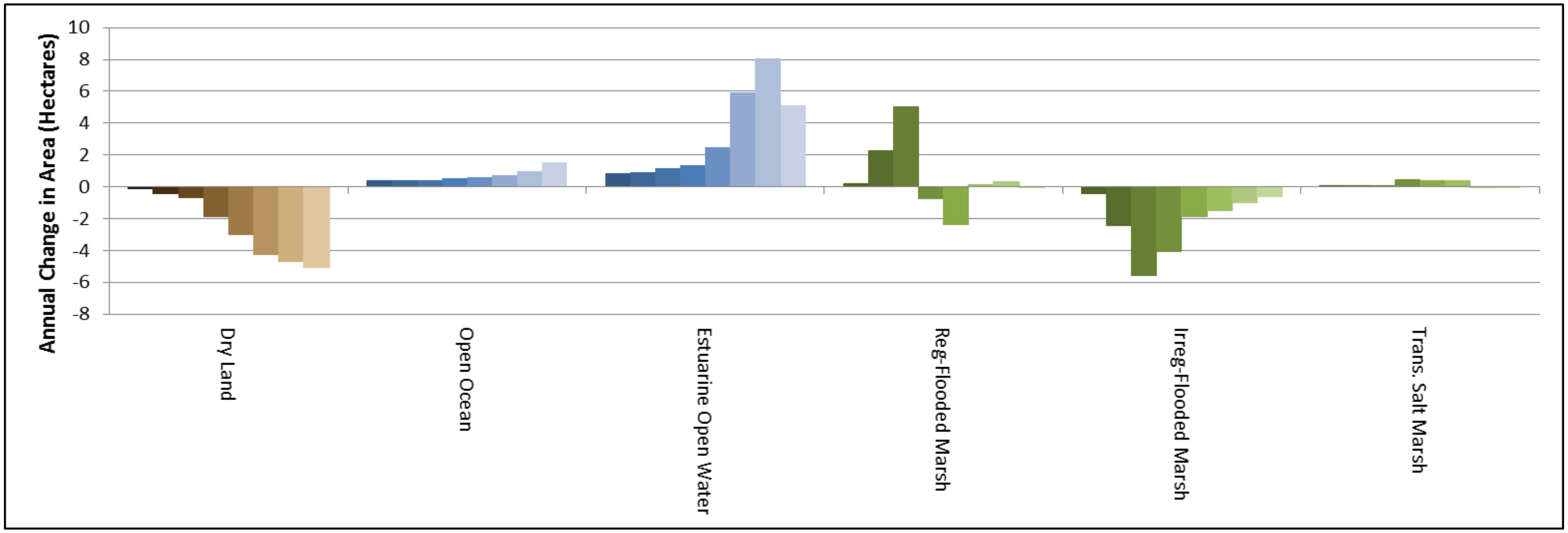

Figure C-25. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Martha's Vineyard Northeast (13) panel.

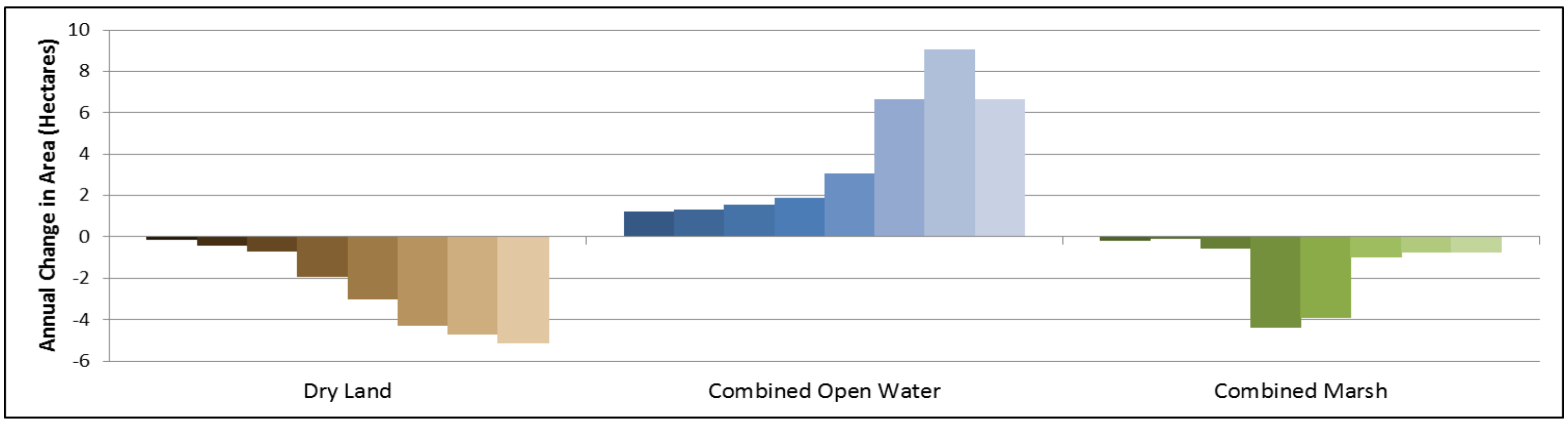

Figure C-26. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Martha's Vineyard Northeast (13) panel.

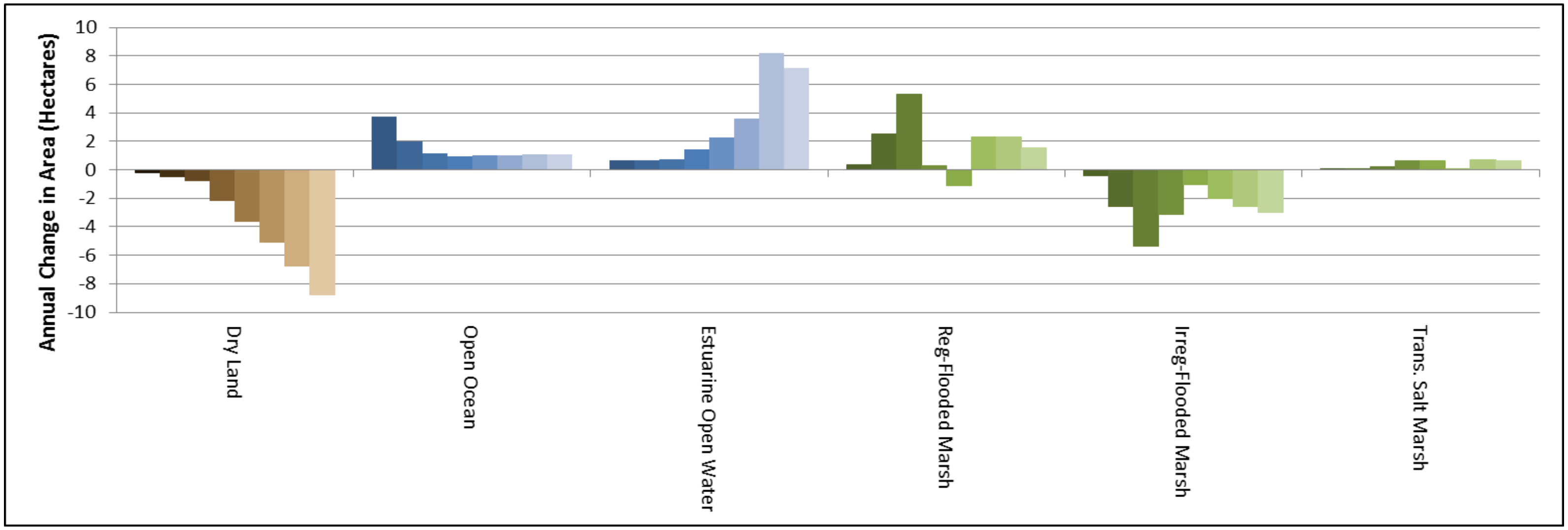

Figure C-27. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Martha's Vineyard South (14) panel.

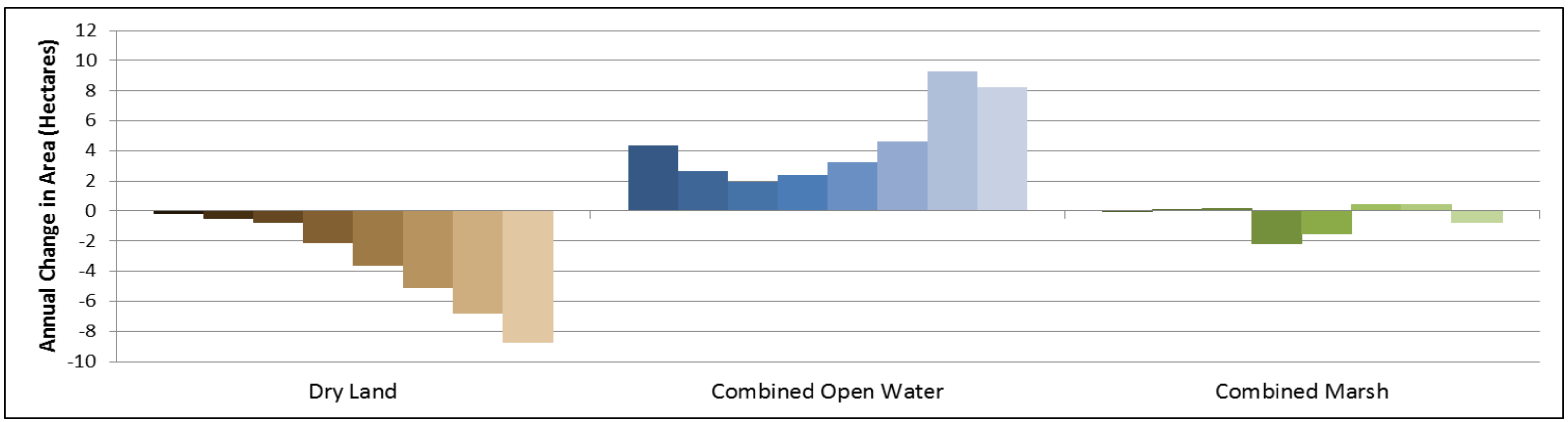

Figure C-28. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Martha's Vineyard South (14) panel.

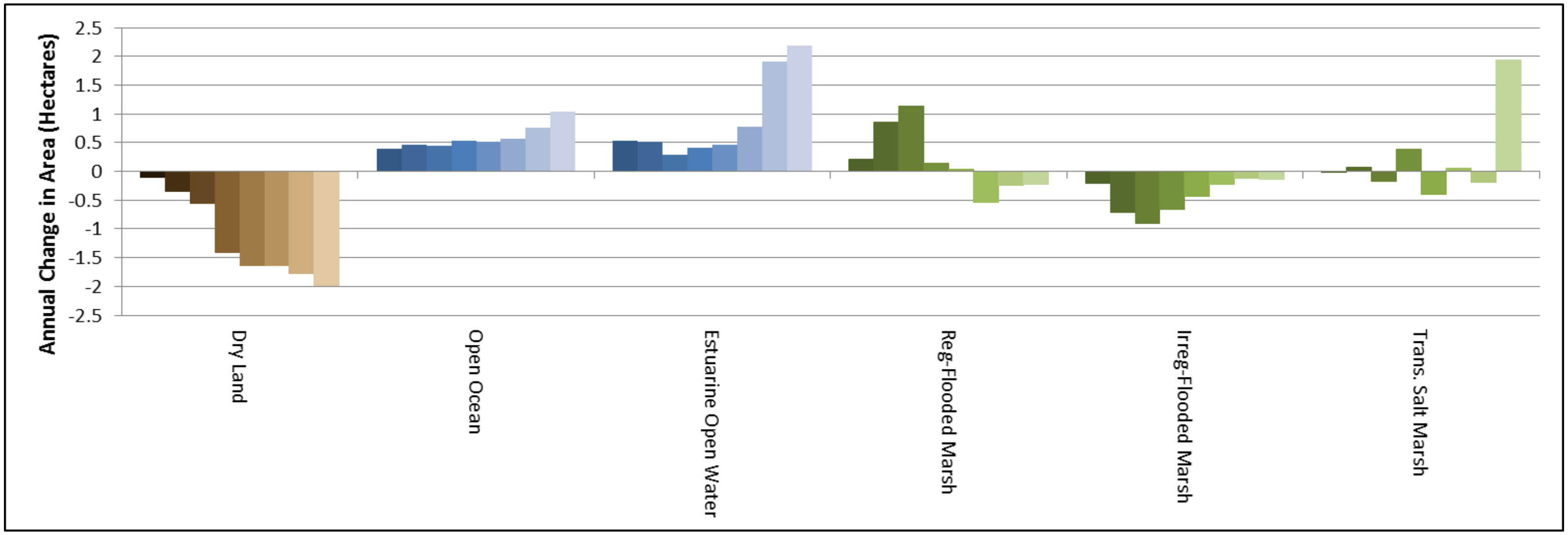

Figure C-29. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Martha's Vineyard Northwest (15) panel.

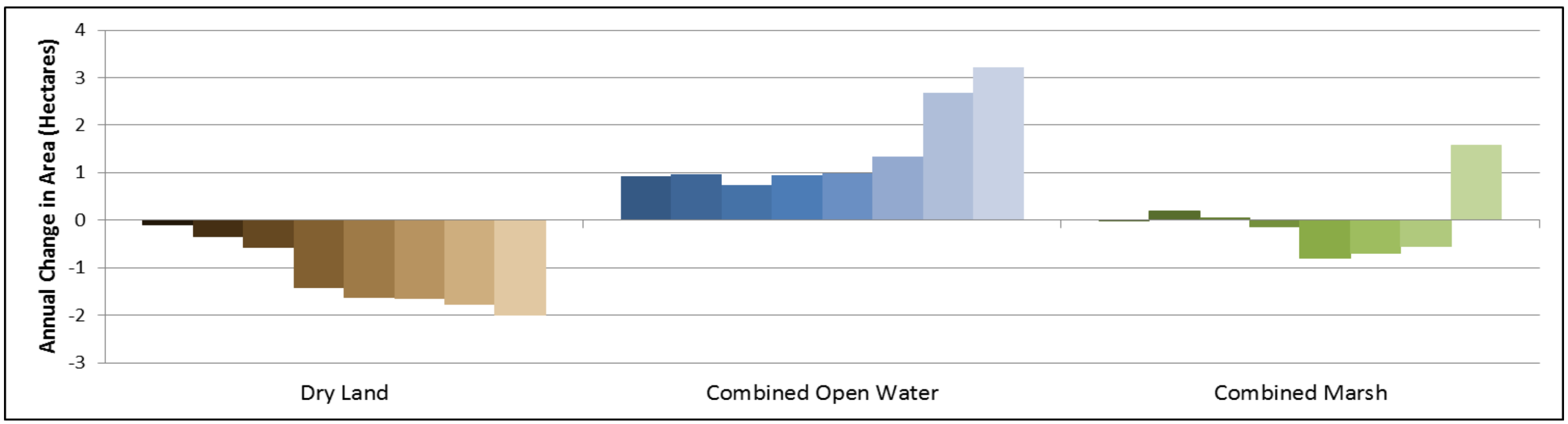

Figure C-30. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Martha's Vineyard Northwest (15) panel.

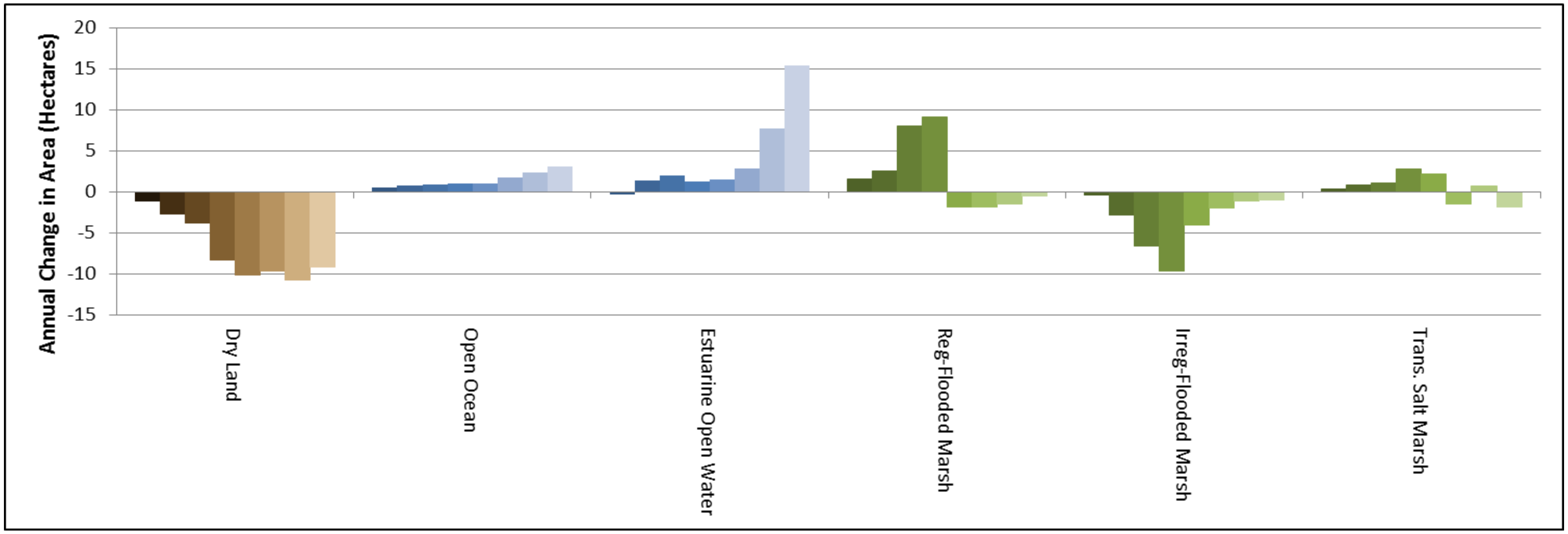

Figure C-31. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Nantucket North (16) panel.

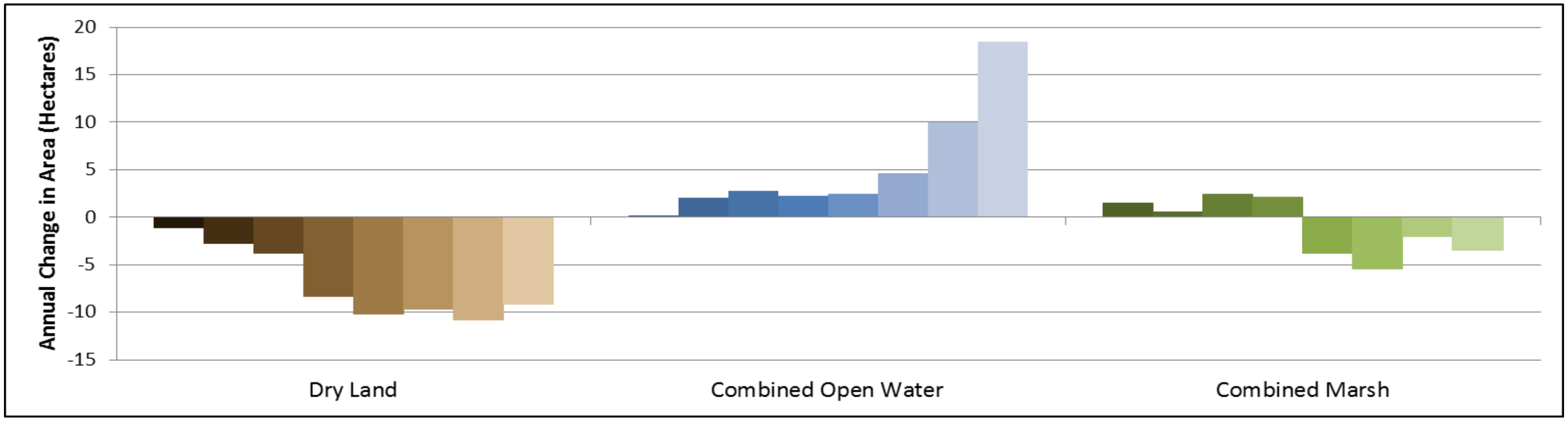

Figure C-32. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Nantucket North (16) panel.

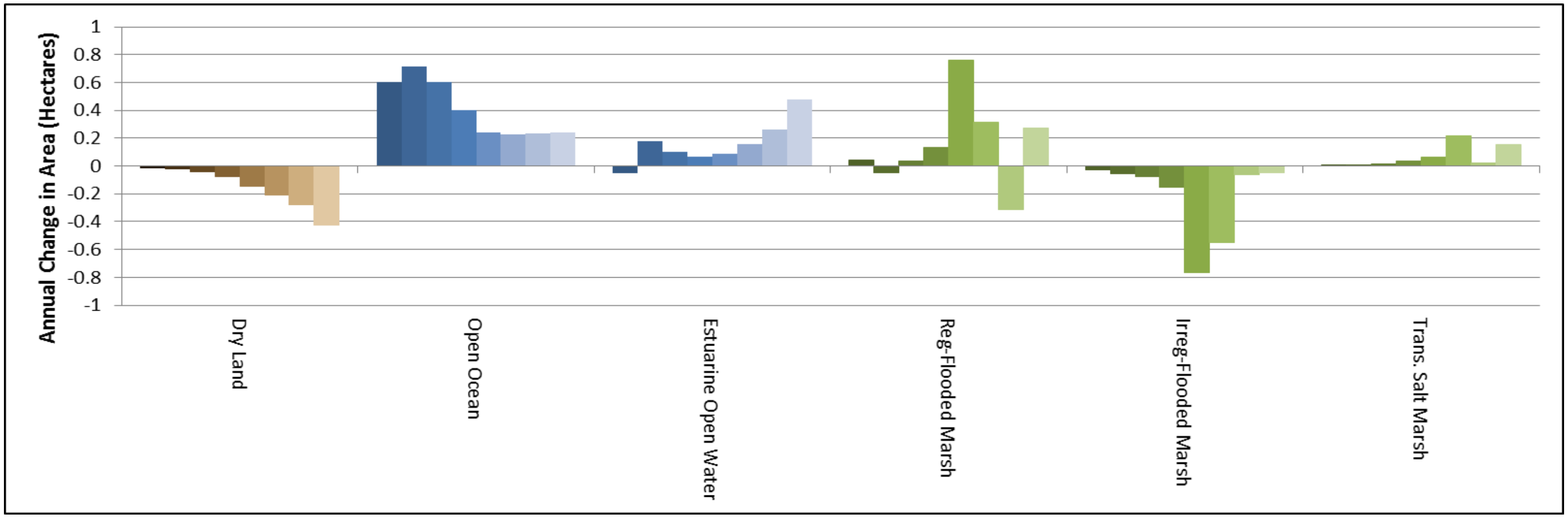

Figure C-33. Annual changes in wetland areas over evaluation periods as shown in Table 3-2 for the Nantucket South (17) panel.

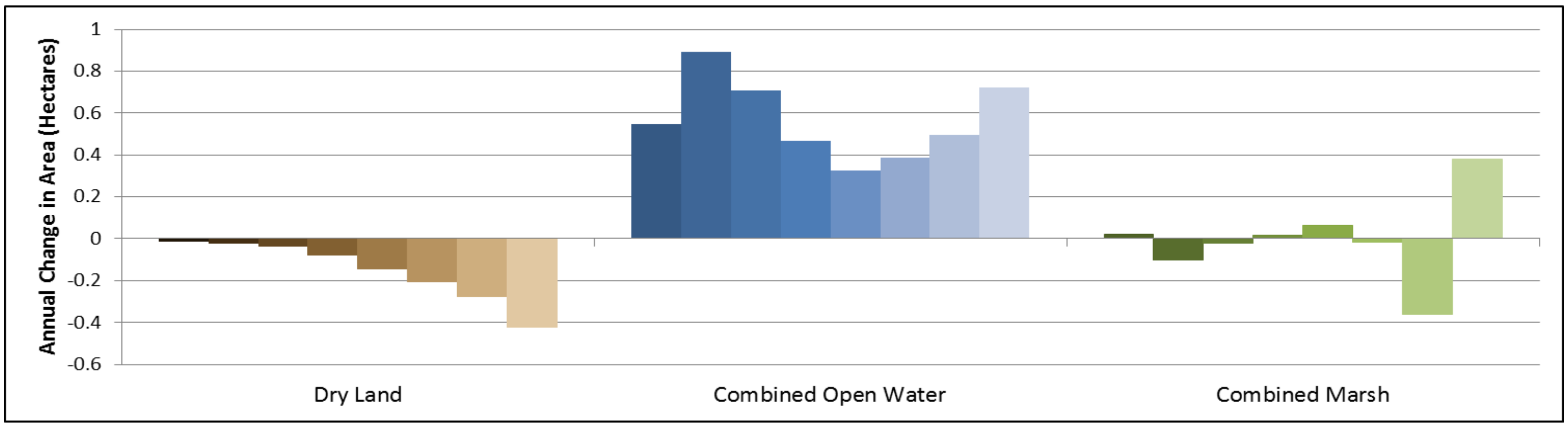

Figure C-34. Annual changes in combined wetland areas over evaluation periods as shown in Table 3-2 for the Nantucket South (17) panel.