Estimating the Monetary and Nonmonetary Benefits of Salt Marsh in the SNEP Region

Final Report

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EXECUTIVE SUMMARY

Salt marshes are biologically productive ecosystems that offer a variety of valuable resources and ecosystem services to coastal communities including flood mitigation, opportunities for ecotourism, carbon sequestration, and more. Salt marsh habitats, and the benefits they provide, are threatened by sea level rise, human development, pollution, and other environmental pressures. In this study, we build on the existing body of research on the economic value of salt marshes by quantifying the future value of flood prevention ecosystem services provided by three salt marshes located in Rhode Island and Massachusetts and discuss other ecosystem services provided by the marshes qualitatively.

In support of the Environmental Protection Agency (EPA), the Great Lakes Environmental Center's (GLEC) subcontractor, Eastern Research Group, Inc. (ERG), used the Sea Level Affecting Marshes Model (SLAMM) to examine how three salt marshes in Southeast New England protect surrounding communities from projected sea level rise and storm surge. To do this, the project team ran SLAMM with two initial marsh condition scenarios: (1) starting with current marsh habitat and (2) starting with no marsh habitat, where any current habitat was converted to open water. The team evaluated the outcomes of these scenarios in 2040 and 2070 given one and two meters of global sea level rise (GSLR) by 2100. The project's three study areas in the EPA Southeast New England Program (SNEP) region encompassed Waquoit Bay on Cape Cod, northern Buzzards Bay in Massachusetts, and Hundred Acre Cove in Rhode Island.

The model output consisted of inundation due to storm surge and sea level rise (SLR) while considering local elevation and geomorphology (the modeling does not, however, consider inundation due to rainfall from storms or wave attenuation based on habitat surface roughness). To evaluate the financial value of the studied marshes, ERG developed estimates for:

- The **total value of property** at risk of inundation when marshes are present compared to when marshes are not present.
- The **property damage costs** from inundation comparing when marshes are present and when they are not present.
- The **cost of projected SLR** (given the two sea level rise scenarios we used) to the areas included in our analysis.
- The **value of traffic delays** from road inundation comparing scenarios when marshes are present to when they are not present.

ERG monetized avoided property damages by applying the U.S. Army Corps of Engineers estimated depth damage function to data characterizing the value of affected parcels. To estimate the number of people affected by inundation, we used 2020 Census block population estimates from the U.S. Census Bureau. Finally, to monetize the value of traffic delays due to road inundation, ERG applied existing estimates of the cost of traffic delays due to road inundation in our affected counties to our geomorphic model outputs (Fant et al., 2021). We did not monetize construction costs related to physical damages to roads, elevating roads, or road relocation due to a lack of reliable data available in the existing pool of literature.

Where applicable, ERG presents total costs incurred between present day and 2040 and between present day and 2070 for these scenarios. ERG also presents the value of avoided costs due to marsh presence in 2040 and 2070 where appropriate. All dollar values in the report reflect 2024 dollars. Additionally, ERG provides qualitative discussions of other road-related impacts from inundation and other ecosystem services from marshes.

Key Findings

- **The presence of marsh habitat mainly reduces the severity of inundation within a property from storms rather than preventing additional properties from being inundated.** In short, similar numbers of properties are inundated during 10-year and 100-year storms in both "marsh present" and "no marsh" scenarios. However, marshes reduce the extent of property inundation by either reducing the frequency at which they experienced inundation or by reducing the area of the property that was inundated.

- **Salt marshes reduce the total value of properties at risk from inundation.** We estimate that the absence of salt marshes led to a substantial increase in the value of property facing inundation. In 2040, the absence of marshes led to an additional $216 million of property inundated from SLR in Waquoit Bay, $173 million in Buzzards Bay, and $14 million in Hundred Acre Cove. By 2070, those values are estimated to be $196 million at Waquoit Bay, $170 million at Buzzards Bay, and $14 million at Hundred Acre Cove. The value of avoided property value inundated is smaller in 2070 than 2040 because the value inundated in the "marsh present" scenario increases disproportionately to the value inundated in the "no marsh" scenario between 2040 and 2070.

- **Salt marshes reduce property damage during storms.** In 2040, salt marshes are estimated to reduce property damage costs from sea level rise and a 100-year storm in Waquoit Bay by about $207 million to $214 million, in Buzzards Bay by $165 million to $171 million, and in Hundred Acre Cove by $13.2 to $13.7 million, assuming 1 meter of sea level rise. By 2070, we estimate salt marsh habitat reduces the total costs from sea level rise and a hypothetical 100-year storm by $188 million to $194 million in Waquoit Bay, $162 million to $169 million in Buzzards Bay, and $13.2 and $13.7 million in Hundred Acre Cove.

- **Avoided Property Inundation.** In 2070 with 1 meter of GSLR by 2100, we estimate marsh habitat protects about 109 homes from inundation from sea level rise in Waquoit Bay, 380 homes in Buzzards Bay, and 46 homes in Hundred Acre Cove. Further, marshes affect the degree to which properties are inundated. We estimated that marshes would reduce property inundation by 7.7 percent on average in Waquoit Bay, 13.2 percent in Buzzards Bay, and 12.6 percent in Hundred Acre Cove.

- **Sea level rise will be destructive in the studied areas with no intervention, even with marsh habitat.** Even with salt marsh habitat present, we found that the cost of one meter of global sea level rise by 2100 would result in the loss of $125 million in property value in Waquoit Bay by 2040, $31 million in property value in Buzzards Bay by 2040, and $2 million in property value in Hundred Acre Cove in 2040.

- **Salt marsh habitat reduces flood inundation to roadways, decreasing costs associated with traffic delays.** The value of reduced roadway-related delays from the presence of salt marsh habitat in Waquoit Bay is estimated to be $66,000 in 2040 and $532,000 in 2070. The values for Buzzards Bay were $60,000 in 2040 and $215,000 in 2070. Interestingly, there were no estimated benefits from reduced delays for Hundred Acre Cove. This happened because the one and two meters GSLR scenarios already inundate all the roads that can be flooded at Hundred

Acre Cove due to elevations of the existing roads in the area. Thus, removing marshes from the modeling process resulted in no new inundated roads for Hundred Acre Cove.

- **Other benefits**. Salt marshes provide a variety of benefits, many of which are not monetized in this report but are discusses qualitatively, including:
    - Protection of public health from inundation events
    - Protection of critical infrastructure, municipal services, and economic activities from disruption due to inundation
    - Support of coastal economies, particularly within the fishing sector
    - Carbon capture
    - Improved water quality
    - Positive impacts on surrounding coastal ecosystems
    - Cultural, religious, and aesthetic values

1 OVERVIEW

A primary objective for the EPA Southeast New England Program (SNEP) is to foster collaboration among regional partners across southeast New England's coastal watersheds to ensure thriving watersheds and natural lands, safe and healthy water, and sustainable communities by promoting innovative approaches, and leveraging economic and environmental investments to meet the needs of current and future generations. SNEP partners with government and non-government organizations to collaborate on projects and issues in the Massachusetts and Rhode Island coastal area, including Cape Cod, The Islands, Buzzards Bay, and Narragansett Bay.

Salt marshes are highly productive ecosystems that offer a variety of valuable resources and ecosystem services to coastal communities including flood mitigation, opportunities for ecotourism, carbon sequestration, and more. Salt marsh habitats, and the benefits they provide, are threatened by sea level rise.

In this study, the Great Lakes Environmental Center (GLEC) and its subcontractor, Eastern Research Group, Inc. (ERG) partnered with SNEP to build on the existing body of research on the economic value of salt marshes by quantifying the future value of inundation prevention provided by three salt marshes located in Rhode Island and Massachusetts and discussing other ecosystem services provided by the marshes qualitatively. The three marshes are Waquoit Bay on Cape Cod, Buzzards Bay in southeastern Massachusetts, and Hundred Acre Cove outside of Providence, Rhode Island. To estimate the inundation protection value of marshes, ERG, used the Sea Level Affecting Marshes Model (SLAMM) to model how the presence of marsh habitat in these three areas would protect people, properties, and roads under future sea level rise. To do this, the project team evaluated how one and two meters of global sea level rise by 2100 (projected to local area tidal gauges) would affect areas around the marsh study areas in 2040 and 2070 under a scenario with marsh habitat present and a scenario where any existing marsh habitat was converted to open water. In this way, the project team could model how the current marsh might migrate and respond to sea level rise and how inundation could change if that marsh habitat was not there.

Section 2 begins with a summary of the literature we reviewed for this work which helped inform our approach and methods. Section 2 then turns to the geomorphic modeling methods and the monetary and nonmonetary valuation methods we employ to derive the results. Section 3 provides the valuation results based on the detailed geomorphic modeling. The monetary valuation results provide the outcomes related to the value of property at risk, the value of avoided damages associated with marsh presence, and the value of reduced roadway-related delays. Section 4 then provides an overview of other nonmonetized ecosystem services provided by marshes in qualitative terms. Section 5 then discusses the limitations of the report. Section 6 summarizes our findings and Section 7 provides references used in this report.

2 METHODOLOGICAL APPROACH

To understand the impacts of salt marshes on ecosystems and communities, we first conducted a review of existing literature on the benefits of salt marshes. Using the literature review to inform our methods, we used a geomorphic model to examine the impact of salt marsh presence on predicted inundation in communities surrounding three salt marshes in Southeast New England in 2040 and 2070 given various scenarios of sea level rise. We monetized the benefits of salt marsh presence by estimating the avoided damages from inundation to residences and roads when salt marsh is present. Avoided property damages were calculated by applying the U.S. Army Corps of Engineers depth damage functions to affected residential properties and land parcels. We estimated avoided damage to roads by applying existing estimates of travel delay costs due to road inundation from the literature to affected roads. In addition to the benefits monetized in our study, we describe nonmonetized benefits qualitatively. The approaches for each of these aspects are described in greater detail below.

2.1 Literature Review

ERG conducted a literature review of available research related to the economic (or other) values of salt marshes. ERG reviewed studies published in the last twenty years that were relevant to salt marshes and wetlands, focusing on studies in the northeast. ERG primarily searched Google Scholar and Academia.edu to find studies, using terms such as “salt march valuation in the northeast” and “economic valuation of salt marshes in the United States.” In total, ERG identified 24 studies with insights and methodologies that we expect to inform our own research as we developed methodologies and assumptions related to salt marsh valuation. Salt marshes provide value through increased opportunities for ecotourism, carbon sequestration, storm and flood mitigation, and more market and non-market benefits. Salt marsh habitats are threatened by human development, sea level rise, temperature increase, and other environmental changes. When salt marshes decrease in area, the benefits that coastal communities derive from them may also decrease in value, and carbon may be released into the atmosphere. Many of the studies identified describe threats to salt marsh area and ecological resilience and attempt to evaluate the impact of smaller or lower quality salt marsh areas on the value salt marshes provide. Often this is expressed quantitatively as losses in ecosystem services or increased costs incurred as property damages from storms.

Studies reviewed frequently modeled the impact of storms and sea level rise on salt marshes. The most common tools to do this were ADCIRC (ADvanced CIRCulation model), SWAN (Simulating WAves Nearshore), and SLAMM (Sea Level Affecting Marshes Model). Often these tools, particularly ADCIRC and SWAN, are coupled together to model storms. ADCIRC is used to simulate storm surges and coastal flooding during extreme weather events, SWAN models waves near the shoreline, and SLAMM evaluates the impacts of sea level rise specifically on wetlands and marshes.

Appendix A provides summaries of the studies from our literature review that informed our methodology. Additional studies that were identified and not used in our work are listed in the references section (Section 7) of this report.

2.2 Identification of Candidate Salt Marshes for Evaluation

2.2.1 Selection Criteria

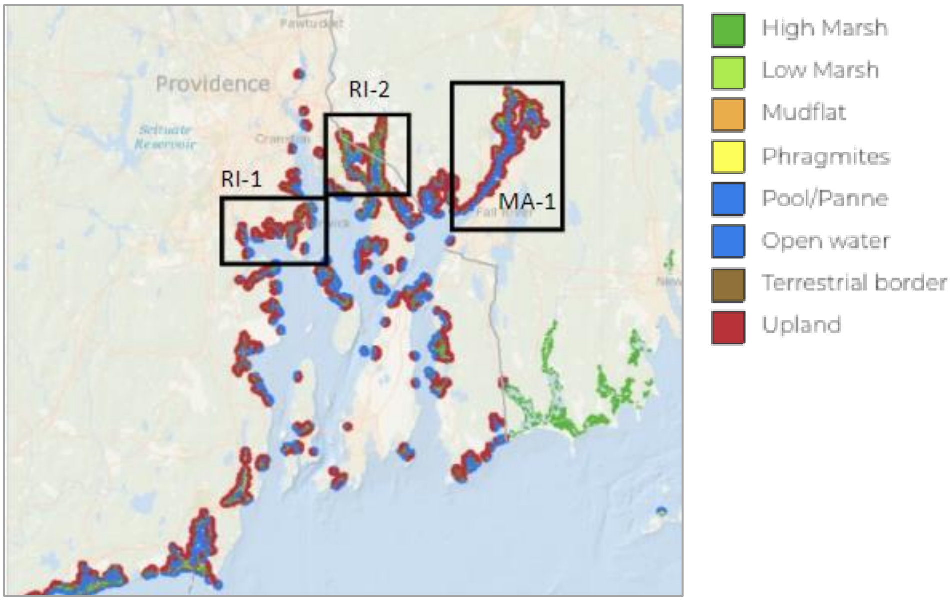
A starting point for developing our analysis was to select a set of marshes for modeling sea-level rise and inundation scenarios. EPA requested that GLEC and ERG select 2-3 marshes for inclusion. Based on discussions with EPA SNEP and GLEC, ERG applied the following criteria when determining whether salt marshes should be considered for inclusion in the study:

- **Location near populated areas**. Marshes that are near homes, businesses, or other infrastructure are preferred since the modeling will provide a sense of the risk posed from sea-level rise.
- **Size**. Larger marsh areas will be preferred; however, GLEC/ERG have not set a minimum size.
- **At risk**. Marshes that are currently under some form of stress or risk would be better candidates since more timely action would be needed; thus, this research can help inform that action.
- **State**. EPA and GLEC/ERG have agreed to select at least one marsh in MA and one in RI.
- **Recreational opportunities**. Marshes that are known for providing recreational opportunities would be preferred since recreational opportunities add economic value.
- **Nursery potential**. Marshes that are a substantial source of commercial or recreational fishing nursery habitat would also be preferred since nursery habitat adds economic value.
- **Cultural importance**. Marshes with some form of cultural (or spiritual) importance to the local area would be preferred since those aspects add value.
- **Local interest**. Marshes where local officials have a strong interest in this form of research would be preferred.

2.2.2 Candidate Marshes

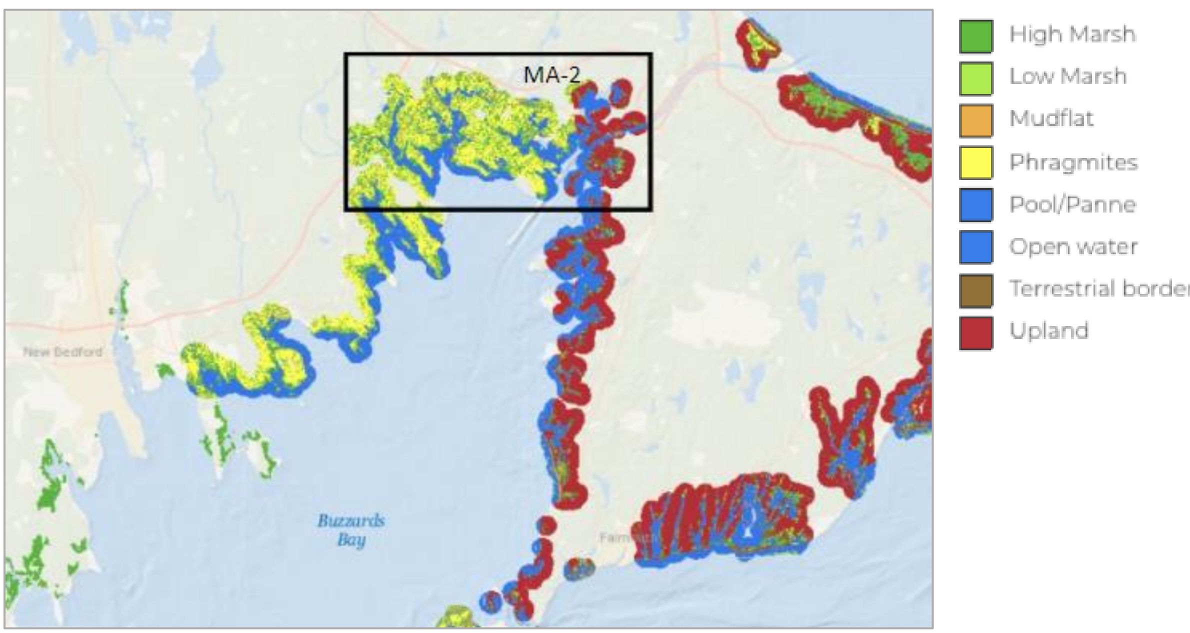
ERG identified seven candidate marshes for study using the Tidal Marsh Vegetation Classification layer from the Northeast Ocean Data Explorer. Two marshes were selected as candidates in Rhode Island in the Narragansett Bay area, as those marshes are near urban centers. ERG also identified five candidate marshes in Massachusetts: three on the southern coast of Cape Cod, one in Buzzards Bay, and one off the coast of Fall River. Marshes on Cape Cod were considered because of their economic and environmental importance to Cape Cod, as well as their significance to local tribal groups. The marsh in Fall River, MA was considered due to its proximity to an urban area (Fall River, MA) and underserved communities, and the marsh in Buzzards Bay was considered due to the significant marsh area encapsulating multiple marsh types with considerations for multiple coastal communities. Maps of the candidate marshes considered are presented in **Figure 1**, **Figure 2**, and **Figure 3**.

Figure 1: Marshes considered in Rhode Island and Fall River, MA



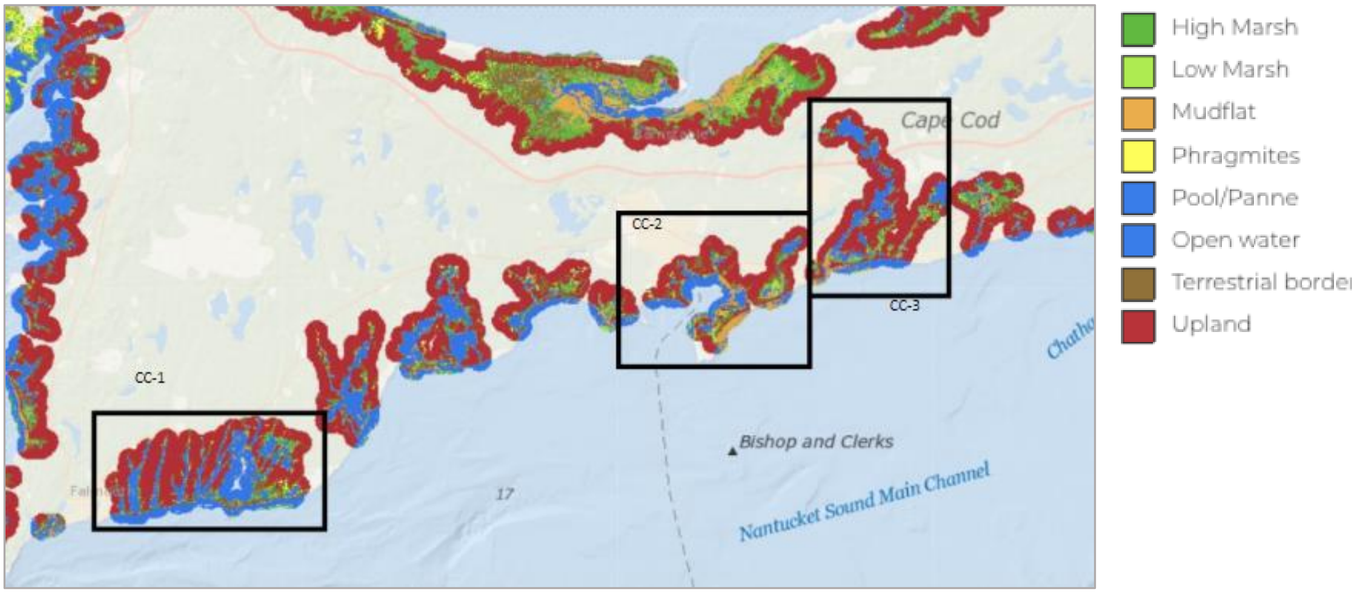
Source: Northeast Ocean Data Explorer

Figure 2: Marsh considered in Buzzards Bay, MA



Source: Northeast Ocean Data Explorer

Figure 3: Marshes considered on Cape Cod, MA



Source: Northeast Ocean Data Explorer

ERG solicited input on these candidate marshes from the EPA SNEP project team who, in turn, solicited input from EPA's Office of Research and Development (ORD) in Narragansett, RI and from the Northeast Regional Ocean Council (NROC).

2.2.3 Final Selection

Following ERG's discussions with the EPA project team and based on the input from EPA ORD and the Northeast Regional Ocean Council (NROC), two study areas containing salt marshes located in Massachusetts and one study area containing salt marsh in Rhode Island were selected for inclusion in the study. From the above maps, the areas labeled as "CC-1" (Waquoit Bay), "MA-2" (Buzzards Bay), and "RI-2" (Hundred Acre Cove) were selected as the marshes to use in the modeling. For each selected area, ERG calculated the area of tidally influenced wetland habitat from the National Wetland Inventory. ERG created a one-mile buffer around the salt marsh to analyze the estimated number of housing units in U.S. Census tract communities that touch the marsh buffer. ERG also estimated the number of people that could be affected by each marsh by summing the number of people in each U.S. Census Tract in the study area. **Table 1, Table 2,** and **Table 3** summarize attributes of the salt marsh sites selected.

Table 1: Waquoit Bay (CC-1) summary of marsh site attributes

Site Attribute	Summary	Source
Tidally Influenced Marsh Area	• 1,289 acres	Calculated using data from the U.S. Fish & Wildlife Service
Nearby residents and Housing Units	• Population of 25,698 • 23,960 housing units	Calculated using data from the U.S. Census Bureau
Tidal Range	• 2 feet	Waquoit Bay National Estuarine Research Reserve
Nursery Potential	• Waquoit Bay National Estuary Research Reserve (WBNERR) has participated in rare shorebird monitoring and conservation efforts since 1990. • WBNERR participates in a horseshoe crab spawning survey. • Home to a population of New England Cottontail rabbits • Manages two rare plant species: Sandplain Gerardia and New England Blazing Star. • Supports local populations of shellfish and finfish.	Waquoit Bay National Estuarine Research Reserve: Habitat, Animals, and Plants
Geomorphic Characteristics	• Contains open waters, salt and fresh marshes, barrier beaches, sand dunes, rivers, mixed pine and oak forests, and sandplain grasslands.	Waquoit Bay National Estuarine Research Reserve
Local Interest	• National Estuarine Research Reserve. • Important to commercial shellfish and finfish operations.	Waquoit Bay National Estuarine Research Reserve: Waquoit Bay
Cultural Importance	• Popular for recreational shellfishing. • Mashpee Wampanoag Nation has lived in the area for 12,000 years.	Mashpee Wampanoag Tribe

Table 2: Buzzards Bay (MA-2) summary of marsh site attributes

Site Attribute	Summary	Source
Tidally Influenced Marsh Area	5,009 acres	Calculated using data from the U.S. Fish & Wildlife Service
Nearby residents and Housing Units	• Population of 43,817 27,765 housing units	Calculated using data from the U.S. Census Bureau
Tidal Range	3.4 feet	NOAA Tides and Current: Buzzards Bay
Nursery Potential	• Habitat for small fish, sand eels, and alewives. Home to one half of North America's endangered roseate tern breeding pairs	Buzzards Bay National Estuary Program: Living Resources
Geomorphic Characteristics	• The west side of the study area is dominated by phragmites with mudflat and high marsh interspersed. The east side is primarily upland marsh.	Northeast Ocean Data Explorer
Local Interest	• Includes fisheries for lobster, shellfish, and finfish. Action has been taken in nearby communities to combat marsh loss.	Buzzards Bay National Estuary Program: Living Resources
Cultural Importance	Popular for recreational activities	Buzzards Bay Coalition: Things to Do

Table 3: Hundred Acre Cove (RI-2) summary of site attributes

Site Attribute	Summary	Source
Tidally Influenced Marsh Area	446 acres	Calculated using data from the U.S. Fish & Wildlife Service
Nearby residents and Housing Units	• Population of 48,641 16,976 housing units	Calculated using data from the U.S. Census Bureau
Tidal Range	3 - 4 feet	Save The Bay Facts and Figures
Nursery Potential	• Important spawning ground for the Diamondback Terrapin and certain species of bird. 42-acre bird sanctuary along the western shore.	Save the Bay: A Comprehensive Plan to Restore Water Quality in Hundred Acre Cove
Geomorphic Characteristics	Primarily high marsh with some areas of low marsh surrounded by upland terrain.	Northeast Ocean Data Explorer
Local Interest	"Save the Bay" initiative seeks to restore local water quality through interventions like reducing runoff, creating marsh migration corridors, and monitoring water quality.	Save the Bay: A Comprehensive Plan to Restore Water Quality in Hundred Acre Cove
Cultural Importance	• Popular for recreational water sports and fishing. Used to be a popular shellfishing spot but has been closed for shellfishing since 1990 due to bacterial pollution.	Save the Bay: A Comprehensive Plan to Restore Water Quality in Hundred Acre Cove

The Waquoit Bay study area depicted in **Figure 4** is a barrier system with open waters, sand dunes, and barrier beaches (Waquoit Bay National Estuarine Research Reserve, 2024b). The vegetation in the study area is dominated by upland species, with characteristic barrier systems and marsh-filled embayments, with small areas of mudflat and freshwater tidal and non-tidal wetlands. Towards the mouth of Waquoit Bay, where the largest section of contiguous tidal salt marsh is located, low and high marsh vegetation is present. The salt marsh's tidal range is estimated to be two feet (Waquoit Bay National Estuarine Research Reserve, 2024b). Waquoit Bay is designated by the National Oceanic and Atmospheric Administration's Office of Coastal Management as a National Estuarine Research Reserve (NERR). As such, it is a center for environmental stewardship, research, training, and education programs. Waquoit Bay is home to thirty-seven documented osprey nests and offers protection for piping plovers, least terns, and other species (Waquoit Bay National Estuarine Research Reserve, 2024a). To the human community, Waquoit Bay offers significant recreational and commercial fishing opportunities. The salt marsh holds significant cultural importance to the Mashpee Wampanoag Nation (Eiring, 2017). The Bay's name "Waquoit" is derived from a Wopanaotaok (Wampanoag language) word meaning "place of light" (Eiring, 2017).

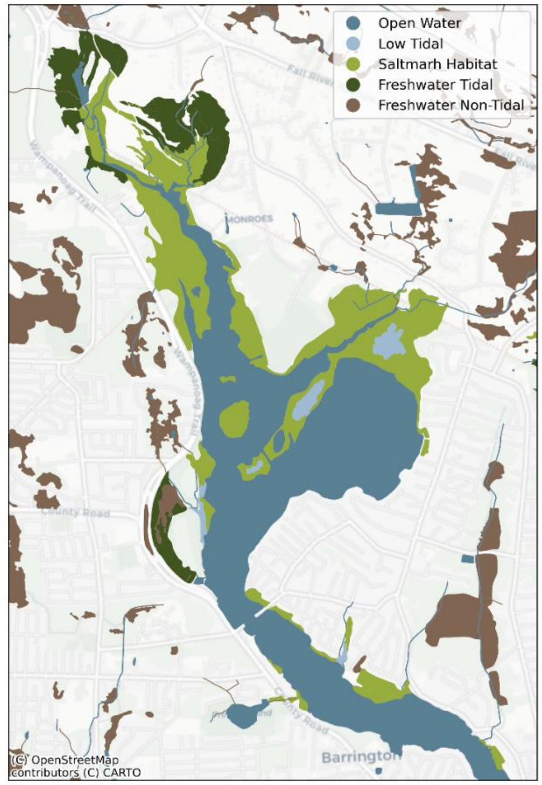
Figure 4: Habitat map for Waquoit Bay salt marsh area

The Buzzards Bay study area is shown in **Figure 5**. Upper Buzzards Bay contains fringing estuary with tidal streams, eelgrass beds, tidal flats, and barrier beaches (Buzzards Bay National Estuary Program, 2024). The study area is dominated by phragmites in its western portion, whereas the eastern portion is primarily upland marsh (National Oceanic and Atmospheric Administration, 2024a). Buzzards Bay is supported by the Buzzards Bay Coalition and Buzzards Bay National Estuary Program, which advances conservation and water quality improvement programs in the area. Buzzards Bay is also home to habitat for finfish (Buzzards Bay National Estuary Program, 2024).

Figure 5: Habitat map for Buzzards Bay salt marsh area

In Rhode Island, we selected the Hundred Acre Cove salt marsh, shown in **Figure 6** for inclusion in the study. The Hundred Acre Cove study area is primarily composed of high marsh with some areas of low marsh surrounded by upland terrain (Schwartz, 2016). The area around the salt marsh is densely populated. The waterways surrounding Hundred Acre Cove are highly polluted and include dangerous levels of fecal coliform bacteria and E. coli (East Bay Media Group, 2018; Northeast Ocean Data, 2024). Despite this, the area is home to a 42-acre bird sanctuary and also serves as an important spawning ground for the Diamondback Terrapin, the only estuarine turtle in North America (Rhode Island Blueways Alliance & Rhode Island Land Trust Council, 2024; Richardson, 2021). A local interest group, "Save The Bay" supports efforts to improve water quality in the salt marsh area and provides educational resources to residents and visitors (Save The Bay Center, 2018).

Figure 6: Habitat Map for Hundred Acre Cove Salt Marsh Area



2.3 Estimation and Modeling of Flood and Storm Surge Capacity / Attenuation

2.3.1 Modeling Software

ERG assessed candidate marsh modeling tools for use in this analysis by considering data and modeling needs, data availability, usefulness of model outputs for salt marsh valuation analyses, and time and resources required to perform the modeling using each tool. ERG decided to use the Sea Level Affecting Marshes Model (SLAMM) version 6.7 which simulates the potential changes to wetlands and shorelines from long-term sea-level rise (Warren Pinnacle Consulting, Inc., 2024). SLAMM was chosen because it incorporates major ecological processes and features, such as elevation, wetland classification, tide range, and sea level rise into one model and is less resource intensive than other models such as ADCIRC and SWAN. SLAMM also allows users to add storm surge depth as an input to the model, which was an important consideration to estimate the area inundated by future sea level rise and storm surge combined.

It is important to note that SLAMM is not a hydrodynamic model. It calculates inundation frequency due to sea level rise and storm surge mainly on the basis of elevation. The model considers wetland elevation, the availability of connective pathways at the water level examined, the 30, 60, and 90-day tidal ranges, and storm surge depth to calculate inundation frequency. SLAMM's technical documentation notes that they assume the process of sea level rise overwhelms any diffusion constraints from surface roughness or unsaturated soil. This reflects SLAMM's large time step configuration and the model's goal to estimate what will happen at equilibrium at certain sea level rise scenarios.

2.3.2 Scenarios

2.3.2.1 Sea level rise

For each salt marsh, ERG analyzed the effects from intermediate and high global sea level rise scenarios as defined by the U.S. Interagency Sea Level Rise Task Force in the Fifth National Climate Assessment (May et al., 2023). These scenarios correspond to one (intermediate) and two (high) meters of global sea level rise by 2100 relative to a 2000 baseline. ERG obtained sea level rise projections specific to Providence and Woods Hole (the tide gauges closest to the study areas) from projections developed by NOAA (Sweet et al., 2022). The sea level rise projections for 2040 and 2070 for these two tide gauges, as well as the global estimates, appear in **Table 4** and in **Figure 7** (one meter global sea level rise) and **Figure 8** (two meters global sea level rise).

Figure 7: One meter of global sea level rise by 2100 extrapolated to each study location

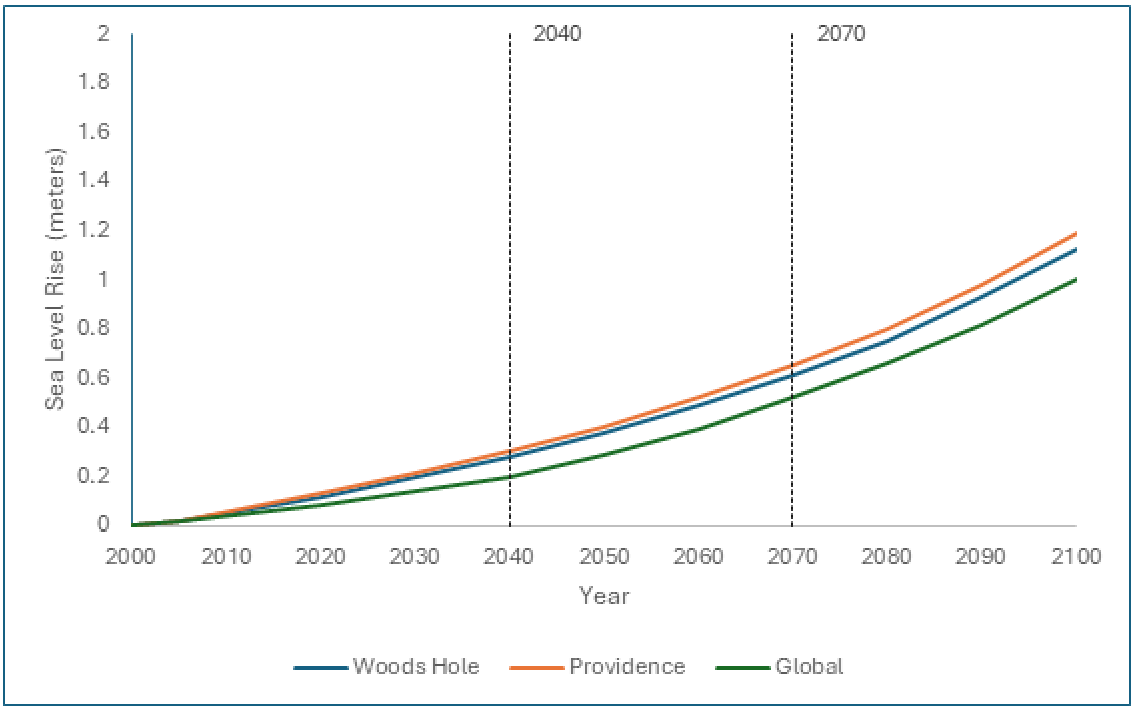


Figure 8: Two meters of global sea level rise by 2100 extrapolated to each study location

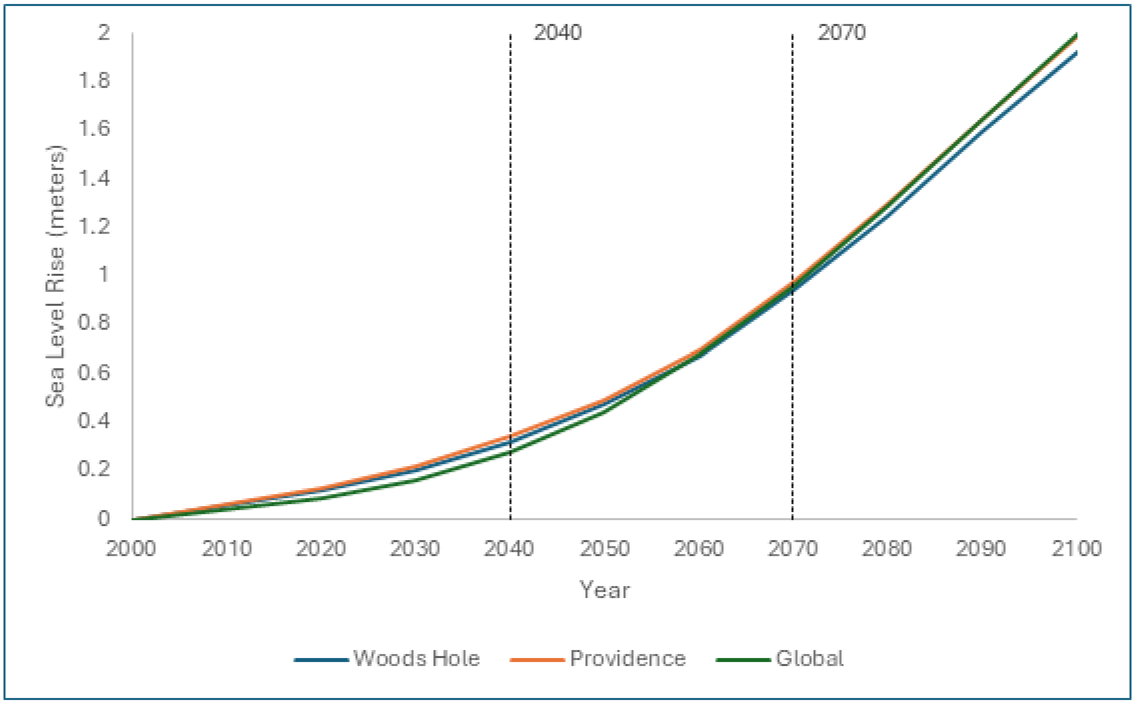


Table 4: Projected relative sea level rise at each tide-gauge station for one and two meters of global sea level rise by 2100

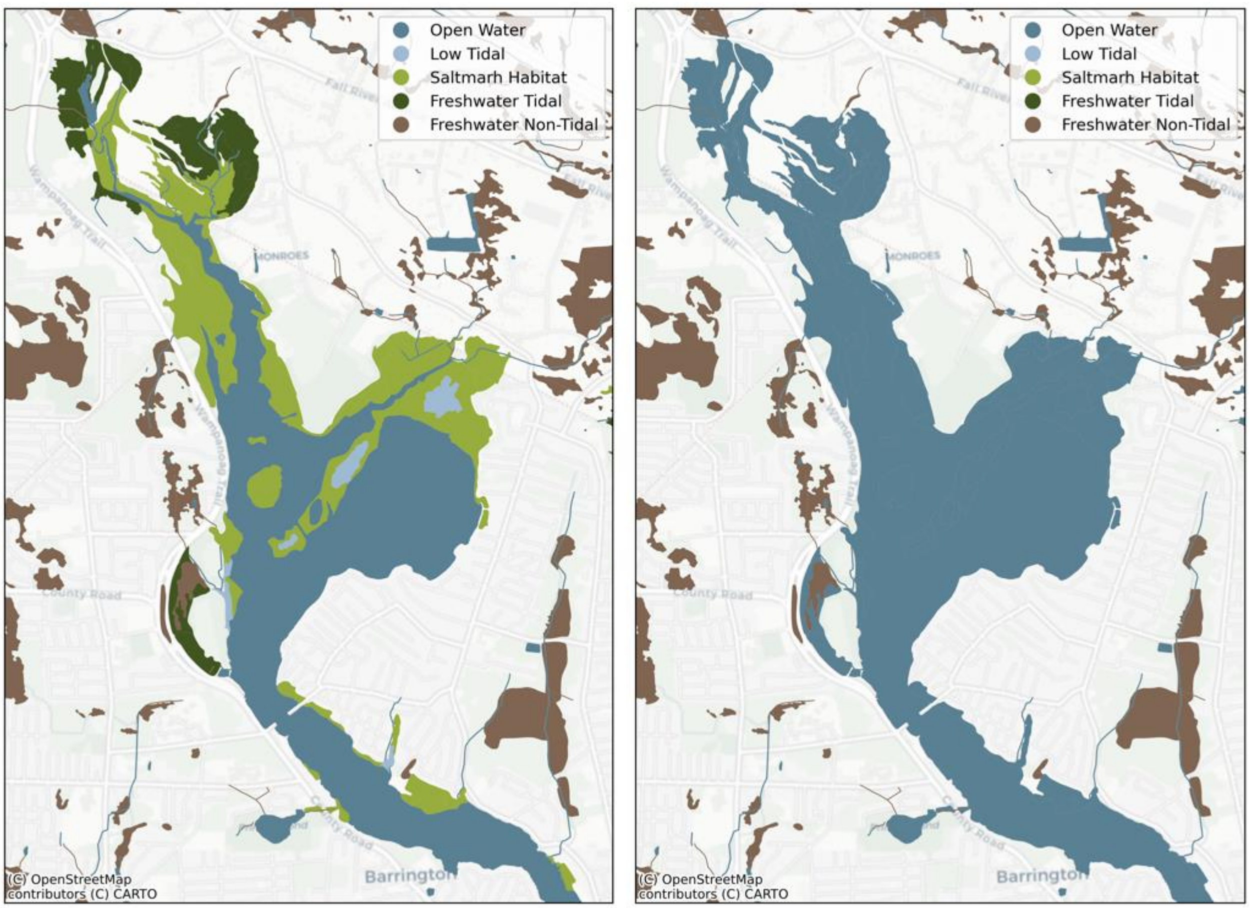
Global Sea Level Rise by 2100	Year	Woods Hole Sea Level Rise	Providence Sea Level Rise
Intermediate (1 meter)	2040	0.3 m (0.98 ft)	0.28 m (0.92 ft)
Intermediate (1 meter)	2070	0.65 m (2.13 ft)	0.61 m (2 ft)
High (2 meter)	2040	0.34 m (1.12 ft)	0.32 m (1.05 ft)
High (2 meter)	2070	0.98 m (3.22 ft)	0.94 m (3.08 ft)

2.3.2.2 Marsh presence

To understand the inundation attenuation ecosystem services of salt marshes in the SNEP region, ERG modeled the impacts of sea level rise and storm surge with and without salt marsh habitat at each of the salt marshes. To do this, the project team used the National Wetland Inventory data, described in Section 2.3.3.3 as the starting wetland habitat data input into SLAMM for each sea level rise scenario. Then, the project team ran the model again but with an initial habitat scenario where all tidally influenced marsh habitat was converted to open water. Prior studies have also estimated the value of salt marshes by developing scenarios with marsh habitat and with marsh habitat replaced by open water (Narayan et al., 2017; Rezaie et al., 2020). **Figure 9** shows a simplified version of the starting marsh habitat data input into SLAMM for each scenario for Hundred Acre Cove.

Because SLAMM is not a hydrodynamic model, the difference between the two marsh scenarios largely depends on the presence of habitat that can naturally accrete and build elevation in response to sea level rise compared to the absence of any habitat that can do this. To put it another way, the marsh presence scenario starts with saltmarsh habitat that is naturally accreting at the historic rate of sea level rise (a parameter input into the model) and creating a natural buffer to inundation. In contrast, the no marsh scenario shows what will happen if there is just open water in place of marsh habitat, which shows the areas that would be inundated if that habitat did not exist.

Figure 9 : Hundred Acre Cove marsh habitat initial condition scenarios for the SLAMM model: marsh present (left) and tidally influenced marsh habitat replaced with open water (right)



2.3.3 Model Inputs

SLAMM requires multiple geospatial inputs that characterize the local environmental and physical conditions for each marsh modeled. The geospatial data inputs ERG used for SLAMM modeling are listed in **Table 5**, and the following subsections provide a brief description of how ERG prepared each dataset for the SLAMM model.

Table 5. Description of geospatial SLAMM input data

Model Input	Marsh	Data Name	Data Source
Digital elevation model	MA-2 and CC-1	Bare earth Lidar DEM	MassGIS
Digital elevation model	RI-2	Topobathymetric Elevation Model of New England	U. S. Geological Survey
Wetlands Classification	All marshes	National Wetlands Inventory	U.S. Fish and Wildlife
Diked Area	All marshes	National Wetlands Inventory	U.S. Fish and Wildlife
Impervious Surfaces	RI-2	RI Impervious Surface	RIGIS
Impervious Surfaces	MA-2 and CC-1	MA Impervious Surface	Massachusetts Executive Office of Energy and Environmental Affairs (EEA)
Storm Surge	All marshes	The Sea Lake and Overland Surges from Hurricanes (SLOSH) model	NOAA

2.3.3.1 Digital Elevation Model

One of the most important inputs into the SLAMM model is elevation data as these data inform the frequency of inundation for wetlands and marshes when combined with tidal range data. To prepare the digital elevation models (DEM) for input into SLAMM, ERG cropped the DEMs to the extent of each marsh's area. To reduce processing time, ERG excluded from the DEM all areas above 60 feet in elevation, as these areas are well above the elevation that would be affected by coastal inundation, following the methods used by the Massachusetts Office of Coastal Zone Management (MA CZM) (Massachusetts Office of Coastal Zone Management, 2016). The final DEM units were in meters with a NAVD88 vertical datum, as required by SLAMM.

2.3.3.2 Slope

The angle of the land area (slope), for each salt marsh area is used by SLAMM to calculate the fraction of each cell that is transferred to another class (i.e., salt marsh type or area inundated). ERG calculated the slope in degrees from the processed DEM using the RichDEM Python library.

2.3.3.3 Wetlands Classification

SLAMM requires wetland classification data as an input into the model because it informs the type of marsh habitat that is present under initial conditions. ERG used data from the National Wetlands Inventory (NWI) and converted the NWI wetland types to the SLAMM wetland types using the SLAMM Cowardin NWI code lookup key provided in the SLAMM software download. ERG manually converted any NWI categories that could not be reclassified with this lookup key by using SLAMM Technical Documentation (Clough et al., 2016). To create a scenario where no marsh habitat was present, ERG reclassified all tidally influenced marsh habitat as open water. Following this conversion, ERG rasterized the wetland polygon to a grid with the same cell size, cell count, and boundaries as the DEM.

2.3.3.4 Diked Area

SLAMM allows for areas that are protected by dikes to be entered as an additional input into the model. This informs which areas may be protected from inundation and sea level rise. ERG identified diked areas using the NWI data. All NWI wetland areas with the “diked or impounded” attribute “h” were assumed to be protected from inundation. However, it is important to note that this method might not include dry land areas that are protected by dikes and seawalls, as the NWI data only has information pertaining to wetlands (Stamp et al., 2019). ERG then converted the polygon to a raster with the same cell size, cell count, and boundaries as the DEM.

2.3.3.5 Impervious Surfaces

The SLAMM model allow users to input an impervious surface layer into the model. This data helps inform which land areas are considered developed areas versus natural land. To prepare the raw impervious surface data for SLAMM, ERG resampled the impervious surfaces raster to the same cell size, cell count, and boundaries as the DEM. The team then multiplied each cell by 100 to convert it from a 0 to 1 scale to a 0 to 100 percent scale to match SLAMM requirements.

2.3.3.6 Storm Surge

As an optional input, SLAMM users can provide a storm surge depth raster layer. This layer is combined with sea level rise to inform the extent of inundation in the model. In this way users can examine the extent of inundation from combined sea level rise and storm surge. **It is important to note that the storm surge layer does not have a direct impact on changes to salt marshes in the SLAMM model.** The model developer, Jonathan Clough, informed ERG via email that this is because “the model theory is that unique storms generally do not impact the long-term equilibrium of wetland locations, and that equilibrium is based on regularly occurring tides.”

For the storm surge depth input, ERG used data from the Sea Lake and Overland Surges from Hurricanes (SLOSH) model. The SLOSH model estimates the height of storm surges from hurricanes by considering the atmospheric pressure, size, forward speed, and track data of different category hurricanes (U.S. Climate Resilience Toolkit, 2024). However, SLAMM requires storm surge depth rasters that are in terms of a 10- and 100-year storm probability rather than as hurricane categories. To convert storm surge hurricane categories to 10- and 100-year storm estimates for the New England area, ERG referred to NOAA hurricane return period maps (National Oceanic and Atmospheric Administration, 2024b). Using these maps, ERG used Category 1 SLOSH data for a 10-year storm surge and Category 2 SLOSH data for a 100-year storm surge. Finally, in modeling the impacts of storms, our modeling does not take into account the effects of precipitation or wave action from storms on overall inundation.

2.3.4 Model Parameters

In addition to the geospatial model input files described above, there are several fixed parameters that SLAMM requires, described in **Table 6**. **Table 7** lists the actual parameters that were input into SLAMM for each marsh.

For the parameters that relied on data from tide gauge stations, the tide gauge stations closest to the marsh for which data were available were used. For example, the Buzzards Bay station is closest to the MA-2 marsh. However, it only had data available to calculate the great diurnal tide range, so Buzzards Bay station was used for this parameter, but Woods Hole station was used for the remaining parameters for MA-2.

Table 6: Description of model parameters and data sources

Parameter	Description and Derivation Method	Data Source
Wetland Data Photo Date	Year that the wetland data layer being used was taken. This date represents the starting date for the simulation.	U.S. Fish and Wildlife
DEM Date	Year of the flight or survey for the elevation data.	RI: U. S. Geological Survey MA: MassGIS
Direction offshore	Direction of water from the shoreline.	Determined by looking at satellite images of the marshes.
Historic SLR Trend	The historic rate of sea level rise in mm/year. These data were collected from tide gauge stations closest to the marsh.	RI: Providence Station, NOAA MA: Woods Hole Station, NOAA
MTL-NAVD88	Elevation correction to be applied when using mean tide level (MTL) as the reference zero elevation. Correction = MTL- NAVD88	RI: Providence Station, NOAA MA: Woods Hole Station, NOAA
GT Great Diurnal Tide Range (m)	Equivalent to the difference between Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW). Obtained from tide gauge stations closest to the marsh.	RI: Conimicut Light Station, NOAA CC-1: Woods Hole Station, NOAA MA-2: Buzzards Bay Station, NOAA
Salt Elevation (m above MTL)	For the Massachusetts marshes, salt elevation was calculated as half of the Great Diurnal Tide Range, following the methods used by the MA CZM.[6] For the Rhode Island marsh, the 30-day inundation level was used, following methods used by the Rhode Island Coastal Resources Management Council.[11]	RI: Conimicut Light Station, NOAA CC-1: Woods Hole Station, NOAA MA-2: Buzzards Bay Station, NOAA
Marsh Accretion (mm/yr)	Equal to the rate of historic sea level rise, in keeping with the methods from the MA CZM.[6] This assumption is based on marshes historically generally keeping pace with sea level rise.	RI: Providence Station, NOAA MA: Woods Hole Station, NOAA
H1 inundation (m above MTL)	30-day inundation. Calculated by taking the 96.7 percentile of maximum daily water levels from 2019-01-01 to 2023-12-31 (the period water level data is available for) at the nearest tide gauge station to the marsh.	RI: Conimicut Light Station, NOAA MA: Woods Hole Station, NOAA

Parameter	Description and Derivation Method	Data Source
H2 inundation (m above MTL; H2>H1)	60-day inundation. Calculated by taking the 98.3 percentile of maximum daily water levels from 2019-01-01 to 2023-12-31 (the period water level data is available for) at the nearest tide gauge station to the marsh.	RI: Conimicut Light Station, NOAA MA: Woods Hole Station, NOAA
H3 inundation (m above MTL: H3>H2)	90-day inundation. Calculated by taking the 98.9 percentile of maximum daily water levels from 2019-01-01 to 2023-12-31 (the period water level data is available for) at the nearest tide gauge station to the marsh.	RI: Conimicut Light Station, NOAA MA: Woods Hole Station, NOAA

Table 7: Parameters input into the SLAMM model for each marsh

Parameter	Waquoit Bay	Buzzards Bay	Hundred Acre Cove
Wetland Data Photo Date	2008	2008	2010
DEM Date	2011	2013	2016
Direction offshore	South	South	South
Historic SLR Trend (mm/yr)	3.07 (1932-2023)	3.07 (1932-2023)	2.58 (1938-2023)
MTL-NAVD88	-0.1	-0.1	-0.027
GT Great Diurnal Tide Range (m)	0.672	1.216	1.397
Salt Elev. (m above MTL)	0.336	0.608	1.192
Regular-Flood Marsh Accretion (mm/yr)	3.07	3.07	2.58
Irregular-Flood Marsh Accretion (mm/yr)	3.07	3.07	2.58
H1 inundation (m above MTL)	0.801	0.801	1.192
H2 inundation (m above MTL; H2>H1)	0.854	0.854	1.242
H3 inundation (m above MTL: H3>H2)	0.872	0.872	1.275

Sea level rise scenarios for each marsh were also incorporated into the model runs for the 2040 and 2070 time steps. SLAMM provides users with the choice to use custom sea level rise time series data. ERG obtained relative sea level rise projection data at tide gauge stations from NOAA for one and two meters of global sea level rise by 2100 (Sweet et al., 2022). The tide gauge station closest to each marsh that had sea level rise projections was the Woods Hole station for Waquoit Bay and Buzzards Bay and the Providence gauge for Hundred Acre Cove.

ERG turned off the “protect developed lands” option for each model run. While in reality, communities likely would build structures to protect developed land from inundation, these scenarios highlight what could happen if no structures, like seawalls, were built to protect developed land.

2.3.5 Modeling Outputs

In summary, we generated scenarios reflecting how each selected study area would be affected by one- and two-meter sea level rise in 2040 and 2070. 2024 marsh conditions were used as a starting point (i.e., "marsh present") and were compared against a scenario in which all current marshes were converted to open water (i.e., "no marsh"). This generated eight scenarios for each marsh (two sea level rise scenarios, two future time periods, and two marsh status conditions) across seven inundation levels for the land area included in the analysis:

- Always inundated – The area is under water at least once a day by high tide
- Inundated at least once every 30 days – The area experiences inundation at least once every 30 days.
- Inundated at least once every 60 days – The area experiences inundation at least once every 60 days.
- Inundated at least once every 90 days – The area experiences inundation at least once every 90 days.
- 10-year storm – The area experiences inundation from a 10-year storm event.
- 100-year storm – The area experiences inundation from a 100-year storm event.
- Protected by dikes – The area was not affected since it was protected by a dike.

In our results below, we focus on the first six levels to present modeling outcomes. In interpreting our results, it is important to consider that land area can and will move between inundation categories. For example, land that was in the "30-day inundation" category under the "marsh present" scenario often moves into the "always inundated" category under the "no marsh" scenario.

2.4 Monetary Valuation

ERG used the inundation frequency categories above to determine how people, residences, and roads might be affected in each scenario. The data used for this analysis are listed in **Table 8**.

Table 8: Data sources for inundation analyses

Metric Calculated	State	Data Name	Data Source
Number of people affected	Both	U.S. Census Blocks, 2020 decennial census	Esri Federal Data
Miles of roads affected	MA	2020 U.S. Census Tiger Roads	MassGIS
Miles of roads affected	RI	RIDOT Roads (2016)	URI Environmental Data Center and RIGIS
Number of residences affected	MA	Property Tax Parcels	MassGIS
Number of residences affected	RI	Town of Barrington Property Tax Parcels	Town of Barrington, data acquired upon request
Number of residences affected	RI	Town of East Providence Property Tax Parcels	

2.4.1 People Affected

ERG used census block population estimates from the 2020 U.S. Census to approximate the number of people affected by inundation under each modelled scenario. To do this, ERG first calculated the fraction of each census block affected by inundation frequency. Then, the team multiplied this fraction by the number of people in the census block to get an estimate for how many people would be affected. This method provides only a rough estimate because people are not necessarily distributed evenly throughout a census block.

2.4.2 Residences Affected

ERG used parcel level data to calculate how many residences would be affected by inundation and the value of the property affected. To focus the analysis on residential properties affected, ERG filtered the property data to the following property types:[1]

Massachusetts

- Single Family Residential
- Mixed Use (Primarily Residential, some Commercial)
- Mixed Use (Primarily Residential, some Agriculture)
- Housing, Other (Charitable Org.)
- Two-Family Residential
- Residential Condominium
- Three-Family Residential
- Mixed Use (Primarily Residential, some Industrial)
- Other Congregate Housing (includes non-transient shared living arrangements)

Rhode Island

- 2 Family
- 3 Family
- 4 Family
- Antique
- Apartment
- Assisted Living
- Bungalow
- Cape
- Cape Condo
- Colonial
- Colonial Con
- Condominium
- Contemporary
- Conventional
- Cottage
- Dormitories
- Group Care Home
- Home/Elderly
- Log Cabin
- Ranch
- Ranch-F/B
- Ranch-Slab
- Split Level

ERG focused on two types of estimates related to property. First, we estimated the value of the property affected, which does not reflect an avoided cost, but rather an estimate of the value at risk. Property and building values were taken from MassGIS and RIGIS and are based on property tax data. ERG calculated the property value, land value, and total value of the parcels affected by each inundation event. We multiplied each property parcel's value by the fraction of the parcel inundated by each

[1] The filters for MA and RI are different because the property data for each state is different and uses a separate set of classifications for property types

inundation event and then summed across the parcels, yielding a total land value inundated, total building value inundated, and total value inundated (building value + land value.) Notably, this method assumes each square foot of land on a parcel is of equal value and that buildings are distributed randomly on parcels. This may result in an overestimate of the value of buildings affected by inundation but assumed to make estimations in lieu of better data.

Second, we calculated an estimated avoided future cost to properties that could be attributed to the marsh presence. We assumed areas that SLAMM categorizes as "always inundated" would lose the entire value of the parcel, inclusive of the land and building value, and that this can be understood as costs due to global sea level rise. For buildings that are inundated from storm surge, we relied on depth-damage functions from the U.S. Army Corps of Engineers (USACE) to translate the values of buildings being inundated to costs. These functions are only applied to buildings and not to land because intermittent land inundation does not degrade property value the same way it degrades building value. For example, a lawn that is inundated occasionally would not incur the same costs as a basement flooded just as frequently. It is likely that if a parcel is inundated at regular intervals the value of the parcel would decrease, but the extent of that decrease depends on the frequency and depth of inundation and would require more detailed data to estimate. Because SLAMM does not output inundation depth and only shows the geographic extent of inundation, ERG picked a low and high depth within the USACE depth-damage functions to create high and low scenarios to estimate costs. These estimates assume a typical residential structure and represent inundation depths of -6 feet, where a basement may be affected, and roughly 6 inches, where insulation and walls may be damaged. These depths correspond to damages of 2 percent and 10 percent of structure value, and we believe are appropriate to convey a wide range of uncertainty.[2]

The final output from our property cost modeling is an estimate of the cost of sea level rise. Specifically, our modeling involves using current marsh conditions as a starting point for each area to reflect the "marsh present" scenarios, and scenarios "with marsh" make the assumption that marshes will continue to accrete at rates that keep pace with SLR. As noted above, one inundation outcome is that an area can be "always inundated." Under the "marsh present" scenarios, the always inundated outcome will reflect the cost of sea level rise to properties in 2040 and 2070 under both the one-and two-meter sea level rise scenarios.

2.4.3 Roads Affected

ERG calculated the miles of roads affected by inundation by intersecting the inundation frequency and roads layers and calculating the length of the intersected roads. ERG relied on existing literature estimates of the cost of inundation to road systems to calculate the economic impacts of road inundation (Fant et al., 2021). Fant et al. (2021) estimates the cost of traffic delays from high tide inundation using hourly tide gauge water levels, global sea level rise projections, and spatial analysis. We use data from Fant et al. (2021) to calculate the average cost of inundation per mile of road impacted. We multiplied that average by the total miles of road inundated for each marsh to estimate the total cost of inundation to affected roads for each global sea level rise scenario and time horizon.

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[2] Although not included here, depth-damage functions can also be used to estimate damages to contents within a house. Due to data limitations, ERG did not estimate the additional costs from content damage during storms, but highlights it as an area for future research.

Our estimates of the cost associated with road inundation likely underestimate actual costs as we do not consider factors such as unique costs due to storm surge flooding and costs associated with physical damage to roads and increased road maintenance needs. Our analysis depends on data from Fant et al. (2021), which assessed the cost of traffic delays due to high tide flooding. Fant et al. (2021) does not consider all possible costs from the scenarios studied in our analysis, such as costs related to storm surge, physical damages to roads, increased maintenance needs, and more. Please see Section 5 for additional information about the limitations of our analysis.

2.4.4 Discounting

The monetary values presented in this report reflect 2024 values for the costs and property values, but do not reflect discounting from 2040 (or 2070) back to 2024. In short, ERG used values reflecting 2024 monetary values. In most cases, monetary values in the future should be discounted back to the present using an appropriate discount rate (e.g., three percent). However, discounting should also take into account inflation. In this analysis, the primary asset being monetized are properties which tend to increase in value at a higher rate than the commonly used three percent rate. As such, any discounting in this work would result in increasing the values we estimate. For example, a three percent discount rate combined with a seven percent inflation would increase our values in 2040 by a factor of 1.8 by 2040 and by 5.8 by 2070. Additionally, we could also expect some impact of inundation on property value increases over time in our study area which we do not have information on to reliably estimate. Thus, we decided the most prudent approach was not simply present the values in undiscounted 2024 dollars rather than introduce further bias and/or uncertainty into the estimated values.

2.5 Nonmonetary Valuation

To assess the value of salt marsh benefits not quantified in this report, ERG conducted a review of existing scientific literature. Many of the studies included in our initial review of the literature, conducted to support development of our analytical methods, and described in Section 2.1, included qualitative discussions of the benefits of salt marshes. We examined these studies to develop nonmonetary values. We also expanded on our initial literature review to identify an additional six studies highlighting benefits of salt marshes that are not monetized in this report. While we focused primarily on qualitative findings related to the value of salt marshes, we also included quantitative findings from existing literature where relevant and available.

3 MONETARY VALUATION RESULTS

In this section, we describe the results of the analyses described above. Due to the number of scenarios considered, we focus on the results for the one-meter global sea level rise by 2100 scenario. All dollar estimates in this section are phrased in terms of 2024 dollars.

3.1 Inundation Modeling Results

Eight scenarios for each marsh were applied in the modeling described above as defined by the following parameters: (1) with and without a marsh present, (2) with one and two meters of sea level rise, and (3) across two time periods (2040 and 2070). For each scenario, SLAMM generated an inundation frequency map that shows which areas around the marsh will be inundated and how frequently using the following categories:

- Always inundated
- Inundated at least once every 30 days
- Inundated at least once every 60 days
- Inundated at least once every 90 days
- Inundated from a 10-year storm surge
- Inundated from a 100-year storm surge
- Protected by dikes

It is important to note that these inundation frequency maps do not include information on the depth or duration of inundation. So, while the area inundated between some scenarios may look similar, it is likely that the duration of inundation would vary greatly. Appendix B presents maps for each marsh area reflecting the one level of global sea level rise scenarios.

We note that inundation in the Hundred Acre Cove marsh varied little between each marsh scenario. For example, the inundation maps across the “marsh present” scenario for 2040 and 2070 for one meter of global sea level rise and for 2040 for two meter of global sea level rise, appears largely the same. This is also true for the without marsh scenario. The only results that differed from the 2040 with one meter of global sea level rise was the 2070 two meter of global sea level rise scenario. The limited difference across marsh and sea level rise scenarios at Hundred Acre Cove may be due to the elevation and topography of the region. Appendix B presents a map that shows the elevation that is less than 6 m (about 20 ft) above sea level. From the map, it is clear that the areas higher than 6 m create a boundary for the areas at risk from inundation. Although the inundation categories stay largely the same across sea level rise scenarios, the depth and duration of that inundation would likely increase. However, the SLAMM model does not measure depth and duration.

3.2 Monetary Valuation

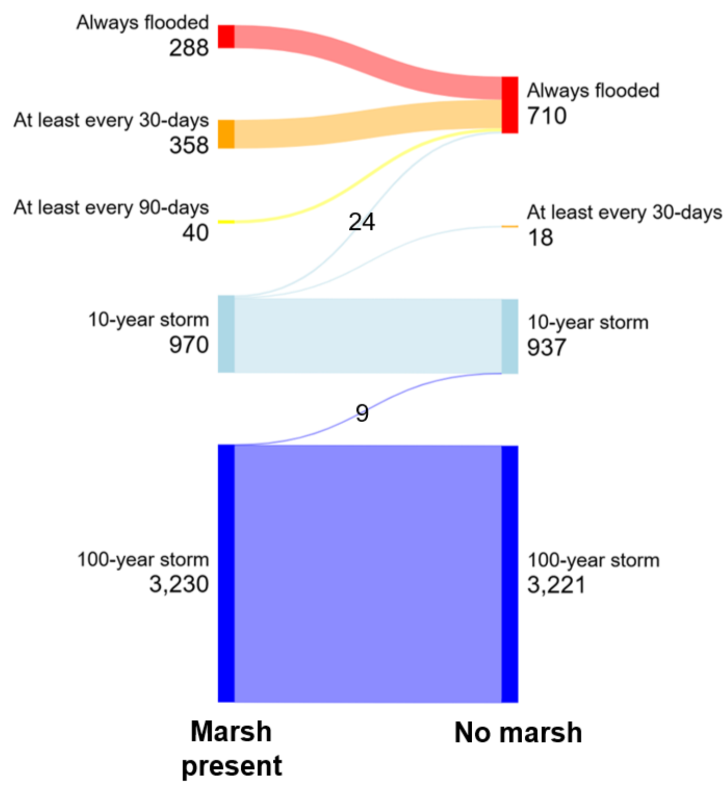
3.2.1 Interpreting Results

The project team initially expected that scenarios with no marsh habitat would have more area around the marsh exposed to inundation. However, we found that while the total area exposed to inundation stayed largely the same across the scenarios, the biggest change between them was the inundation frequency between areas. This is likely because the elevation and topography around the marsh limits the area that could be affected by a few feet of sea level rise and storm surge. For example, an area might only be at risk from inundation during a 10-year storm if there is salt marsh habitat present, but if that habitat were removed, that same area might now be at risk from inundation every 90 days. This means that without salt marsh habitat, an area is at risk of being inundated more often than if that salt marsh habitat were present and providing protection against inundation.

Figure 10 illustrates an example of how the inundation frequency categories migrate across marsh scenarios.[3] The figure shows the number of people affected by inundation in Waquoit Bay in 2040 with one meter of global sea level rise by 2100. On the left-hand side is the total number of people affected by each inundation frequency category with Waquoit Bay's natural marsh habitat. The flow of categories to the righthand side shows how the number of people affected would change under the "no marsh" scenario. In this example, the number of people who were only affected by inundation every 30 or 90 days with marsh present would be affected by inundation more often if there was no salt marsh habitat in the bay.

In this way, our results highlight a key finding of this work. Specifically, the total amount of land area, and the number of properties and people impacted do not change significantly between the "marsh present" and "no marsh" scenarios, but that they would be affected more frequently due to sea level rise and the lack of mitigating marsh habitat.

Figure 10: Number of people affected by inundation in Waquoit Bay in 2040 with one meter of global sea level rise by 2100, marsh present and no marsh scenarios



3.2.2 Number of People Affected

Based on methodologies described in Section 2.4, ERG estimated the total number of people who could be affected by inundation for each marsh. For brevity, this section focuses on the one meter of global sea level rise by 2100 scenario.

3.2.1.1 Waquoit Bay Marsh (Cape Cod), MA

In Waquoit Bay, the main difference across scenarios is in the number of people affected by constant inundation and tidal inundation. The number of people affected by storm surge stayed about the same across the scenarios, as seen in **Figure 11**.

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[3] The style of this figure is known as a Sankey Diagram.

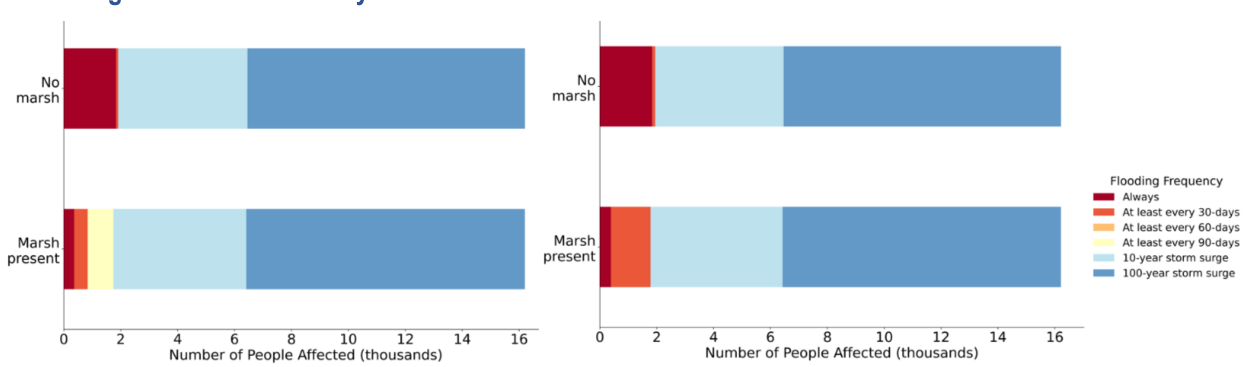
As described and illustrated in section 3.2.1 Interpreting Results, almost 400 people who were affected by inundation about every 30 or 90 days with a marsh present, would be consistently affected by inundation if Waquoit Bay had no marsh habitat to attenuate inundation.

Figure 11: Number of people affected by inundation in Waquoit Bay Marsh in 2070 with one meter of global sea level rise by 2100

3.2.1.2 Buzzards Bay Marsh, MA

Buzzards Bay Marsh had similar results to Waquoit Bay, where people who were sometimes affected by tidal inundation with marsh habitat present transitioned to always being affected by inundation if no marsh habitat were present (**Figure 12**). In the "marsh present" scenario in 2070, most people who were affected by inundation at least once every 90 days in 2040 became at risk from more frequent 30-day inundation. This shift in inundation frequency is also apparent between 2040 and 2070 under the same marsh scenario. In 2040 with a marsh present there is some area of the Bay that would be inundated every 90 days, but by 2070 that area has largely converted to being inundated every 60 days. In this way removing marsh habitat is similar to accelerating the effects of the sea level rise on inundation to a community.

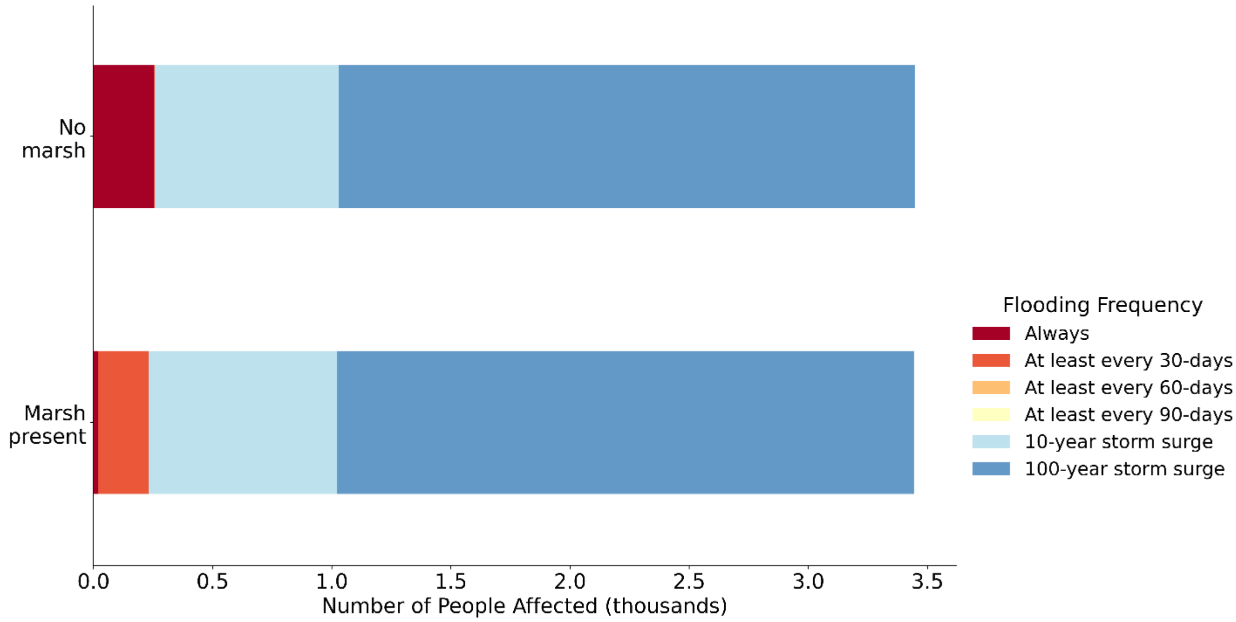
Figure 12: Number of people affected by inundation in Buzzards Bay in 2040 (left) and 2070 (right) with one meter of global sea level rise by 2100



3.2.1.3 Hundred Acre Cove

The Hundred Acre Cove Marsh in Rhode Island had similar results to the Massachusetts marshes regarding the difference between marsh scenarios. However, unlike the Massachusetts marshes, there was no difference in the number of people affected across inundation frequencies between 2040 and 2070. As such, **Figure 13** below shows the results for both 2040 and 2070 with one meter of global sea level rise by 2100. It is important to note that while the frequency of inundation might not change between 2040 and 2070, the depth and duration of the inundation likely would, which is not captured by the model.

Figure 13: Number of people affected by inundation in Hundred Acre Cove in 2040 and 2070 with one meter of global sea level rise by 2100



3.2.3 Properties Affected

Based on methodologies described in Section 2.4 Monetary Valuation, ERG estimated the total number and value of the properties affected by inundation for each marsh, as well as the expected future avoided costs due to marsh presence. Given that each marsh has eight scenarios, we present only a few scenarios results for each marsh, focusing on the one meter of sea level rise scenarios.

3.2.3.1 Waquoit Bay

Table 9 provides the distribution of the extent to which properties were affected by inundation across the six inundation scenarios. We find that marsh habitat in Waquoit Bay helps protect properties from inundation, and for properties that are inundated, marshes generally lessen the degree of inundation relative to "no marsh" scenarios. For example, the total number of properties that are always inundated increases by 109 properties under the "no marsh" scenario. However, we also see that the proportion of properties that have five percent of their property always inundated is much higher under the "marsh present" scenario. That is, the total number of properties increased in the most extreme category and the extent of inundation (as measured by percent of property affected) among the remaining properties also increased substantially.

Table 9: Number of properties affected by inundation (frequency and percent of property inundated), Waquoit Bay, 2070, one meter of global sea level rise by 2100

Inundation Frequency	>0% to 5%	>5% to 20%	>20% to 40%	>40% to 60%	>60% to 80%	>80% to 100%	Total Properties Affected
No Marsh							
Always Inundated	389	598	302	74	21	2	1386
30-Day Inundation	386	611	305	76	21	2	1401
60-Day Inundation	386	611	305	76	21	2	1401
90-Day Inundation	386	611	305	76	21	2	1401
10-year Storm	470	692	598	276	193	324	2553
100-year Storm	476	584	578	502	392	2998	5530
Marsh Present							
Always Inundated	683	486	96	11	1	0	1277
30-Day Inundation	385	623	281	65	21	1	1376
60-Day Inundation	385	623	281	65	21	1	1376
90-Day Inundation	385	623	281	65	21	1	1376
10-year Storm	459	698	589	273	194	323	2536
100-year Storm	458	583	578	503	393	2996	5511

The total value of residential property in Waquoit Bay expected to be affected by inundation due to global sea level rise and storm surge is substantial both with and without marsh habitat present (**Table 10**). Under "no marsh" scenarios, roughly $210 million and $190 million worth of additional property will be always inundated compared with the "marsh present" scenario in 2040 and 2070, respectively. The value of property inundated is similar between 10-year and 100-year storms, which shows benefits of roughly $16 million in avoided property inundated for a 2040 10-year storm, roughly $16 million in avoided property inundated in a 2070 10-year storm, and roughly $6 million of avoided property inundated during a 2040 and 2070 100-year storm. These numbers show that although a 10-year and 100-year storm affect a similar area of properties with and without a marsh, marshes provide significant resilience against global sea level rise, or the "always inundated" scenario. Additionally, we note that our modeling did not provide outputs presenting the depth or duration of inundation, so it is possible that inundated areas in the "no marsh" scenario are affected more significantly by inundation in ways which we are not able to describe here.

Table 10: Value of inundated property (millions of 2024 dollars), Waquoit Bay Marsh, one meter of global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Always inundated	$124.7	$340.3	$144.9	$340.7
30-day inundation	$280.3	$348.1	$319.0	$350.2
60-day inundation	$280.3	$348.1	$319.0	$350.2
90-day inundation	$313.8	$348.1	$319.0	$350.2
10-year storm	$1,016.3	$1,032.3	$1,017.1	$1,032.7
100-year storm	$3,568.7	$3,574.3	$3,568.9	$3,574.5

We also note that our results allow us to estimate a cost of sea level rise based on the "marsh present" scenario alone. For example, the "marsh present" scenario indicates that in 2040, $124.7 million in property will be "always inundated". The starting point for our modeling represents current conditions (in 2024). Thus, moving from now to 2040 (or 2070), the value of affected property under the "marsh present" scenario represents a cost associated with sea level rise, irrespective of marsh presence. That is, **one meter of global sea level rise by 2100 will place $124.7 million worth of property in the Waquoit Bay area into the always inundated category in 2040 and by 2070 that figure increases by $20.2 million to $144.8 million.**

Using the methods described in Section 2.4.2 that relies on the USACE depth-damage curves, we translated the inundation estimates into expected future costs avoided from marsh presence. Total costs for a 10-year and 100-year storm are shown in **Table 11**. It is important to note that these costs include the costs from the other scenarios as well because any parcel that is inundated under those scenarios will also be inundated during a 10-year or 100-year storm. ERG estimates that the total avoided future costs attributable to marsh presence during a 100-year storm to be between $206.5 million and $213.8 million in 2040 and between $187.5 million and $194.1 million in 2070.

Table 11: Total costs for Waquoit Bay from a 10-year and 100-year storm (millions of 2024 dollars), one meter of global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Costs during a 10-year storm	$132.24 to $162.41	$346.10 to $369.37	$152.26 to $181.78	$346.50 to $369.75
Costs during a 100-year storm	$156.16 to $282.02	$369.92 to $488.47	$176.18 to $301.35	$370.32 to $488.84

3.2.3.2 Buzzards Bay

Table 12 shows properties by percent inundation in Buzzards Bay based on our modeling. For this area, the total number of affected properties remains the same under "marsh present" and "no marsh" scenarios (5.514). However, as with Waquoit Bay, scenarios without a marsh lead to higher degrees of property inundation than scenarios with a marsh. For example, we see that the number of properties with "always inundated" areas in 2070 increases from 588 with the marsh to 968 without the marsh. Furthermore, 25 properties have 20 percent or more of their area always inundated by 2070 with the marsh, but without the marsh 375 properties have 20 percent or more of their area always inundated by 2070.

Table 12: Number of properties affected by inundation (frequency and percent property inundated), Buzzards Bay 2070, one meter of global sea level rise by 2100

Inundation Frequency	0% to 5%	>5% to 20%	>20% to 40%	>40% to 60%	>60% to 80%	>80% to 100%	Total Properties Affected
No Marsh							
Always Inundated	247	346	254	94	26	1	968
30-Day Inundation	238	349	260	100	27	1	975
60-Day Inundation	238	349	260	100	27	1	975
90-Day Inundation	238	349	260	100	27	1	975
10-year Storm	328	455	482	347	251	904	2767
100-year Storm	338	434	495	385	429	3433	5514
Marsh Present							
Always Inundated	401	162	21	4	0	0	588
30-Day Inundation	244	347	231	74	18	1	915
60-Day Inundation	244	347	231	74	18	1	915
90-Day Inundation	244	347	231	74	18	1	915
10-year Storm	327	465	478	337	249	904	2760
100-year Storm	338	440	492	384	432	3428	5514

ERG estimates the total value of property inundated for different scenarios in **Table 13**. We estimate that roughly $31.0 million and $33.6 million of property value is inundated in the presence of a marsh in 2040 and 2070, respectively, compared to roughly $203.7 million of inundated property value in 2040 and $203.9 million in 2070 without a marsh. We find again that the total value of properties inundated is similar between 10-year and 100-year storms, but that there is a significant difference between the intermediate inundation scenarios, and the always inundated scenario.

Table 13: Value of inundated property (millions of 2024 dollars), Buzzards Bay Marsh, one meter of global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Always inundated	$31.0	$203.7	$33.6	$203.9
30-day inundation	$119.1	$207.2	$176.6	$208.0
60-day inundation	$119.1	$207.2	$176.6	$208.0
90-day inundation	$175.8	$207.2	$176.6	$208.0
10-year storm	$1,171.1	$1,179.1	$1,171.5	$1,179.5
100-year storm	$3,339.7	$3,343.2	$3,340.1	$3,343.6

By looking only at the “always inundated” scenario, ERG estimates that the cost of global sea level rise under current conditions is roughly $31.0 million in 2040 and $33.6 million by 2070. As with the Waquoit Bay marsh, this tells us that salt marshes provide significant resilience benefits against sea level rise.

ERG presents total costs for a 10-year and 100-year storm in **Table 14**, noting again that these costs are inclusive of global sea level rise. ERG estimates that costs from a 100-year storm are between roughly

$69 million and $221 million with a marsh and between roughly $240 million and $385 million without a marsh. We therefore estimate that a salt marsh results in roughly $165 million to $171 million in avoided costs in a 100-year storm in 2040 and $163 million to $169 million in avoided costs in a 100-year storm in 2070.

Table 14: Buzzards Bay Costs from a 10-year and 100-year storm (millions of 2024 dollars), one meter global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Costs during a 10-year storm	$42.98 to $91.00	$214.13 to $255.82	$45.63 to $93.56	$214.34 to $256.04
Costs during a 100-year storm	$68.93 to $220.79	$240.04 to $385.37	$71.59 to $223.35	$240.25 to $385.59

3.2.3.3 Hundred Acre Cove

The results for Hundred Acre Cove were similar to the other two marshes, but with smaller numbers of properties. In total, only 122 properties are affected by inundation in 2070 (see **Table 15**) with one meter of global sea level rise and no marsh, compared with 1,386 properties in Waquoit Bay and 968 properties in Buzzards Bay under the same conditions. This is likely because most of the marsh is substantially lower in elevation than the elevation of properties and roads (as seen in the elevation map in **Figure 14** on page 37), meaning increased global sea level rise does not reach many of the properties even when the marsh is removed. As with Waquoit Bay and Buzzards Bay, “marsh present” scenarios typically have fewer properties facing inundation, and the inundation tends to be less severe in terms of percent property inundated than in “no marsh” scenarios.

Table 15: Number of properties affected by inundation (frequency and percent of property inundated), Hundred Acre Cove, RI

Inundation Frequency	<0% to 5%	>5% to 20%	>20% to 40%	>40% to 60%	>60% to 80%	>80% to 100%	Total Properties Affected
No Marsh							
Always Inundated	46	36	18	15	5	2	122
30-Day Inundation	45	37	18	15	5	2	122
60-Day Inundation	45	37	18	15	5	2	122
90-Day Inundation	45	37	18	15	5	2	122
10-year Storm	81	112	96	83	63	86	521
100-year Storm	122	138	123	114	128	879	1504
Marsh Present							
Always Inundated	51	21	3	1	0	0	76
30-Day Inundation	46	34	15	11	4	2	112
60-Day Inundation	46	34	15	11	4	2	112
90-Day Inundation	46	34	15	11	4	2	112
10-year Storm	82	112	96	82	63	86	521
100-year Storm	122	138	124	115	126	879	1504

We find that the value of inundated property in Hundred Acre Cove is smaller across all scenarios than the values of inundated property in Buzzards Bay and Waquoit Bay. This finding is not surprising given the number of properties affected by inundation and the elevation map of the area. However, we still find "marsh present" scenarios to be beneficial when compared with "no marsh" scenarios, with almost seven times as much property value being always inundated in the "no marsh" scenario than the "marsh present" scenario (**Table 16**). Similar to Buzzards Bay and Waquoit Bay, the difference in the value of the property inundated gets smaller moving to other inundation scenarios. We also find that the effect of global sea level rise is the same between 2040 and 2070, which is in line with our expectations given the elevation of properties in the area are substantially higher than the marsh area.

Table 16: Total value of property inundated (millions of 2024 dollars), Hundred Acre Cove, one meter of global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Always inundated	$2.4	$16.3	$2.4	$16.3
30-day inundation	$13.7	$16.3	$13.7	$16.3
60-day inundation	$13.7	$16.3	$13.7	$16.3
90-day inundation	$13.7	$16.3	$13.7	$16.3
10-year storm	$116.3	$117.0	$116.3	$117.0
100-year storm	$538.6	$539.2	$538.6	$539.2

As with other marshes, the value of the property that is always inundated with the marsh present is conceptualized as the cost due to one meter of global sea level rise by 2100. Here we see costs of $2.4

million in 2040 and 2070. Once again, the elevation of the area is the reason the value is the same between the two time periods.

Table 17 provides the estimated costs of the marsh loss. We find that marshes lead to between $13.2 and $13.7 million dollars in avoided total costs following 10-year and 100-year storms in 2070. These costs are inclusive of costs resulting from global sea level rise because all property inundated due to global sea level rise will also be inundated during a 10-year and 100-year storm.

Table 17: Hundred Acre Cove Total Costs from a 10-year and 100-year storm (millions of 2024 dollars), one meter of global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Costs during a 10-year storm	$3.53 to $8.01	$17.25 to $21.22	$3.53 to $8.01	$17.25 to $21.22
Costs during a 100-year storm	$8.29 to $31.83	$22.01 to $45.03	$8.29 to $31.83	$22.01 to $45.03

3.2.4 Roads Affected

Based on the methods described in Section 2.4.3 Roads Affected, ERG estimated the total miles of road affected by inundation frequency and associated cost impacts.

4.2.4.1 Waquoit Bay

Salt marsh habitat protects some roads from being inundated around Waquoit Bay with future sea level rise. **Table 18** describes the miles of road expected to be inundated around Waquoit Bay Marsh in 2040 and 2070 given one meter of global sea level rise by 2100 with and without salt marsh habitat present. We found that salt marshes prevent constant inundation of more than one mile of road in both 2040 and 2070. **Table 19** describes costs associated with road inundation taking into account all inundation scenarios. **When salt marsh habitat is present, we estimate that around $66 thousand and $532 thousand in inundation costs are avoided by 2040 and 2070, respectively.**

Table 18: Miles of roads inundated surrounding Waquoit Bay Marsh, one meter of global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Miles that are always inundated	0.20	1.25	0.21	1.25
Miles inundated every 30 days	0.66	1.27	0.83	1.27
Miles inundated during a 10-year storm	22.34	22.77	22.51	22.77
Miles inundated during a 100-year storm	92.07	92.44	92.24	92.44

Table 19: Costs of road inundation (millions of 2024 dollars) surrounding Waquoit Bay Marsh, one meter of global sea level rise by 2100

2040		2070	
Marsh Present	No Marsh	Marsh Present	No Marsh
$16.6	$16.7	$246.9	$247.5

3.2.4.2 Buzzards Bay

Table 20 describes predicted road inundation in 2040 and 2070 around Buzzards Bay Marsh given one meter of global sea level rise by 2100 with and without salt marsh habitat present**. We find that salt marshes prevent constant inundation of over 1.2 miles of road in both 2040 and 2070. Table 21** describes costs associated with all levels of road inundation frequencies. When salt marsh is present, we estimate that approximately $60 thousand and $215 thousand in inundation costs are avoided by 2040 and 2070, respectively.

Table 20: Miles of road inundated surrounding Buzzards Bay Marsh given one meter global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Miles that are always inundated	1.01	2.21	1.02	2.21
Miles inundated every 30 days	1.31	2.21	1.44	2.22
Miles inundated during a 10-year storm	73.69	73.93	73.83	73.93
Miles inundated during a 100-year storm	241.39	241.61	241.53	241.62

Table 21: Costs of road inundation (millions of 2024 dollars) surrounding Buzzards Bay Marsh given one meter global sea level rise by 2100

2040		2070	
Marsh Present	No Marsh	Marsh Present	No Marsh
$64.3	$64.3	$573.4	$573.6

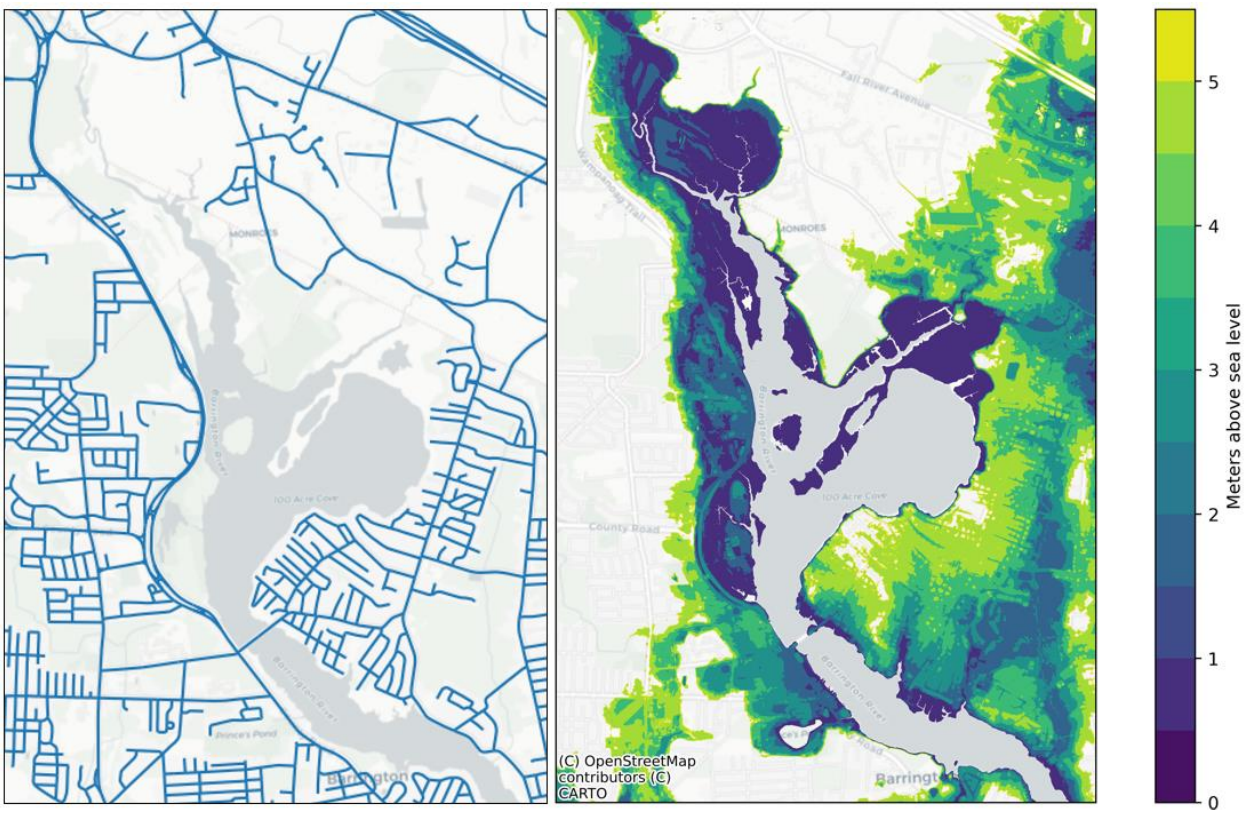
3.2.4.3 Hundred Acre Cove

Table 22 describes predicted road inundation around Buzzards Bay Marsh in 2040 and 2070 given one meter of global sea level rise by 2100 with and without salt marsh habitat present. Our model predicts that **marsh presence has no impact on the miles of roads inundated** under any of the global sea level rise scenarios we considered in RI, and thus the presence of the salt marsh does not result in any avoided costs. However, the road systems surrounding Hundred Acre Cove Marsh, shown in **Figure 14**, are generally at a relatively high elevation. Roads located in lower elevations are not near salt marsh habitat, and so are not protected by them.

Table 22: Miles of road inundated surrounding Hundred Acre Cove Marsh given one meter global sea level rise by 2100

Inundation Frequency	2040		2070	
	Marsh Present	No Marsh	Marsh Present	No Marsh
Miles that are always inundated	0.10	0.10	0.10	0.10
Miles inundated during a 10-year storm	6.35	6.35	6.35	6.35
Miles inundated during a 100-year storm	25.91	25.91	25.91	25.91

Figure 14: Hundred Acre Cove roads (left) and elevation less than 6 m above sea level (right)



3.2.4.4 Other impacts to roads

The results above describe expected inundation of roads and associated costs due to time delays. Flooding of road systems may result in additional impacts to roads, including:

- Physical damage to road systems
- Need to elevate roads
- Need to relocate roads
- Disruption of services and activities dependent on road systems

Quantitative cost data related to these impacts are limited. Fant et al. (2021) does not attempt to estimate the cost of physical damage to roads since they are highly dependent on local conditions. The authors do estimate physical damage costs for a case study area in South Carolina. Fant et al. (2021) found that road system repair costs accounted for a small portion of total costs, equal to approximately 0.8% to 1.3% of the value of costs due to traffic delays. Though this case study provides evidence that costs associated with physical damage to road systems may make up a relatively small portion of total costs, they are not well-suited to our study areas since physical damage costs are expected to vary widely by geographic location. Additionally, Fant et al. (2021) only considered physical damages from high tide inundation. Storm surge may cause substantially more damage to road systems than high tide inundation.

Costs associated with road elevation and relocation have not been widely evaluated. Communities may choose to elevate or relocate roads, especially if they are always inundated under future global sea level rise conditions. Local data are not available to effectively characterize road elevation costs in Southern New England. Data that are available to characterize road elevation costs are outdated or specific to geographic areas that are drastically different from Southern New England to the point of being inappropriate to inform research on our study area, such as Southern Florida, and Northern Alaska. Data related to road relocation costs are, similarly, not widely available, however one study estimates that the cost of building one mile of new road to adapt to inundation impacts in Barnstable County would be approximately $7 million dollars (Eastern Research Group, Inc. & Synapse Energy Economics, Inc., 2021). Based on this figure, we could expect to see road relocation costs of up to $8.75, $15.47, and $0.7 million faced by the communities surrounding Waquoit Bay, Buzzards Bay, and Hundred Acre Cove, respectively. Some Southern New England communities have initiated projects that will assess the feasibility and cost of road elevation; evaluations are ongoing (Avery, 2021; Commonwealth of Massachusetts, 2020).

Disruptions of road systems can substantially impact services and activities that rely on ground transportation and can result in severe consequences for human health, community well-being, and economic prosperity. Though we do not attempt to quantify costs related to these consequences, we do describe them qualitatively in Section 4 of this report.

3.2.5 Estimating the Value of Marshes for Reducing Property Impacts in the SNEP Region

As part of this work, ERG was asked to assess whether the estimates from this work could be extrapolated to the SNEP region as a whole. Based on the extent of the modeling performed, ERG's professional assessment is that extrapolation to other marsh areas in the SNEP region would be limited. Specifically, the work we performed under this project involved a great deal of site-specific data to develop our estimates. This included the detailed geomorphic data described in Section 2.3.3 and the parcel-level population and building/land value data we used to develop the impact estimates. Despite this, ERG expects that a rough estimate of the value from other areas could be approximated taking the following steps:[4]

1. Identify a set of geographic units (e.g., Census blocks or tracts) across the SNEP region that could be reasonably affected by marsh presence. This may be any Census tract that has marsh within the tract or adjacent to the tract.
2. Use Census data to calculate the average or median property value in each of those units.
3. Estimate the average or median property value for the areas we used in our analysis, possibly focusing on just Buzzards Bay (see below).
4. Calculate an index for property values for each unit identified in #1 using the ratio of #2 to #3.
5. For each unit identified in #1, multiply the index in #4 by a per-acre value derived from our estimates in this report. For Buzzards Bay, we estimate the per-acre value of avoiding damages in 2070 (from one meter global sea level rise in 2100) to be $32,904; for Waquoit Bay, we estimate that value to be $147,048 per acre. Based on the significant difference, we recommend using Buzzards Bay as the point estimate to use.
6. Multiply the value from #5 for each unit in #1 by the number of acres for each unit in #1.

This type of calculation would result in an estimate of the value of avoided damages associated with marsh presence, adjusted for differences in property values. The drawbacks of this approach are that (1) it does not adjust for how sea level rise would affect each parcel in #1, (2) it does to account for the idea that marshes affect areas outside the geographic unit they are located in,[5] and (3) it assumes our primary finding that marshes protect about the same number of parcels, but reduces the extent of inundation in those parcels applies to other marsh areas as well.

We also note, however, that our three marshes actually represent a large proportion of all marsh acres in the SNEP region. The Buzzards Bay marsh is approximately 5,000 acres, Waquoit Bay is approximately 1,300 acres, and Hundred Acre Cove is approximately 450 acres. Overall, the SNEP region has 39,430 total acres of marsh, meaning that our analysis covered approximately 17 percent of the total marsh area in the SNEP region. Thus, an extrapolation as described above may provide a reasonable estimate.

[4] We note that these steps are meant to mimic the approach used in the three study areas without recreating the detailed geomorphic modeling.

[5] An extension of this limitation is that geographic units with marsh will tend to have less area for property parcels.

4 NONMONETARY VALUATION RESULTS

In addition to the benefits we monetized in this report, salt marshes also provide numerous benefits that are beyond the scope of our work to monetize. Flood prevention services provided by salt marshes also include avoidance of public health impacts from flooding, disruption of utility services, emergency response delays and obstructions, disruptions of municipal services, and disruption of economic activities. Along with the flood prevention services that salt marsh habitat provides, salt marshes also provide carbon captures services, economic opportunities, recreational opportunities, and cultural, religious, and aesthetic value to coastal communities. In this section, we discuss additional benefits of salt marshes qualitatively.

4.1 Additional Benefits from Inundation Reduction

4.1.1 Avoided public health impacts and disruption of utility services

Salt marshes mitigate inundation severity and frequency, reducing deaths and injuries caused by dangerous flooding events. Flooding is the leading cause of natural disaster fatalities globally (Doocy et al., 2013). Drowning is the greatest immediate threat to individuals impacted by flooding, with drowning accounting for 75% of deaths in flooding disasters (Doocy et al., 2013). Additional immediate risks to affected individuals include injuries, hypothermia, electrocution, animal bites, and more (Du et al., 2010). Flooding can also lead to damage to healthcare facilities, loss of health workers, and disruptions to medical supply chains (Du et al., 2010).

In addition to reducing immediate risks due to flooding, salt marshes also protect public health by reducing the likelihood of utility service disruptions. Storm surge can overwhelm aging or under-funded infrastructure such as sewers, powerplants, and stormwater and drinking water systems. Infrastructure failures can lead to increased exposure to water-borne illnesses due to water filtration and transportation system failures. Healthcare can also be affected by transportation disruptions and power outages that impact people who rely on electricity-dependent medical equipment. Populations with greater vulnerability to flood-related illnesses and health impacts include older adults and individuals with existing illnesses who may be dependent on routine medical treatments (Bell et al., 2016; MacLeod et al., 2015; U.S. Environmental Protection Agency, 2021). Power outages caused by flooding also often lead to carbon monoxide poisonings due to failures of carbon monoxide detection devices that depend on electricity (Waite et al., 2014).

4.1.2 Avoided emergency response delays

Salt marshes help to reduce inundation, preventing damage to emergency response infrastructure that can delay emergency responders. Inundation can cripple infrastructure that emergency responders rely on to source critical supplies and reach emergency sites, such as communications networks, public utilities, and transportation networks. Damage to these infrastructure systems can cause severe delays in emergency responders' ability to reach the sites of emergencies and administer aid (Sturdevant Rees et al., 2018). Emergency response delays can cause adverse outcomes for property and health, even resulting in loss of life (Schramm et al., 2023; Sturdevant Rees et al., 2018).

Inundation can also prevent community members from evacuating dangerous areas (Li et al., 2015). Disruptions to transportation systems, such as road closures due to inundation, can prevent individuals from evacuating areas threatened by inclement weather, forest fire, and other emergencies. Stranded community members may need to shelter in place, endangering their safety (Li et al., 2015).

4.1.3 Avoided disruptions of non-emergency municipal services

Inundation can also cause delays and obstacles to non-emergency service provision which prevent community members from accessing valuable services including public education, social services, public transportation, and waste management (Porter et al., 2021). Inundation can damage or destroy buildings and infrastructure used to provide non-emergency services like schools, subway systems, landfills, libraries, and more. Alternatively, inundation of road systems can prevent community members or municipal workers from accessing municipal services they must travel to. Community members regularly rely on non-emergency services to facilitate their daily activities. For example, disruptions to public education create burdens for families who rely on public schools for childcare, nutrition, and other social services (Garcia & Cowan, 2022; Kinsey et al., 2020). Furthermore, school closures or other obstructions to public education access (such as obstructions to transportation) can lead to adverse outcomes for children's educational attainment (Venegas Marin et al., 2024). Disruptions to public transportation can prevent community members from working, accessing social and medical services, and obtaining critical supplies including food, hygienic items, and more (Jacobs et al., 2018). Disabled adults are disproportionately affected by disruptions of public transportation systems since they rely on public transportation services at a greater rate than the general population (United States Department of Transportation, Bureau of Transportation Statistics, 2024). Loss of non-emergency municipal services leave communities vulnerable to adverse outcomes in many areas of their lives. Salt marshes help to mitigate inundation impacts and maintain communities' access to non-emergency services.

4.1.4 Avoided disruption of economic activities

Salt marshes help to mitigate the frequency and severity of inundation and prevent floods, which can disrupt economic activity in affected communities (Sun et al., 2022; U.S. Environmental Protection Agency, 2021). During floods, economic activities may be disrupted due to business establishment flooding, destruction of inventory, inability to transport goods due to road closures or damage to vehicles, inability to travel to provide services, and inability for staff to report to work. Evidence suggests that minor flooding events do not have a substantial impact on local economic activity (Sun et al., 2022). Following a severe flooding event, however, local economic activity may be suppressed if community members have evacuated or relocated, or if extensive damage has occurred preventing businesses from opening or customers from shopping due to issues with access or financial hardship caused by flooding (Sun et al., 2022). Business disruptions due to severe flooding can last days to weeks, and lead to long-term financial implications (Sun et al., 2022). Small businesses are particularly likely to experience economic hardship due to flooding because of a lack of resources to prepare for and respond to natural hazards (Sun et al., 2022).

4.1.4.1 Impacts to cranberry bogs

Massachusetts is the second largest producer of cranberries in the United States, with production concentrated in the Southeastern portion of the state (Cape Cod Cranberry Growers' Association, 2024; Laughton, 2023). In 2022, Massachusetts cranberry producers generated $73.4 million in farm-gate value (Laughton, 2023). Cranberry farming activities generated $151 million in economic output and supported 1,916 jobs in 2022 (Laughton, 2023). An additional 4,476 jobs and $1.6 billion in economic output were generated by cranberry processing, marketing, and logistics activities in 2022 (Laughton, 2023). There are over 1,000 and 100 acres of cranberry bogs in the area surrounding Buzzards Bay and Waquoit Bay, respectively. As seen in **Figure 15** and **Figure 16**, most of the cranberry bogs in both Buzzards Bay and Waquoit Bay would be in the 10 to 100 year storm flood zone in 2040 with one meter of GSLR by 2100. Exposure to storm surge could contaminate the cranberry bogs with salt water and affect crop yields. However, in Waquoit Bay, six cranberry bog restoration projects have been completed (denoted by the green star in **Figure 16**) to return these areas to more natural freshwater wetland conditions.

Figure 15: Buzzards Bay Marsh inundation frequency in 2040 with One Meter of GSL. Location of cranberry bogs are outlined in red

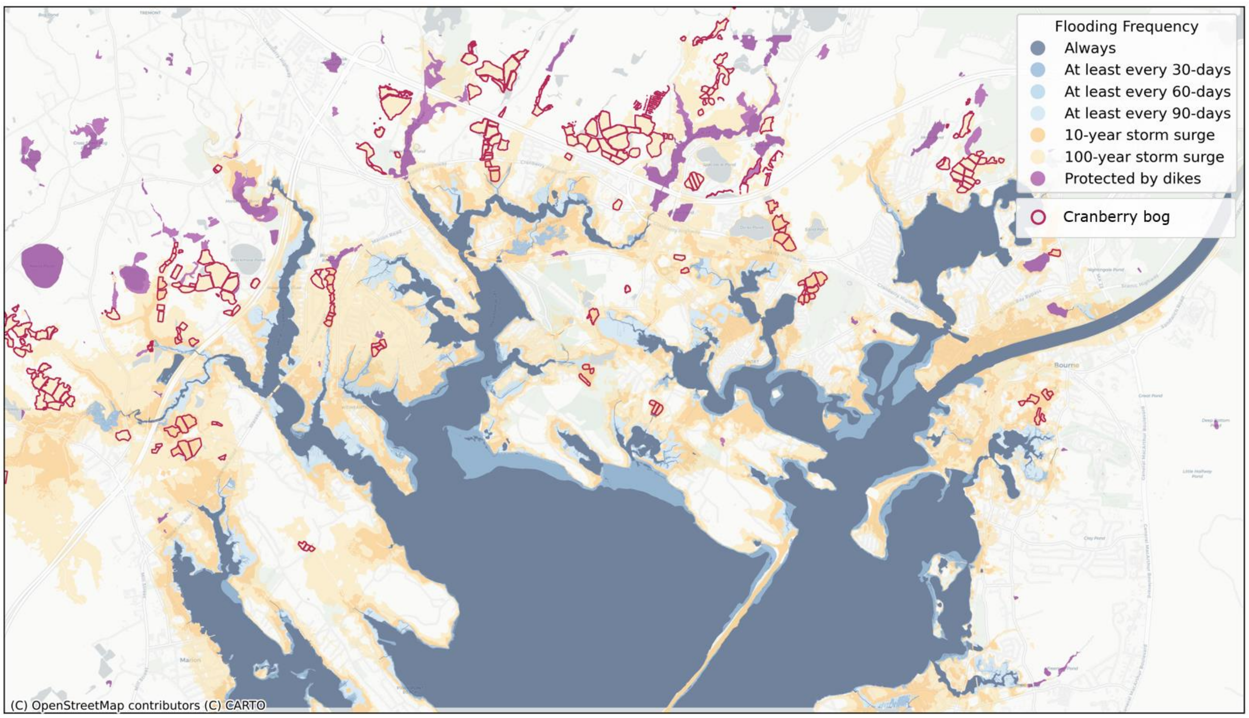
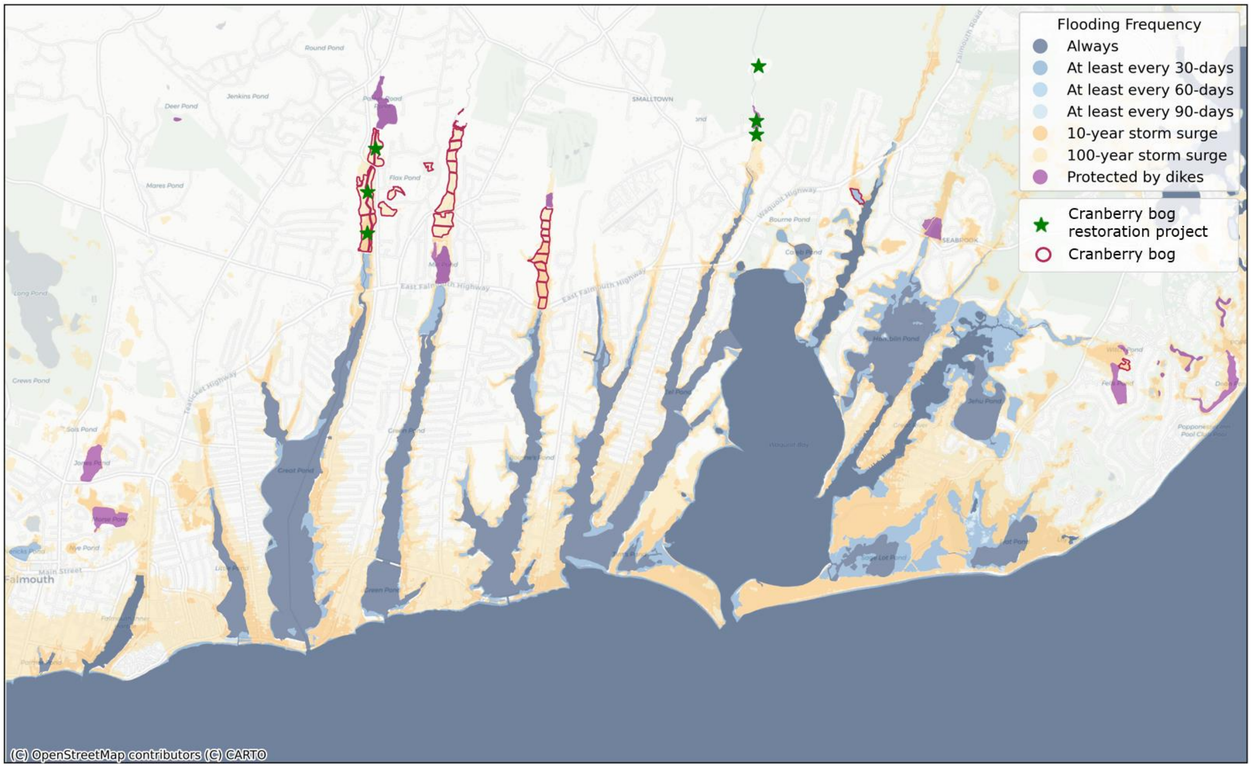


Figure 16: Waquoit Bay inundation frequency in 2040 with one meter of global sea level rise by 2100, location of cranberry bogs are outlined in red



4.2 Other Benefits of Salt Marshes

4.2.1 Carbon capture

Salt marshes are integral parts of coastal ecosystems that act as carbon dioxide "sinks". The U.S. Environmental Protection Agency (EPA) estimates that eelgrass meadows and salt marshes located from Maine to Long Island, NY, sequester over 7.5 million megagrams of carbon, equivalent to the annual emissions of approximately 6 million passenger vehicles (Colarusso et al., 2023). Research on the economic benefits of salt marshes suggests that salt marshes provide an annual average value of $1,863 per acre in atmospheric carbon dioxide sequestration services (Mazzocco et al., 2022). Waquoit Bay National Estuarine Research Reserve led a four-year program (2011-2015), "Bringing Wetlands to Market" (BWM), that conducted scientific research in Waquoit Bay to examine the relationship between salt marsh and carbon sequestration (Waquoit Bay National Estuarine Research Reserve, 2013).

4.2.2 Ecological benefits

Salt marshes are an important component of coastal ecosystems. Salt marshes generate biological productivity and diversity, providing important habitat for many flora and fauna (Barbier et al., 2011). As we discussed in Section 2.2.3, salt marshes are especially important as nursery habitat for certain species including horseshoe crabs, sand eels, alewives, rare plants and rare shorebirds such as the roseate tern and salt marsh sparrow. As salt marshes migrate or disappear, the viability of these species is increasingly threatened. Salt marshes also support sediment stabilization and soil retention that help to maintain coastlines (Barbier et al., 2011). They help to purify water, taking up excess nutrients and pollutants that otherwise would negatively impact water quality (Barbier et al., 2011). Excess nutrients in particular can cause toxic algal blooms and marine dead zones, from storm runoff water before it enters estuaries. Researchers estimate that, globally, each acre of salt marsh provides nutrient filtration services valued at about $14,000 in 2024 dollars (Gedan et al., 2009). Salt marshes' nutrient filtration services help to reduce the frequency and severity of harmful blooms, preventing adverse health impacts and avoiding additional healthcare costs to coastal communities. Children and elderly individuals are especially at risk of adverse health impacts from harmful algal blooms (National Institute of Environmental Health Sciences, 2024). Waquoit Bay National Estuarine Research Reserve is heavily involved in nutrient monitoring in Waquoit Bay and has led many programs evaluating Waquoit Bay's interactions with influent nutrients (Waquoit Bay National Estuarine Research Reserve, 2024c).

4.2.3 Recreational opportunities

Many recreational opportunities are available to visitors of salt marshes, including wildlife viewing, recreational fishing, water sports, hunting, camping, hiking, enjoyment of nature, and more.

4.2.4 Cultural, religious, and aesthetic value

In addition to the protective, ecological, and economic benefits that salt marshes provide, they also provide important social and culture benefits to communities. Salt marshes can be important to local traditions, rituals, and community identity. Salt marshes often hold particular social and culture importance to certain Native Nations people whose history, heritage, and culture are deeply tied to North American coastal areas. These indigenous peoples developed ways of life timed to salt marsh abundance, harvesting fish, shellfish, and berries for food and using salt marsh wildflowers for dye (Moore, 2023; Wampanoag Tribe of Gay Head, 2024). Salt marshes are also culturally valuable to many communities settled during American colonialism thanks to their historical importance to agricultural practices, heating, insulation and more. Early farmers would harvest valuable marsh hay for a myriad of purposes including animal feed, home insulation, mattress stuffing, and more (Oliver, 2022). Marsh peat was burned as an alternative fuel source in lieu of wood or coal (Oliver, 2022). In addition to their social and cultural importance, salt marshes also make for unique and stunning coastal landscapes, creating aesthetic value to community members and visitors.

4.2.5 Economic opportunities

Salt marshes support commercial activities by providing crucial nursery habitat for popular commercially harvested marine species like fish, crab, and shrimp. Research suggests that each acre of salt marsh provides nursery habitat for commercially harvested species valued at over $400 in 2024 dollars (Gedan et al., 2009). Additionally, salt marsh restoration work can improve coastal economies by improving their resilience while generating jobs and stimulating total economic activity.

Tourists may be attracted to the recreational opportunities and aesthetic value of salt marshes. Tourists inject revenue into many sectors of the economy, including lodging, restaurants, transportation, and more.

5 LIMITATIONS

ERG acknowledges several limitations that present opportunities for future work and increase the degree of uncertainty in our output. The modeling software used, SLAMM, is used widely to model marsh migration, but is not as sophisticated as other models to model attenuation, wave damage, and inundation associated with rainfall. While we support our modeling output, other software could be used in the future to generate more precise inundation estimates. For example, future research efforts could supplement our analysis with applying the ADCIRC+SWAN model for the studied areas to further study the impacts of wave action and storm surge on the salt marshes.

SLAMM is also limited in its inundation output, showing layers of inundation frequency, but not depth or duration of the inundation. This makes translating inundation to economic damages challenging, as damages are a function of depth and duration of inundation. We used conservative estimates derived from USACE's depth damage curves to estimate high and low damage scenarios, but more information, particularly as it pertains to depth of inundation, would have allowed us to estimate damage to structures more accurately. Further, because we don't know the exact location of a building within a parcel, we assumed that as a parcel gets inundated so too does its building. This assumes that buildings are distributed evenly across parcels, which may overestimate damage to buildings in situations where a small percent of a parcel is inundated, and the building itself is untouched.

Our estimates of the cost associated with road inundation likely underestimate actual costs as we do not consider factors such as unique costs due to storm surge inundation and costs associated with physical damage to roads and increased road maintenance needs. Our analysis depends on data from Fant et al. (2021), which assessed the cost of traffic delays due to high tide inundation. Fant et al. (2021) does not attempt to estimate the cost impacts of traffic delays due to storm surge, which are likely to occur less frequently than high tide inundation but lead to greater costs during each occurrence since storm surge often penetrates further inland than high tide inundation. Additionally, Fant et al. (2021) did not consider the cost of physical damages to road infrastructure caused by inundation. Fant et al. (2021) state that road maintenance costs to repair damages to road infrastructure caused by inundation will vary greatly across geographic areas since they are highly dependent on local conditions such as hydrology, permeability, construction materials, and more. Fant et al. (2021) state that estimating road maintenance costs would require extensive data compilation efforts covering a plethora of localized data systems and be subject to substantial data gaps and limitations if certain data are not available. Fant et al. (2021) do include a case study where they estimate road maintenance costs incurred due to inundation on a single road segment in South Carolina. In that case study, road maintenance costs were found to account for approximately 0.8% to 1.3% of total costs due to inundation. Since we use an average cost of traffic delays due to road inundation across each county, our study does not consider differences in the impacts of individual roads on traffic patterns. Some roads may have disproportionate impacts on the traffic patterns. Some roads that are threatened by SLR in Southern New England, such as Argilla Road in Ipswich, MA, and Great Island Road in West Yarmouth, MA, serve as the only access point for coastal areas and their inundation could completely disrupt the flow of traffic to and from the areas they serve (Avery, 2021; Commonwealth of Massachusetts, 2020). Though not monetized in this report, frequent isolation of coastal areas could lead to a decline in the property values of affected homes and compromise community safety and economic vitality. Please see Section 4.1 for more information about benefits from reduced inundation that are not monetized in this report.

6 SUMMARY

The goal of this study was to assess the value of services provided by salt marshes to surrounding ecosystems and communities and provide insights into how these services may vary with global sea level rise and time horizon. Our place-based monetary valuation analysis focused on inundation protection services provided by salt marsh habitat adjacent to three coastal communities in Southern New England. We assessed additional values derived from salt marsh presence, including those not related to inundation protection services, qualitatively. Our results demonstrate the substantial monetary and nonmonetary value of salt marshes to coastal communities. These findings suggest that natural salt marsh habitats can contribute to the resilience of coastal communities, properties, and ecosystems that are vulnerable to sea level rise and storm surge. As coastal inundation from both high tides and storm surge has become a rising concern, coastal communities will need to explore ecosystem-based inundation protection approaches. Salt marsh preservation and restoration offers a promising pathway to increased resilience.

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APPENDIX A: REVIEW OF LITERATURE USED TO DEVELOP METHODOLOGY

A.1 Overview

ERG conducted a literature review of the research related to the economic (or other) values of salt marshes. ERG reviewed studies published in the last twenty years that were relevant to salt marshes and wetlands, focusing in particular on studies in the northeast.[1] ERG primarily searched Google Scholar and Academia.edu to find studies, using terms such as "salt marsh valuation in the northeast" and "economic valuation of salt marshes in the United States". In total, ERG includes 24 studies with insights and methodologies that we expect to inform our own research as we develop methodologies and assumptions related to salt marsh valuation. Generally, studies indicated that salt marshes are highly biologically productive ecosystems that offer a variety of valuable resources and ecosystem services to human communities including protection of life and property from storms, provision of critical habitat for commercially significant marine species, biogeochemical filtering of water, and more. Salt marshes provide value through increased opportunities for ecotourism, carbon sequestration, storm and flood mitigation, and more market and non-market benefits. Salt marsh habitats are threatened by human development, sea level rise, temperature increase, and other environmental changes. When salt marshes decrease in area, the benefits that coastal communities derive from them may also decrease in value, and carbon may be released into the atmosphere. Many of the studies summarized below describe threats to salt marsh area and ecological resilience and attempt to evaluate the impact of smaller or lower quality salt marsh areas on the value salt marshes provide. Often this is expressed quantitatively as losses in ecosystem services or increased costs incurred as damages to properties from storms.

Studies reviewed frequently modeled the impact storms and sea level rise have on salt marshes. The most common tools to do this were ADCIRC (ADvanced CIRCulation model), SWAN (Simulating WAves Nearshore), and SLAMM (Sea Level Affecting Marshes Model). Often these tools, particularly ADCIRC and SWAN, are coupled together to model storms. ADCIRC is used to simulate storm surges and coastal flooding during extreme weather events, SWAN models waves near the shoreline, and SLAMM evaluates the impacts of sea level rise specifically on wetlands and marshes.

ERG drafted summaries of key findings and core methodologies employed by the study authors to conduct their analyses. For convenience, we have divided the literature summaries into two categories: (1) studies that quantify the value of salt marshes and (2) studies that provide useful context for our analyses.

A.2 Studies That Quantify the Value of Salt Marshes

Barbier, E. B., Georgiou, I. Y., Enchelmeyer, B., & Reed, D. J. (2013). The Value of Wetlands in Protecting Southeast Louisiana from Hurricane Storm Surges. PLoS ONE, 8(3), e58715. https://doi.org/10.1371/journal.pone.0058715

This study evaluated the impacts of wetlands and vegetation on storm surge from hurricanes in Louisiana. The study modeled simulations through ADCRIC modeling. Authors of this study found that small increases in wetland to water ratios and wetland roughness significantly decrease storm surge attenuation. They found that a 1% decrease in the ratio of water to wetland decreases storm surge by 8.4% and 11.2%. They also found that a 1% increase in wetland roughness (as measured in Manning's n) decreases storm surge by 15.4% to 28.1%.

Boutwell, J. L., & Westra, J. V. (2015). Evidence of Diminishing Marginal Product of Wetlands for Damage Mitigation. Natural Resources, 06(01), 48–55. https://doi.org/10.4236/nr.2015.61006

Boutwell & Westra (2015) use hurricane simulation data to estimate county- or parish-level damages based on observed damages from 24 coastal storms that made landfall on the Gulf coast between 1995 and 2008. To estimate wetlands' protective ecosystem services, the authors use a model that describes damages as a function of wetland area, storm intensity, and socio-economic conditions. The study relies on the National Oceanic and Atmospheric Administration (NOAA) and National Climatic Data Center (NCDC) for extreme weather data, the US Fish and Wildlife Service (USFWS) for wetland areal data, and the US Census Bureau for demographic data. Damages were informed by the NCDC and attributed to counties and parishes using model simulation results from HAZUS (hazards USA), a hurricane modeling simulation tool. The researchers divided the dataset into two at the median of the wetland variable and applied an ordinary least squares regression to investigate the impact of wetlands' size on their relationship to damages. The authors found that wind was generally highly significant in predicting damages and associated with higher costs and that wetlands generally reduced damages significantly. A gain of one hectare of wetland per kilometer of coastline was expected to result in avoided damages of $26,410 per storm. Additionally, benefits (avoided damages) from wetlands are most significant in areas where wetlands are scarce. Marginal benefits from increased wetland area in areas where wetlands are already large in area are insignificant.

Costanza, R., Pérez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., & Mulder, K. (2008). The Value of Coastal Wetlands for Hurricane Protection. AMBIO: A Journal of the Human Environment, 37(4), 241–248. https://doi.org/10.1579/0044-7447(2008)37[241:TVOCWF]2.0.CO;2

In this research paper, Costanza et al. (2008) use a multiple regression analysis using data from 34 major hurricanes in the US since 1980 with relative damages (in GDP) as the dependent variable and wind speed and wetland area as the independent variables. The relationship between damages and the dependent variables (wetland area and wind speed) was found to be highly significant and explained 60% of variation in damages. Then, the researchers used this relationship and data on annual hurricane frequency to estimate the annual value of wetlands for storm protection. The study found that a loss of one hectare of wetland in the model corresponded to an average of $33 thousand in additional storm damage impacts from one storm. The authors mapped the annual value of coastal wetlands across the U.S. and found that the annual value of coastal wetlands ranges from between $250 to $51 thousand per hectare per year with a mean value of $8,240 per hectare per year. In total, U.S. coastal wetlands were estimated to provide $23.2 billion in ecosystem services annually.

Fairchild, T., Bennett, W., Smith, G., Day, B., Skov, M., Möller, I., Beaumont, N., Karunarathna, H., & Griffin, J. (2021). Coastal wetlands mitigate storm flooding and associated costs in estuaries. https://doi.org/10.21203/rs.3.rs-244327/v1

In this paper, the authors estimated environmental and economic impacts of eight estuaries along the coast of Wales. The study modeled 100-year storms, 10-year storms, and 1-year storms for each estuary with varying degrees of vegetation using Delft3D FLOW and WAVE (SWAN Cycle III 41.31) hydrodynamic models. Aggregated flood damage for residential, commercial, industrial, and agricultural properties, as well as damages to public buildings and water and electricity utility installation were estimated from the Multi-Coloured Manual. Finally, the authors used a mixed effects beta regression model in the glmmTMPpackage. The authors found that estuaries reduced flooding by 35% in 100-year storms and reduced cost damages by 37%.

Fant, C., Gentile, L. E., Herold, N., Kunkle, H., Kerrich, Z., Neumann, J., & Martinich, J. (2022). Valuation of long-term coastal wetland changes in the U.S. Ocean & Coastal Management, 226, 106248. https://doi.org/10.1016/j.ocecoaman.2022.106248

In this study by Fant et al. (2022), the authors estimate a set of future changes to coastal wetland areas. They consider future greenhouse gas emissions, sea level rise, and accretion rate uncertainty. The study depends on outputs from the National Ocean and Atmospheric Administration (NOAA) marsh migration model. The researchers look at coastal wetland area losses and translates those losses into monetary amounts valued using two approaches: ecosystem services and restoration costs. The project uses estimates of changes in sea level rise from Sweet et al. (2017) to project changes in land use and evaluates six scenarios of sea level rise ranging from low (30 cm) to extreme (250 cm). They set parameters for accretion, the growth by deposition of suspended particles and plant material in areas with occasional or permanent flooding, using the results of a broad literature review and data from multiple sources. They consider three accretion rate scenarios. The authors calculate relative sea level heights for each year they have data for and each sea level rise and accretion scenario. They calculate restoration cost estimates using data on restoration costs from Environmental Law Institute (2007). To value loss of ecosystem services, they use estimates of avoided damages to coastal property by county per unit area of marsh cover from Sun and Carson (2020) and carbon sequestration service value estimates from EPA's Greenhouse Gas Inventory for 1990-2019. The research team found that by the end of this century, annual marsh restoration costs reach $1.5 and $3.1 billion for two scenarios representing low and high levels of environmental change. Lost ecosystem services results in annual economic impacts of $2.5 billion to $6.1 billion.

Ghermandi, A., van den Bergh, J. C. J. M., Brander, L. M., de Groot, H. L. F., & Nunes, P. A. L. D. (2010). Values of natural and human-made wetlands: A meta-analysis. Water Resources Research, 46(12). https://doi.org/10.1029/2010WR009071

Ghermandi et al. (2010) reviewed existing studies on wetland valuation to understand how different wetland characteristics influence value. The authors created a dataset of 418 value observations from 170 valuation studies. Of these estimates, 132 estimates were from North American, 106 were from Asia, 93 were from Europe, 53 were from Africa, 22 were from South America, and 16 were from Australasia. Authors ran a meta-regression model with context specific explanatory variables. Authors found that methodological heterogeneity did not influence regression results, meaning estimates from studies with different methods are comparable. In total, the authors evaluate the effect of more than 30 independent variables on wetland valuation. They find high values for water quality improvement from salt marshes, while the provision of wood for fuel and recreational hunting are less valued. The authors found that all coefficients for environmental pressure were positive and increase with pressure, meaning that greater anthropogenic pressure produces higher salt marsh valuation estimates. Authors found that human made wetlands have the highest values followed by marine wetlands. Overall, the study's use of a meta-analysis allows for estimation of per-acre values of salt marsh ecosystem services for 10 ecosystem services and allows for some customization of those values based on local conditions (e.g., presence of other marshes nearby, economic conditions, population density).

Guerry, A. D., Silver, J., Beagle, J., Wyatt, K., Arkema, K., Lowe, J., Hamel, P., Griffin, R., Wolny, S., Plane, E., Griswold, M., Papendick, H., & Sharma, J. (2022). Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise. Npj Urban Sustainability, 2(1), 13. https://doi.org/10.1038/s42949-022-00056-y

Based on guiding principles developed through working sessions with local leaders and stakeholders, Guerry et al. (2022) created three strategies for coastal adaptation to expected environmental changes within San Mateo County, CA. The researchers used existing literature to develop three sea-level rise scenarios and identified a range of nature-based adaptation measures that could be implemented to mitigate the effects of sea level rise. Next, the authors identified areas along the shore that had suitable conditions to implement the given strategies. Strategies for coastal adaptation were developed that describe possible future approaches to sea level rise adaptation that incorporate varying degrees of nature-based solutions. Guerry et al. (2022) estimated changes in spatial productivity for four types of ecosystem services generated in tidal marsh and beach habitat: stormwater nutrient pollution reduction, recreation, carbon sequestration, and provision of habitat for a key endangered species. InVEST models were used to estimate changes in stormwater nutrient pollution reductions, recreation reductions, and increases in carbon sequestration. A simple linear regression was applied to identify the relationship between tidal marsh habitat and occurrence of the key endangered species. The study finds that adaptation options that incorporate investment into nature-based adaptation measures deliver up to eight times the benefits that an engineered baseline provides.

Mazzocco, V., Hasan, T., Trandafir, S., & Uchida, E. (2022). Economic Value of Salt Marshes under Uncertainty of Sea Level Rise: A Case Study of the Narragansett Bay. Coastal Management, 50(4), 306–324. https://doi.org/10.1080/08920753.2022.2078174

Authors of this paper evaluated three sea level rise scenarios and two marsh migration conditions on the value of salt marshes in the Narragansett Bay. They used SLAMM modeling to estimate changes in land cover, accounting for uncertainty in sea level rise. The authors found that in all scenarios, sea level rise will result in more salt marsh area than the baseline scenario, due to saltwater moving inward and converting land to marsh (authors note SLAMM modeling does not account for local efforts to stop marsh migration). Authors find that the value of an acre of salt marsh is $4,400 (from carbon storage and non-carbon benefits). Authors derive values from the market value of carbon and from Brander et al. (2006) and (2012). The authors find that the value of marshes will increase in the future if the acreage of marshes increase but note that change in marsh coverage will differ by locality.

Narayan, S., Beck, M. W., Wilson, P., Thomas, C. J., Guerrero, A., Shepard, C. C., Reguero, B. G., Franco, G., Ingram, J. C., & Trespalacios, D. (2017). The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. Scientific Reports, 7(1), 9463. https://doi.org/10.1038/s41598-017-09269-z

Narayan et al. (2017) uses high-resolution flood and loss models to estimate the impacts of northeastern US wetlands on regional flood damages caused by Hurricane Sandy and local annual flood losses in Barnegat Bay in Ocean County, NJ. The impacts of coastal wetlands on food risk to properties were examined both regionally across the entire northeast US coastline for one storm event and at the local level for Barnegat Bay in Ocean County, NJ across hundreds of storms. The authors based their flood model on data from the US Geological Survey National Elevation Dataset and the Danish Hydraulic Institute (DHI) Mike-21 model, an unstructured mesh, 2-dimensional hydrodynamic mode that calculates the propagation of storm surges from the coastal shelf to land. The authors used a damage function derived from observations of flood related damage developed by the US Army Corps of Engineers. For the regional study, the authors ran two scenarios, a “Wetlands present” and a “Wetlands lost” scenario. Results indicate that the presence of wetlands resulted in avoidance of $625 million in direct flood damages during Hurricane Sandy. The local scenario measured the protective role of marshes by dividing a selected area into areas with and without marshes. The researchers estimated annual flood height exceedance probabilities in all locations for over 2000 events using the flood mode, estimated associated damages for ~5,600 properties with and without marshes, and measured the difference in annual loss between properties with and without marshes. The results indicate a 16% average reduction in annual flood losses by salt marshes with higher reductions at lower elevations.

Peter Sheng, Y., Paramygin, V. A., Rivera-Nieves, A. A., Zou, R., Fernald, S., Hall, T., & Jacob, K. (2022). Coastal marshes provide valuable protection for coastal communities from storm-induced wave,

flood, and structural loss in a changing climate. Scientific Reports, 12(1), 3051. https://doi.org/10.1038/s41598-022-06850-z

Peter Sheng et al. (2022) examined marshes' buffering capacity in a changing climate considering scenarios of both marsh loss from sea-level rise and marsh restoration from human intervention. The authors used the North Atlantic Stochastic Hurricane Model (NASHM) in combination with sea-surface temperature (SST) projections from climate models to estimate changes in US tropical cyclones activity in the future. They used a coupled hydrodynamic-wave model, CH3D-SSMS to accurately represent estuaries and coastal waters in their analyses. The research team used the statistical method Joint Probability Method with Optimal Sampling (JPM-OS) to generate a set of representative storms in the area of interest (the coast of NJ/NY/CT). Then, they used a parcel-based economic analysis using the simulated storms along with building footprint data and damage functions to estimate economic impacts of storms. Multiple scenarios of sea-level rise were examined. Key results show that from 2020 to 2100 structural loss, waves, and extreme flooding are likely to increase. However, marshes will buffer approximately 11-12% of structural losses until 2050. Under extreme sea-level rise conditions, marsh buffering capacity will be lost by 2080-2100.

Rezaie, A. M., & Ferreira, C. (2016). Projected Storm Surge Flooding in Maryland and Virginia for 2100 and Valuation of Protective Ecosystem Services of Wetland and marshes for current condition.

Authors used ADCIRC (ADvanced CIRCulation model) and SWAN (Simulating WAves Nearshore) to model the effects of wetlands to damages from five historic hurricanes (ranging from low to high intensity). The study uses ADCIRC to compute the water level, current, and wind velocities due to hurricane storms, and SWAN to calculate the wave heights and relevant wave parameters. ADCIRC simulates the water level, currents, and wind, and passes it to SWAN which generates the wave and then passes it back to ADCIRC. The authors found that the average value per acre of wetland was between $59.81 and $275.94, depending on the storm evaluated. Total value of wetlands was between $53.1 million and $245 million.

Rezaie, A. M., Loerzel, J., & Ferreira, C. M. (2020). Valuing natural habitats for enhancing coastal resilience: Wetlands reduce property damage from storm surge and sea level rise. PLOS ONE, 15(1), e0226275. https://doi.org/10.1371/journal.pone.0226275

This study evaluated the effect of marshes on three coastal counties in New Jersey during simulated 25-year and 50-year storms, as well as hurricane sandy. The study used ARCIRC+SWAN models and WAVE models to simulate flooding from historical and synthetic storms. They used SLAMM modeling to predict potential marsh migration due to storms and Sea level rise. Authors modeled storms in scenarios with current marsh coverage and with no marsh coverage (where all marsh is replaced with open water). The study finds that marshes can reduce up to 14% of both flood depth and property damage during low intensity storm events compared to a scenario where marsh is replaced by open water. This translates to between $13.1 and $31 million in residential property damage during the 50-year storm and hurricane sandy under current conditions. ADCIRC, which is a coastal hydrodynamic model, and SWAN, which is a nearshore waves model, were combined to model storm surge. ADCIRC computes wave levels, currents, and wind information, which it passes to SWAN, which calculates radiation stresses and passes it back to ADCIRC as a forcing function. Wetlands were characterized using LULC classification by the C-CAP database which categorizes wetlands and marshes. Authors find that the presence of natural habitats (as opposed to scenarios where natural habitat is replaced with open water) can reduce total property damage by 13.8% in the study area in the current conditions.

Vázquez-González, C., Moreno-Casasola, P., Peralta Peláez, L. A., Monroy, R., & Espejel, I. (2019). The value of coastal wetland flood prevention lost to urbanization on the coastal plain of the Gulf of

Mexico: An analysis of flood damage by hurricane impacts. International Journal of Disaster Risk Reduction, 37, 101180. https://doi.org/10.1016/j.ijdrr.2019.101180

Vázquez-González et al. (2019) estimate the economic value of flood prevention services provided by coastal wetlands in this paper. The paper used data from a conurbation in Veracruz, Mexico affected by hurricane Karl in 2010 to measure their estimates. The authors quantified land use change and loss of water retention capacity as a wetlands loss function. They also calculated the economic cost (considering lost appliances and furniture) to households affected by flooding resulting from hurricane Karl. The research estimated the economic value of flood prevention ecosystem services provided by freshwater marsh, flooded grasslands, and mangroves by first dividing the total cost of flooding by the total water retained by the change in land use and then multiplying the amount of water retained in the soil by the value of the water retained in the soil. This process was carried out for each respective type of ecosystem (freshwater marsh, flooded grasslands, and mangroves) to generate unique estimates of the value of each. The resulting economic values of flood prevention were, in 2007 dollars: flooded grassland at $148,277/HA, freshwater marsh at $190,863/ha, and mangroves at $193,674/ha.

Wamsley, T. V., Cialone, M. A., Smith, J. M., Atkinson, J. H., & Rosati, J. D. (2009). The potential of wetlands in reducing storm surge. Ocean Engineering, 37(1), 59–68. https://doi.org/10.1016/j.oceaneng.2009.07.018

Wamsley et al. (2009) used a numerical storm surge model to evaluate the sensitivity of storm surge response to wetland loss. The researchers used data from Hurricane Rita, which made landfall near the Texas and Louisiana border in 2005 and used the TC96 Planetary Boundary Layer model, ADCIRC (Advanced CIRculation) model, WAM (wave model), and STeady-state spectral WAVE (STWAVE) model to model synthetic storms, storm surge, and direction wave spectra, and near-coast wave generation and transformation, respectively. Wetlands were represented in the model as bathymetric and frictional resistance. The authors simulated both a base condition landscape in South Louisiana (based on data from the USGS and National Wetland Research Center) and an estimated future condition landscape (based on predictions from the Coastal Louisiana Ecosystem Assessment and Restoration model, a coastal forecast system that changes in water quality, ecological succession, geomorphic features, and physical processes). The study concluded that wetlands do generally attenuate storm surge and should be considered when developing a coastal protection plan. The authors find that the loss of wetlands increase water surface elevation by .15 meters in one study location, and .3 meters in the second study location during a 100-year storm. However, the authors emphasize that the effectiveness of wetlands is highly dependent on the landscape and storm characteristics.

A.3 Studies That Provide Useful Context

Annis, G. M., Pearsall, D. R., Kahl, K. J., Washburn, E. L., May, C. A., Franks Taylor, R., Cole, J. B., Ewert, D. N., Game, E. T., & Doran, P. J. (2017). Designing coastal conservation to deliver ecosystem and human well-being benefits. PLOS ONE, 12(2), e0172458. https://doi.org/10.1371/journal.pone.0172458

Annis et al. develop a spatially explicit conservation plan identifying the most efficient locations for conservation intervention while sustaining or improving human well-being within the coastal and nearshore areas of western Lake Erie basin. Authors identify regionally relevant ecological priorities such as protecting migrating birds, insects and bats that depend on the Lake Erie shoreline through stakeholder interviews. Based on regional priorities, they are able to identify optimal areas for ecological and human goals. The authors find that including human well-being features in their analysis influences solutions at high levels.

Bozek, C. M., & Burdick, D. M. (2005). Impacts of Seawalls on Saltmarsh Plant Communities in the Great Bay Estuary, New Hampshire USA. Wetlands Ecology and Management, 13(5), 553–568. https://doi.org/10.1007/s11273-004-5543-z

Authors chose five study sites in the Great Bay Estuary, with each site consisting of a marsh with a seawall upland and a marsh with a natural transition to an upland area (acting as a control). Authors found that there was no significant effect of seawall treatment on sediment weight. Authors also did not find significant differences between canopy height, *S. alterniflora* stem height, and total biomass between marshes with seawalls and marshes without seawalls. However, authors found that biodiversity was greatest in the transition zone of the marshes without seawalls (which is not present in marshes with seawalls). They conclude that as more seawalls are built, marsh diversity will be reduced, with potential impacts on marsh ecosystems.

Castagno, K. A. (2018). Salt Marsh Restoration and the Shellfishing Industry: Co-evaluation of Success Components. Coastal Management, 46(4), 297–315. https://doi.org/10.1080/08920753.2018.1474069

This study evaluated the effectiveness of restoring wetlands for shellfish habitat in five towns on Cape Cod (Orleans, Eastham, Wellfleet, Truro, and Provincetown). They highlight a restored marsh in Truro, MA, which was recolonized by quahogs and soft-shelled clams two years after restoration. The authors found that salinity increased significantly after implementation of restoration projects in all five marshes. Authors analyzed shellfish yield and found no statistically significant difference in two of the marshes, insufficient data for two of the marshes, and increases in bivalve colonization in one marsh. Authors also interviewed 42 shell fisherman and found that 35 had a positive opinion of salt marsh restoration, and 7 had neutral opinions. Although this study did not find a significant increase in shellfish harvest on the outer cape, public opinions were positive, leading the authors to conclude that the benefit exists on a social level. Authors find that the restoration projects in this study are largely considered successful, and the authors conclude that increased shellfish population is a benefit from salt marsh restoration, even if shellfish catch has not reflected this. Finally, the authors assert that there is a robust social connection associated with salt marsh restoration.

Gedan, K. B., Altieri, A. H., & Bertness, M. D. (2011). Uncertain future of New England salt marshes. Marine Ecology Progress Series, 434, 229–237. https://doi.org/10.3354/meps09084

In this study, Gedan et al. (2011) examine major threats to New England salt marshes (such as temperature increase, die-off, and sea level rise) to project the trajectory of these ecosystems. The authors describe the value of ecosystem services provided by marshes. They reference them as providing valuable resources, protecting human communities form storms, working as biogeochemical filters, and providing nursery habitat for commercially harvested marine species. The authors discuss existing threats to salt marshes and examine data linking those threats to marsh decline. They also examine new and emerging threats to salt marsh vitality and resilience. The authors provide key insights into salt marsh management strategies and associated environmental tradeoffs. They recommend that management strategies focus on maintaining the ecosystem resilience of New England salt marshes.

Glassberg, D. (2017). The Changing Cape: Using History to Engage Coastal Residents in Community Conversations about Climate Change. The George Wright Forum, 34(3), 285–298.

This document by David Glassberg (2017) is largely qualitative in nature. It reports findings of the "Changing Cape" project, a series of community engagement efforts by the National Park Service (NPS) in relation to the Cape Cod National Seashore in 2016. The project framed community discussions as dialogues about historical change on Cape Cod, emphasizing physical and ecological change. Many community members shared stories of fear, grief, and loss about physical, ecological, and demographic changes on the Cape. The conversations identified a disconnect in what climate scientists and the public consider as changes as opposed to losses. Certain events, such as the return of seal and shark species to the Cape ecosystem or the changing coastlines may be viewed as changes by scientists, however, local community members may view them as losses in recreational, economic, and cultural losses. Furthermore, it is sometimes unclear when a change passes from being a “change” to a loss. For example, it is unclear when increased storm activity and flooding becomes a loss compared to a natural variation. Many Cape residents emphasized that they saw climate change as only of many threats to the continued existence of their communities. Many community members chose to bring up concerns about economic and demographic changes before climate change.

Glick, P., Powell, E., Schlesinger, S., Ritter, J., Stein, B. A., & Fuller, A. (2020). The Protective Value of Nature: A Review of the Effectiveness of Natural Infrastructure for Hazard Risk Reduction. National Wildlife Federation.

This report, published by the National Wildlife Federation in 2020, is intended to enhance awareness of the benefits of natural infrastructure solutions and increase public understanding of their usefulness. The report walks through several natural hazards including flooding, sea level rise, extreme weather, and wildfires and shares natural infrastructure approaches to protecting communities from the impacts of such natural hazards. The report offers some insight into the benefits of natural infrastructure at a high level; however, it does not provide guidance on identification and measurement of key benefits from natural infrastructure.

Morris, J. T., Sundberg, K., & Hopkinson, C. S. (2013). Salt Marsh Primary Production and Its Responses to Relative Sea Level and Nutrients in Estuaries at Plum Island, Massachusetts, and North Inlet, South Carolina, USA. Oceanography, 26(3), 78–84.

Morris et al. (2013) publish the results of scientific studies conducting research on Plum Island, MA, and at North Inlet, SC, to better understand natural processes that dictate the productivity and ability of saltwater marshes to maintain elevation. Maintenance of elevation indicates a higher likelihood that a marsh will be resilient in the face of accelerating sea level rise associated with climate change. The scientists observed the response of marsh biomass and productivity, nutrient levels, vegetation growth, and water levels over time to track changes in the marsh ecosystem as sea level rises. The researchers found that productivity of key species found in the marshes increased when water levels increased. They concluded that they expect marsh productivity to increase initially as sea level rises, but later decline once a certain threshold flooding depth or duration is exceeded.

Seminara, G., Lanzoni, S., & Cecconi, G. (2011). Coastal wetlands at risk: Learning from Venice and New Orleans. Ecohydrology & Hydrobiology, 11(3–4), 183–202. https://doi.org/10.2478/v10104-011-0040-5

Seminara et al. (2011) provides an overview of the state of knowledge on coastal community vulnerability to intense hydrodynamic and atmospheric events by looking at two community case studies: Venice, Italy, and New Orleans, U.S.A. The authors examine major natural and anthropogenic factors contributing to the communities’ vulnerability including eustacy, isostasy, soil compaction, reduced sediment supply, and reduced extension of natural defenses such as coastal wetlands or barrier islands. Finally, the authors provide information about potential paths forward to protect New Orleans and Venice. Seminara et al. (2011) point to a combination of natural and gray infrastructure projects that could be implemented to increase resilience in the face of natural hazards. Natural infrastructure investments recommended include expanding salt marsh vegetation cover and redirecting water and sediments to degrading wetlands.

Shiao, T., Kammeyer, C., Brill, G., Feinstein, L., Matosich, M., Vigerstol, K., & Müller-Zantop, C. (2020). Benefit Accounting of Nature-based Solutions for Watersheds Landscape Assessment (B. McLaughlin & D. Beigel, Eds.). United Nations Global Compact CEO Water Mandate and Pacific Institute.

This report, published in 2020, informs the path forward for working with the private sector to invest in nature-based solutions (NBS) to environmental issues. The authors used a combination of interviews with representatives of businesses, civil society, and academia who have previously implemented NBS projects or intend to implement NBS projects and a literature review investigating current thinking about NBS and challenges and opportunities facing potential implementing parties. While many of the key findings of the report addresses the current state of NBS within the private sector and how implementation of NBS could be improved and generally increased within the private sector, the authors also include detailed information about current practices related to benefit identification and accounting. The authors include a list of currently used tools for identifying and accounting for benefits across a variety of categories. They also published a list of regularly employed metrics to measure benefits from existing water accounting and evaluation methods.

Timpane-Padgham, B. L., Beechie, T., & Klinger, T. (2017). A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. PLOS ONE, 12(3), e0173812. https://doi.org/10.1371/journal.pone.0173812

Timpane-Padgham et al. conducted a review of the scientific literature to identify studies that include or examine attributes of environmental systems that confer ecological resilience. Attributes from these studies were filtered by a series of criteria including being in relation to climate change or climate impacts, being typical of more than one ecosystem or species, being distinct from other attributes, and being measurable. 45 resilience attributes remained after filtering. The authors classified the 45 attributes into five categories equating to ecological scale. The intention of the attribute classifications is to allow for the creation of decision support tables by using a filtering function so that practitioners can identify resilience attributes that are best suited to their specific project. Decision support tables can be sorted according to the practitioner's project priorities and desired project scale to create sub-lists of resilience attributes that are more likely to be relevant to the specific plan or project. The paper found that seven studies examined or included attributes of salt marshes.

APPENDIX B: MAPS FOR MODELING RESULTS

B.1.1 Waquoit Bay Marsh

Figure B-1 to **Figure B-4** show the mapped results for Waquoit Bay for one-meter global sea level rise by 2100. Comparing **Figure B-1** to **Figure B-3** shows how the presence of a marsh in 2040 protects areas. Comparing **Figure B-2** and **Figure B-4** shows the same for 2070. The implications of these modeled results are interpreted in the previous sections.

Figure B-1: Waquoit Bay marsh in 2040 with one meter of global sea level rise by 2100 and marsh present

Figure B-2: Waquoit Bay marsh in 2070 with one meter of global sea level rise by 2100 and marsh present

Figure B-3: Waquoit Bay marsh in 2040 with one meter of global sea level rise by 2100 and no tidally influenced marsh

Figure B-4: Waquoit Bay marsh in 2070 with one meter of global sea level rise by 2100 and no tidally influenced marsh

Figure B-5: Waquoit Bay marsh in 2040 with two meters of global sea level rise by 2100 and marsh present

Figure B-6: Waquoit Bay marsh in 2040 with two meters of global sea level rise by 2100 and no marsh present

Figure B-7: Waquoit Bay marsh in 2070 with two meters of global sea level rise by 2100 and marsh present

Figure B-8: Waquoit Bay marsh in 2070 with two meters of global sea level rise by 2100 and no marsh present

B.1.2 Buzzards Bay Marsh

In contrast to the Hundred Acre Cove Marsh, there are obvious differences in inundation frequency across marsh and sea level rise scenarios and over each time period for the Buzzards Bay marsh. **Figure B-9** and **Figure B-10** show expected inundation frequency in 2040 and 2070 given one meter of GLSR by 2100 with salt marsh present. **Figure B-11** and **Figure B-12** depict expected inundation frequency in 2040 and 2070 given one meter of GLSR by 2100 without salt marsh present. **Figure B-13** and **Figure B-15** describe expected inundation frequency in 2040 given two meters of GLSR by 2100 with and without salt marsh present. **Figure B-15** and **Figure B-16** show expected inundation frequency in 2070 given one meter of GLSR by 2100 with and without salt marsh present.

Figure B-9: Buzzards Bay marsh in 2040 with one meter of global sea level rise by 2100 and marsh present

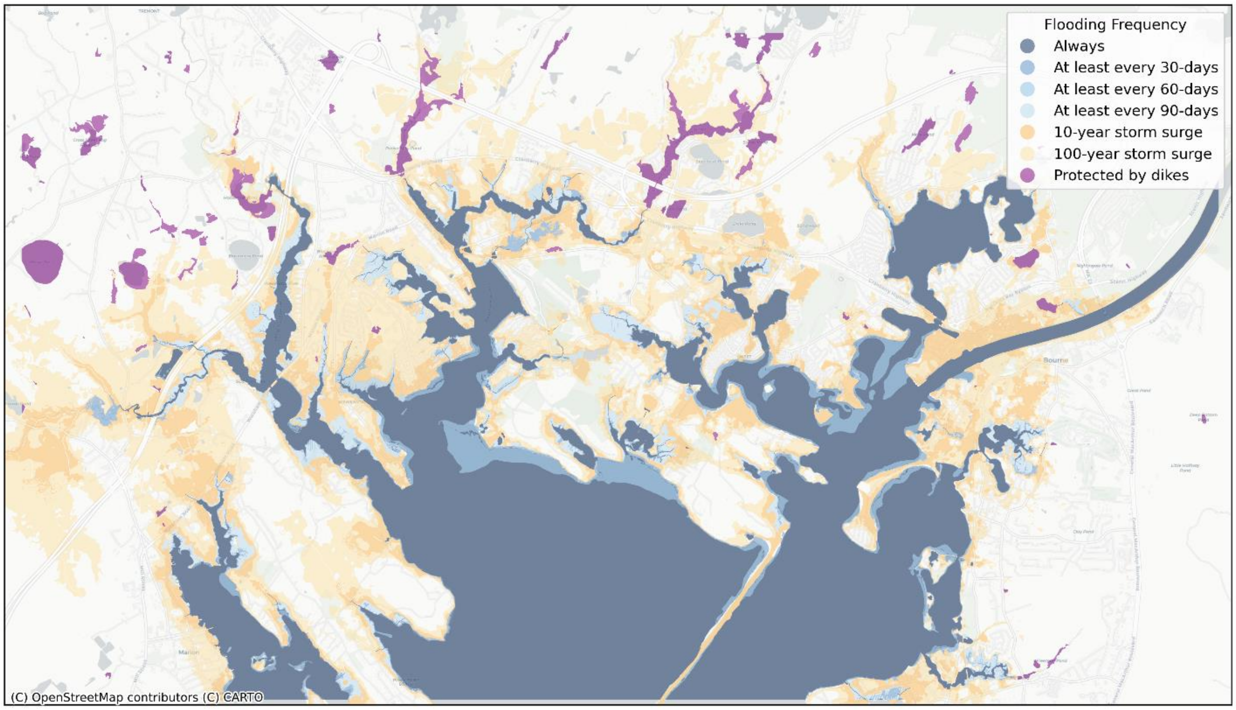


Figure B-10: Buzzards Bay marsh in 2070 with one meter of global sea level rise by 2100 and marsh present

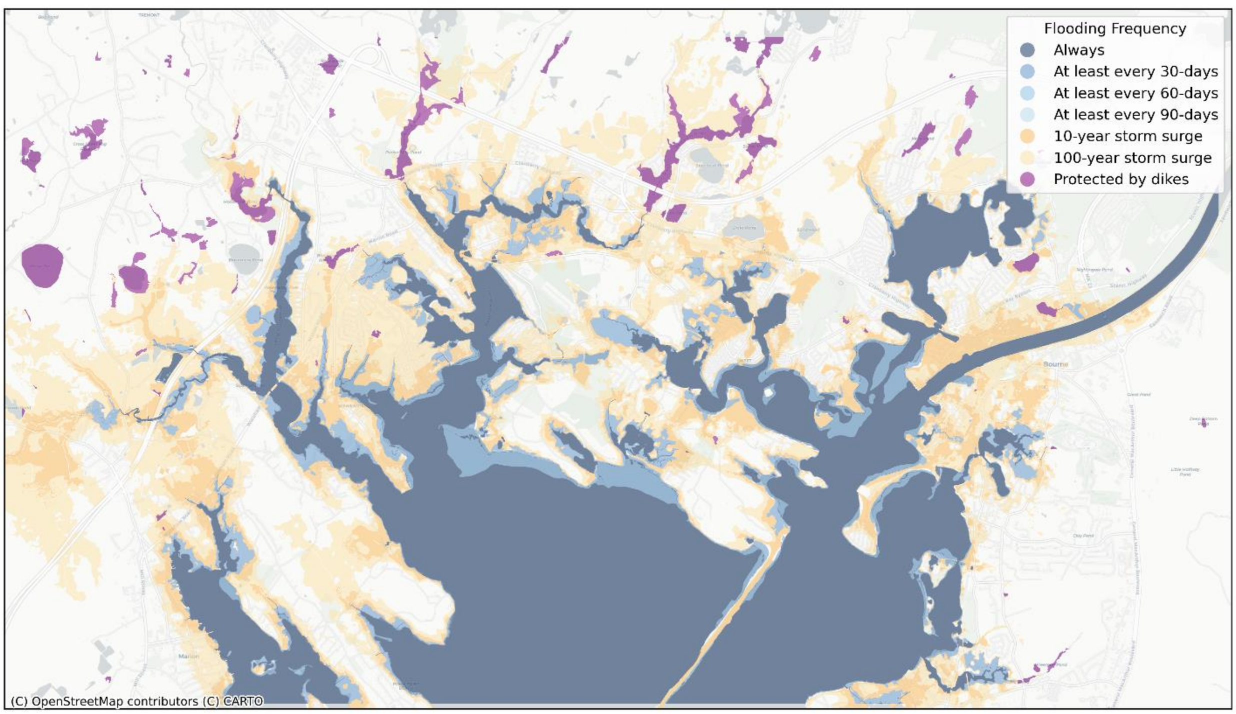


Figure B-11: Buzzards Bay marsh in 2040 with one meter of global sea level rise by 2100 and no tidally influenced marsh

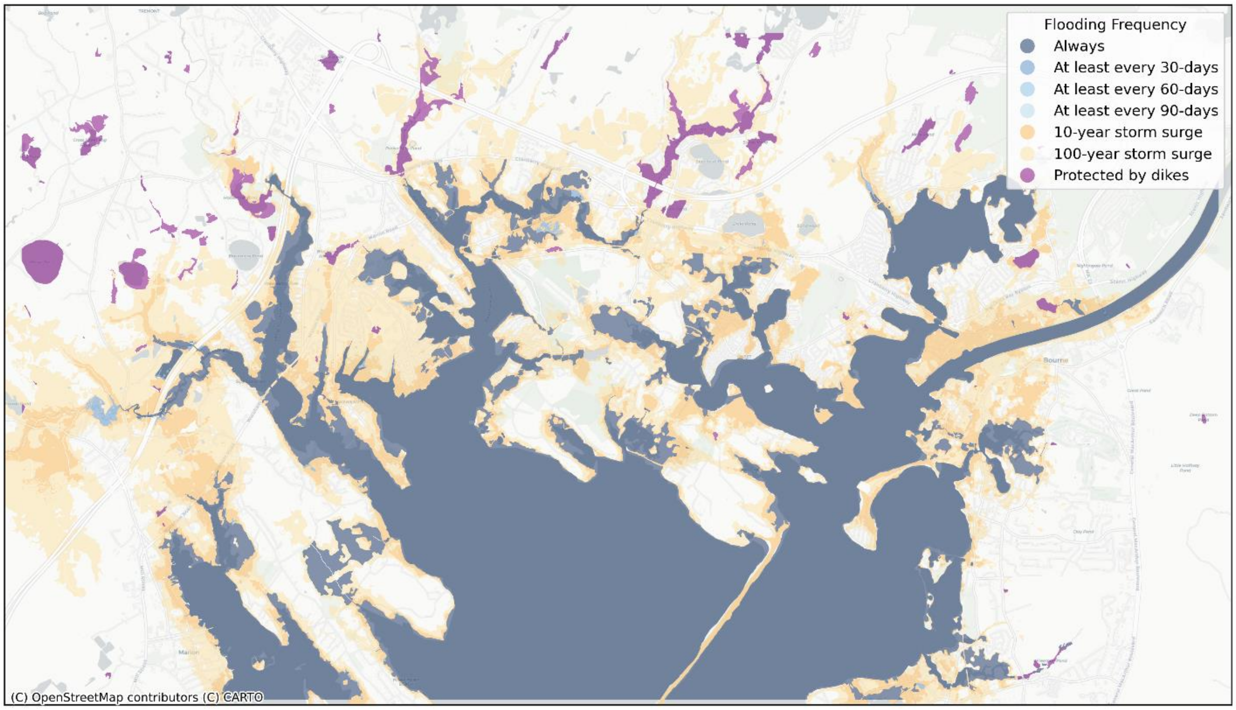


Figure B-12: Buzzards Bay marsh in 2070 with one meter of global sea level rise by 2100 and no tidally influenced marsh

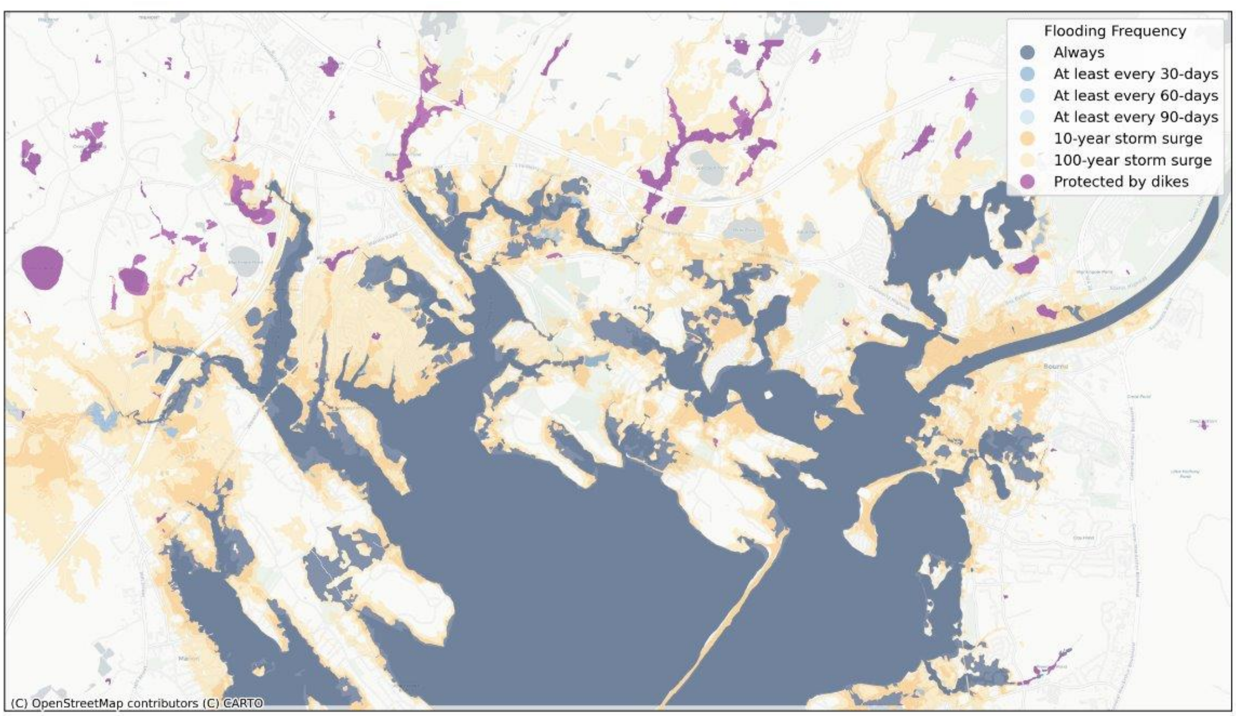


Figure B-13: Buzzards Bay marsh in 2040 with two meters of global sea level rise by 2100 and marsh present

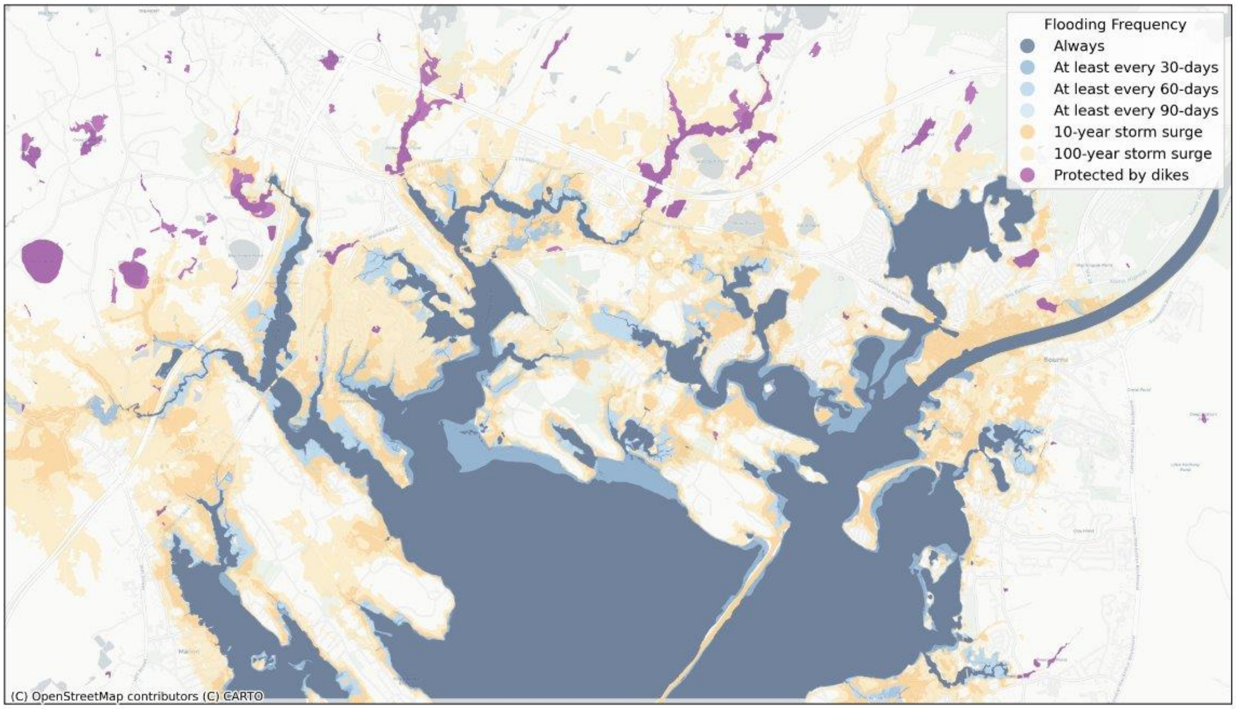


Figure B-14: Buzzards Bay marsh in 2040 with two meters of global sea level rise by 2100 and no marsh present

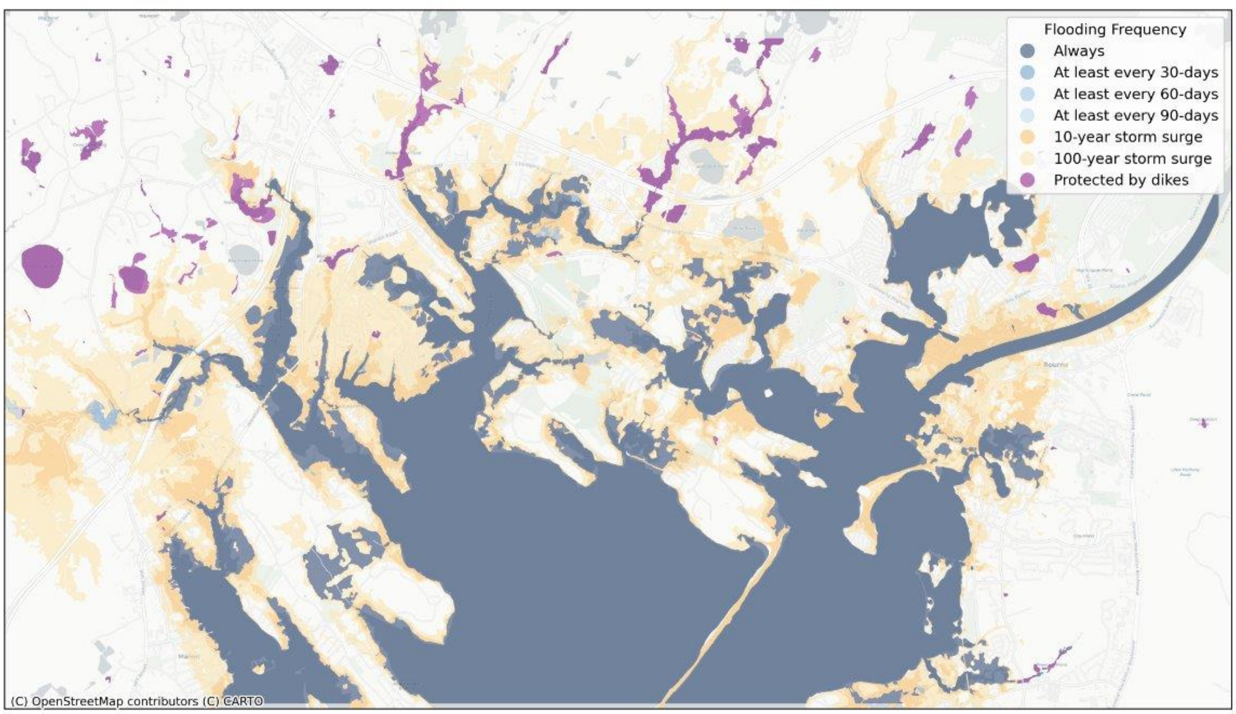


Figure B-15: Buzzards Bay marsh in 2070 with two meters of global sea level rise by 2100 and marsh present

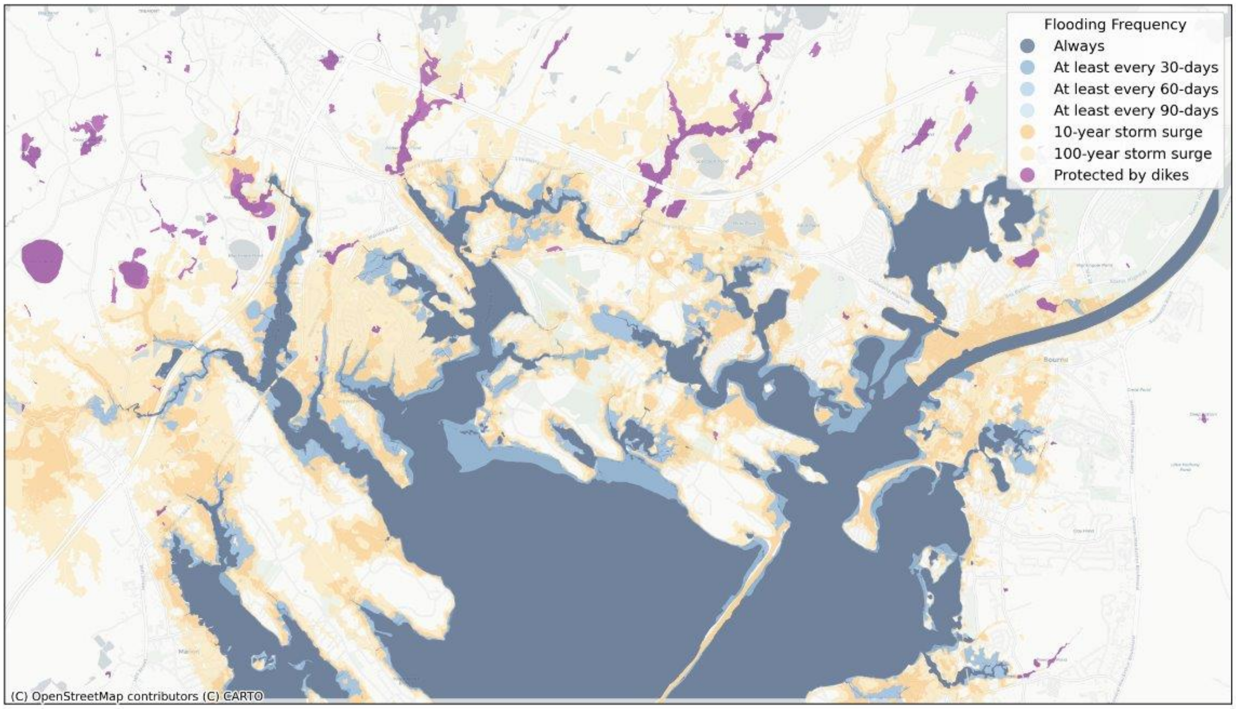
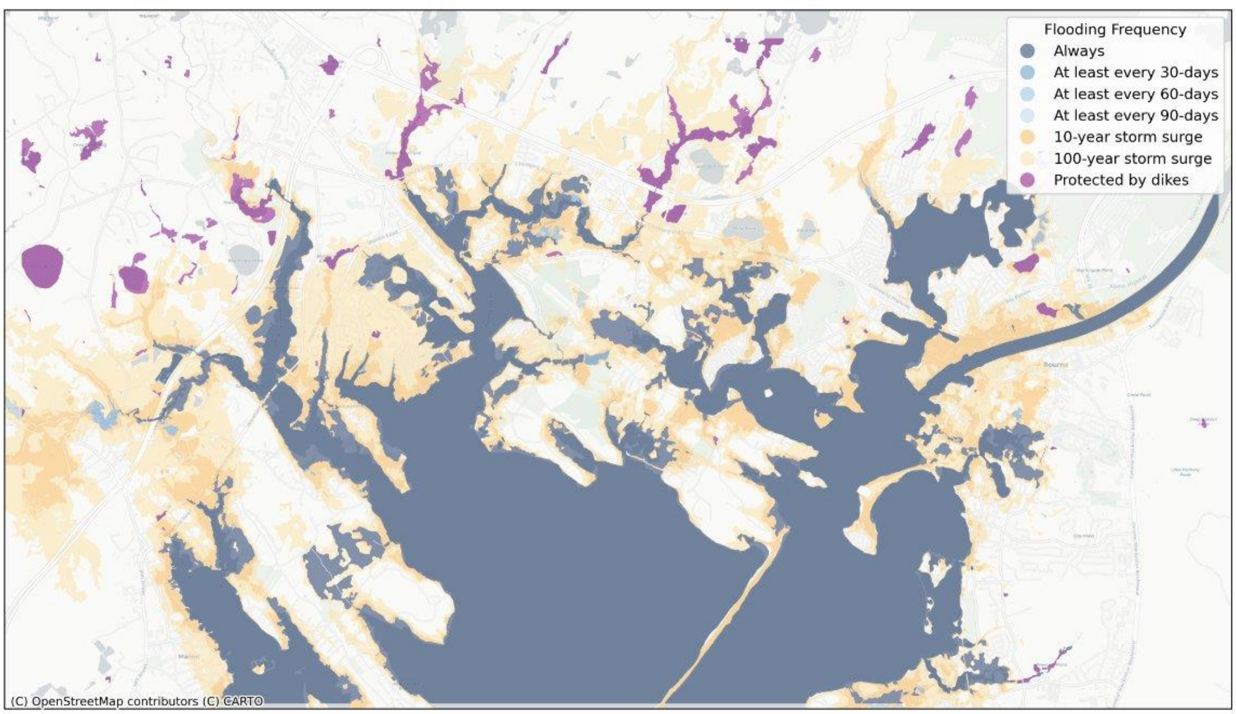


Figure B-16: Buzzards Bay marsh in 2070 with two meters of global sea level rise by 2100 and no marsh present



B.1.3 Hundred Acre Cove Marsh

Flooding inundation in the Hundred Acre Cove marsh varied little within each marsh scenario. For example, the inundation maps across the "marsh present" scenario for 2040 and 2070 for one meter of global sea level rise and for 2040 for two meters of global sea level rise, appears largely the same. This is also true for the scenario without tidal marsh habitat present. The only results that differed from the 2040 with one meter of global sea level rise, shown in **Figure B-17** was the 2070 two meters of global sea level rise scenario, shown in **Figure B-18**.

The limited difference across marsh and sea level rise scenarios at Hundred Acre Cove may be due to the elevation and topography of the region. **Figure B-19** shows the elevation that is less than 6 m (about 20 ft) above sea level. From the map, it is clear that the areas higher than 6 m create a boundary of which areas the marsh can be inundated. Although the inundation categories stay largely the same across sea level rise scenarios, the depth and duration of that inundation would likely increase. However, the SLAMM model does not measure these factors.

Figure B-17: Hundred Acre Cove marsh in 2040 with one meter of global sea level rise by 2100. The marsh present scenario is displayed on the left and the scenario with tidally influenced marsh habitat replaced with open water is shown on the right. These maps are also reflective of the modeling results for 2070 with one meter of global sea level rise and 2040 with two meters of global sea level rise

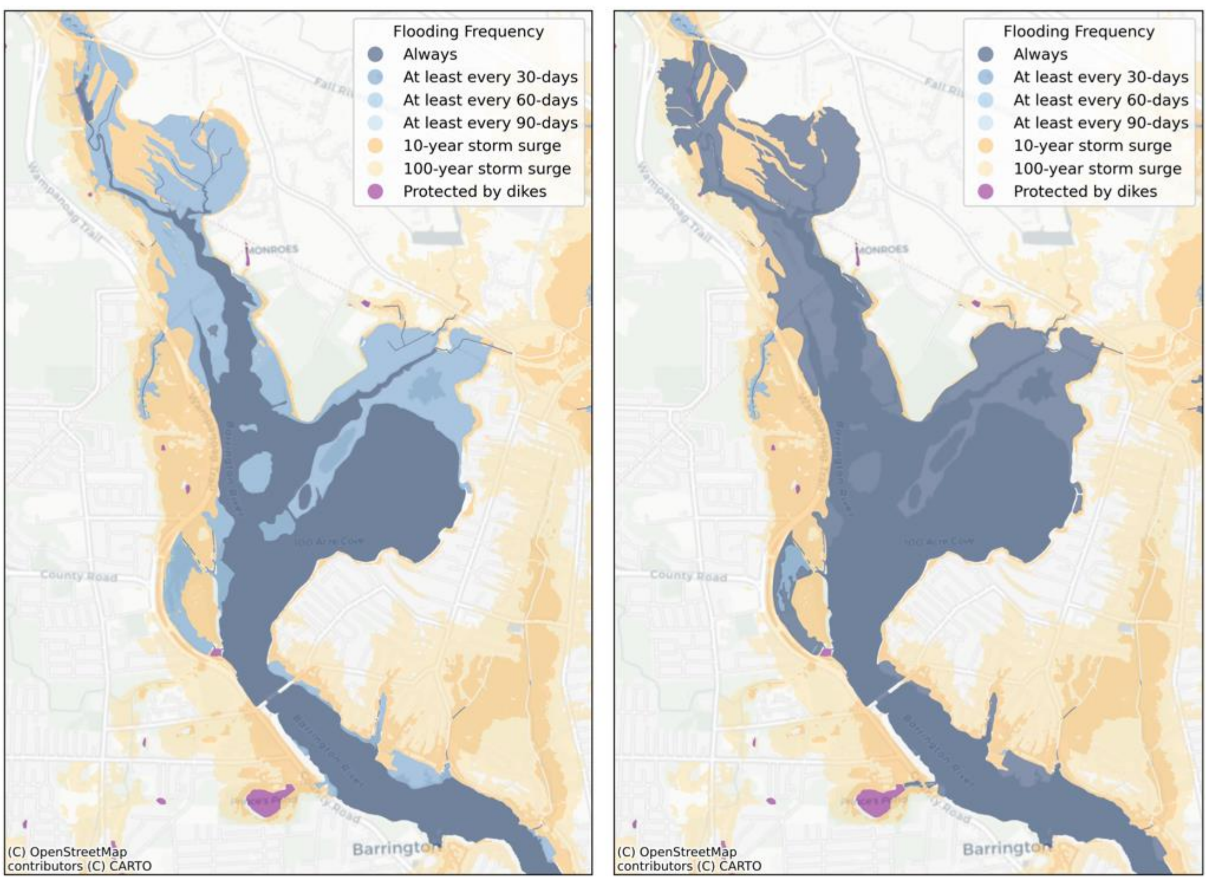


Figure B-18: Hundred Acre Cove marsh in 2070 with two meters of global sea level rise by 2100. The marsh present scenario is displayed on the left and the scenario with tidally influenced marsh habitat replaced with open water is shown on the right

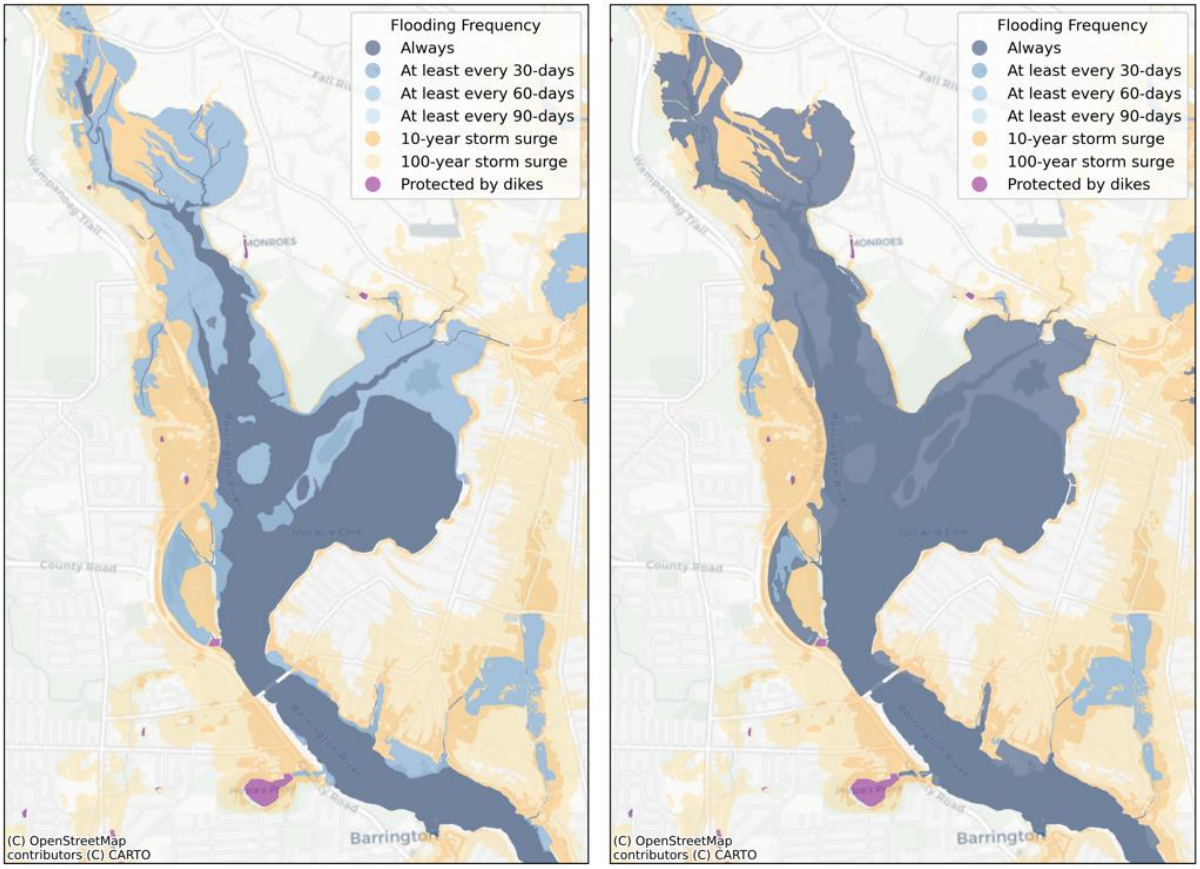


Figure B-19: Hundred Acre Cove marsh in 2040 with one meter of global sea level rise by 2100 (left) compared to the elevation under six meters (19.7 ft) around the marsh (right)