

Report of the Massachusetts Coastal Erosion Commission

Volume 2: Working Group Reports

December 2015

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Erosion Impacts Working Group
Report to the Coastal Erosion Commission

Erosion Impacts Working Group Members

Rebecca Haney, MA Office of Coastal Zone Management, Co-Chair
Richard Zingarelli, MA Department of Conservation and Recreation, Co-Chair
Scott MacLeod, MA Emergency Management Agency
Sarah White, MA Emergency Management Agency

Erosion Impacts Working Group Tasks

A Coastal Erosion Impacts Working Group was established to address the following three tasks assigned by the Coastal Erosion Commission:

1. Assist the Commission in making an appraisal of the financial amount of damage to property, infrastructure, and beach and dune resources which has been sustained from 1978 to the present
    A. Inventory available data sources and information.
2. Assist the Commission in making a reasonable estimate of the value of damages likely to occur in the next 10 years by:
    A. Use Science/Technical Working Group best advice on erosion estimates in the next 10 years.
    B. Develop and apply method to estimate impacts.
3. Assist the Commission by providing preliminary suggestions as to potential Commission recommendations or strategies related to continued or new efforts and methods to characterize and assess financial impacts of storm damage to property, infrastructure located on bank, beach, and dune resources.

This report describes approaches taken by the working group to address these tasks, and presents the information compiled by the working group.

Task 1A: Assist the Commission in making an appraisal of the financial amount of damage to property, infrastructure, and beach and dune resources which has been sustained from 1978 to the present by providing an inventory of available data sources and information.

Inventoried available data sources

The work group reviewed available and potential source of financial damage data, estimates of damages by location, post-storm damage reports, repair records, etc. The work group contacted the following organizations and groups to assess what damage data and other related information may be available.

MA Emergency Management Agency
Federal Emergency Management Agency
MA Division of Insurance
MA Executive Office of Housing & Economic Development
Institute of Business and Home Safety
Insurance Information Institute
American Insurance Association
FM Global
CERES
Town of Chatham
Town of Scituate
Town of Hull
Town of Salisbury

The following programs, data, reports, and records from the various agencies and organizations reflect the current sources of available information related to damages.

Federal Disaster Assistance Programs

The Massachusetts Emergency Management Agency (MEMA) works with the Federal Emergency Management Agency (FEMA) primarily on the following three disaster recovery programs, described below. These programs are triggered when the state experiences a disaster or event that exceeds its capacity and expressed dollar damage thresholds set by FEMA or Small Business Administration (SBA). The State conducts an assessment (described in more detail in Attachment 1) to determine if damages meet these requirements.

FEMA Public Assistance (PA) Program

- Cities, Towns, State Agencies and certain Private Non-Profit's are eligible for this post-disaster funding program. This assistance is not available for homeowners or businesses.
- FEMA grant assistance for disaster related costs, if declared, will cover up to 75% of the costs for damages for disaster related eligible work.
- FEMA eligible categories of work include: Debris Removal; Emergency Protective Measures; and Repair, Restoration, or Replacement of Road Systems and Bridges, Water Control Facilities, Buildings, Contents and Equipment, Utilities, and Parks, Recreational Facilities, and Other Facilities.
- MEMA manages reimbursements made through this program as a pass through to eligible applicants.

FEMA Individual Assistance (IA) Program

- A variety of assistance programs are available to provide direct FEMA grants to eligible individuals and businesses for storm related costs (not otherwise covered by insurance).
- The program includes rental assistance, home repairs to make them safe and sanitary, and replacement of household items (not covered by insurance).
- After the program is initiated, applicants apply and work directly with FEMA to receive funds.

Small Business Administration (SBA) Disaster Assistance

- Low-interest loans are made available to individuals and businesses.
- This disaster loan assistance may be used in concert with FEMA assistance.
- After the program is initiated, applicants work directly with SBA to apply and receive loan funds.

FEMA and MEMA Damage Assessment Process and Goals

The damage assessment that is undertaken by MEMA after an event is a multi-step process to determine if federal disaster assistance may be requested based on the federally established criteria. More in-depth information regarding the damage assessment process is provided in Attachment 1. Depending on the scope, magnitude, and geographic extent of the impacts from the event, the assessment may include:

- Assessment of damages to public infrastructure.
- Assessment of impacts to residential structures & businesses.

The damage assessments are meant to be a quick snapshot of estimated damage costs to facilitate the most efficient recovery and request for federal aid. A very detailed assessment would hinder the ability to provide aid as quickly as possible after a storm. Therefore, this quick evaluation does not account for all damages that occur during the event. It also will not account for damages not covered by FEMA programs such as private property damages beyond damage to the primary dwelling, such as erosion to the property.

Due to the nature of FEMA's disaster assistance programs being based on county and statewide thresholds, very localized pockets of erosion or damage from smaller coastal storms may not be large enough to warrant the collection of any damage estimates at all.

FY14 State & County Public Assistance Damage Thresholds

Table 1: Fiscal Year 2014 State & County Public Assistance Damage Thresholds. The gray shaded rows are the Coastal Counties. Damage thresholds are calculated by FEMA based on population and Consumer Price Index and are updated every Federal Fiscal Year.

COUNTY	POPULATION	THRESHOLD x $3.50
Barnstable	215,888	**$755,608**
Berkshire	131,219	**$459,266**
Bristol	548,285	**$1,918,997**
Dukes	16,535	**$57,872**
Essex	743,159	**$2,601,056**
Franklin	71,372	**$249,802**
Hampden	463,490	**$1,622,215**
Hampshire	158,080	**$553,280**
Middlesex	1,503,085	**$5,260,797**
Nantucket	10,172	**$35,602**
Norfolk	670,850	**$2,347,975**
Plymouth	494,919	**$1,732,216**
Suffolk	722,023	**$2,527,080**
Worcester	798,552	**$2,794,932**

MA Federal Disaster Declaration History

Massachusetts has had forty-one FEMA disaster declarations from 1978 to 2013. Of these, twenty-three were 'Major Disaster Declarations'—events that met or exceeded the federal thresholds, triggering all of the categories of FEMA's PA program, including permanent repairs.

Table 2: Summary of Federal Disaster Declarations for Massachusetts since 1978.
Source: https://www.fema.gov/disasters/grid/state-tribal-government/2?field_disaster_type_term_tid_1=All

Massachusetts Disaster Declaration Type (1978-2013)	**Number**
Emergency Declaration	17
Fire Management Assistance Declaration	1
Major Disaster Declaration	23
Grand Total	41

It is important to note that the events that have triggered these disaster declarations are not limited to coastal erosion events, but represent all types of hazards over a range of geographic areas across Massachusetts. Since the declarations are tracked at the county level, and not by community, it is difficult to look at past disaster declaration data to determine if an event caused coastal erosion or other damage to the immediate coast. The types of events that have triggered FEMA disaster assistance since 1978 are: Flooding, Severe Winter Storm (Nor'easter), Snow, Tornado, Tropical Storm, and Hurricane. Though it is not likely that flooding or tornado events caused coastal erosion, the other storm types may have been a significant factor.

Federal Disaster Damage Reports
Another potential source of information may be disaster damage reports from federal agencies such as FEMA and the U.S. Army Corps of Engineers (ACOE). These studies, though very detailed, are generally limited to large catastrophic events. For example there are two detailed reports from the ACOE for the Blizzard of '78 and Hurricane Bob.

Cost of Disaster Declarations
The chart below depicts the federal disaster declarations that have occurred in Massachusetts coastal counties since 1978. This list of disasters was further cross referenced with the National Flood Insurance Program claims data explained in the next section to ensure that these events did result in coastal impacts (e.g., flooding, erosion). Although these federal payments include all damages (not just coastal erosion), the chart shows the trend and magnitude of costs in present dollars to illustrate the significant cost of the 1978 and 1991 events. Those costs far outweigh the cost of the more recent, albeit more frequent and less damaging events declared in the Commonwealth.

Federal Dollars Paid for Damages

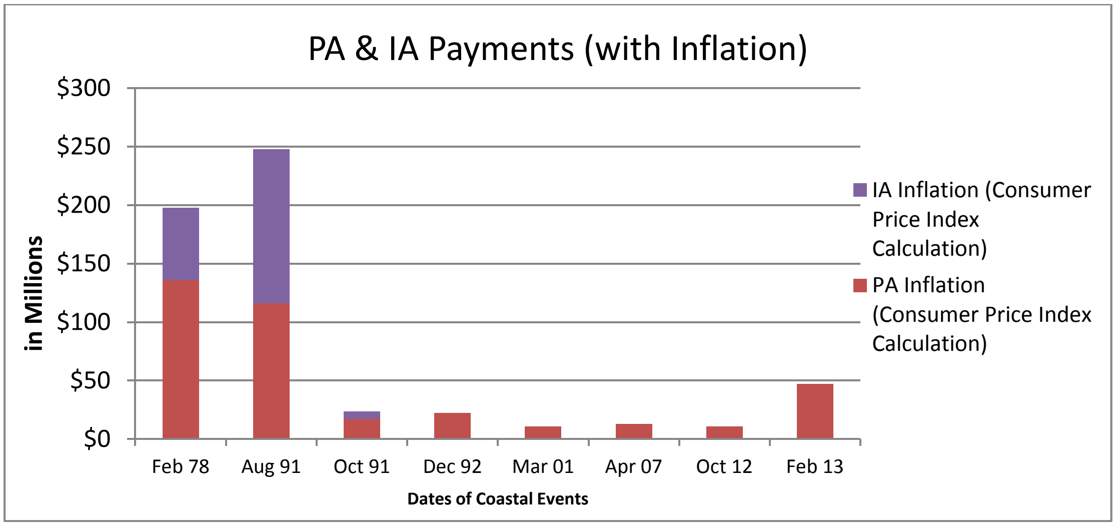

Figure 1: FEMA Disaster Declarations for Massachusetts. Data from Massachusetts Emergency Management Agency, July 2014. Note: The October 2012 and February 2013 costs are not final; FEMA is still reviewing these.

National Flood Insurance Program (NFIP) Claims Data

One readily available measure of damage from coastal events is the amount of flood insurance claims paid through the National Flood Insurance Program (NFIP). The NFIP is a federal program, administered by FEMA, which makes flood insurance available to property owners in communities that agree to adopt floodplain management regulations that will reduce future flood damages. The value of NFIP claims data as a measure of coastal damage is limited by the fact that it only includes payments made under NFIP flood insurance for damage from flooding to insured buildings and their contents. As a result, these figures do not include uninsured damages--damages that were not insured because the property did not have a flood insurance policy through the NFIP or because the damage was not covered under the policy (e.g., deductible limits, damage above the coverage amount). Additionally, damage from coastal erosion that is not directly connected with a flood event is not covered by the NFIP.

Note: NFIP claims data do not represent all damages.

Analysis of Statewide NFIP Claims Data for Coastal Communities

For this report, the data for all NFIP claims in MA from January 1, 1978 were obtained from FEMA's database and reviewed to determine which events had clusters of claims within coastal communities. To identify those events of greatest impact to coastal communities, the events were compared to the dates of the FEMA disaster declarations (referenced in the previous section of this report) and known coastal storm events with moderate to major impacts along the Massachusetts coast.

Claims totals for these events include claims for damages from both coastal and inland flooding sources (since there is no method for separating these based on the available information). While flood insurance claims are not a direct measure of the damage caused by coastal erosion, because they include damage from all flooding, the relative magnitude of the events can give insight into which events likely had the greatest damage from coastal erosion.

The claim totals for each event were converted to constant 2014 dollar values through the use of the Consumer Price Index. The figures below show trends and magnitude of costs to illustrate the relative significance of individual events. The cost of the 1978 and 1991 events far exceeds the cost of more recent events. The more recent events appear to be more frequent, but much less damaging than the earlier events. This does not rule out the fact that Massachusetts will experience another very severe coastal storm that will result in very high damages.

Table 3. NFIP Claim Totals by Event for Coastal Communities

Coastal Flood Event	NFIP Claims - 2014 $
February 1978	72,424,237
January 1987	10,109,639
August 1991	76,160,852
October 1991	142,561,430
December 1992	29,954,478
March 2001	2,996,426
January 2003	2,535,020
April 2007	5,043,333
December 2010	8,539,816
October 2012	2,182,738
February 2013	14,399,292
March 2013	2,898,741
Total for All Events	369,806,003

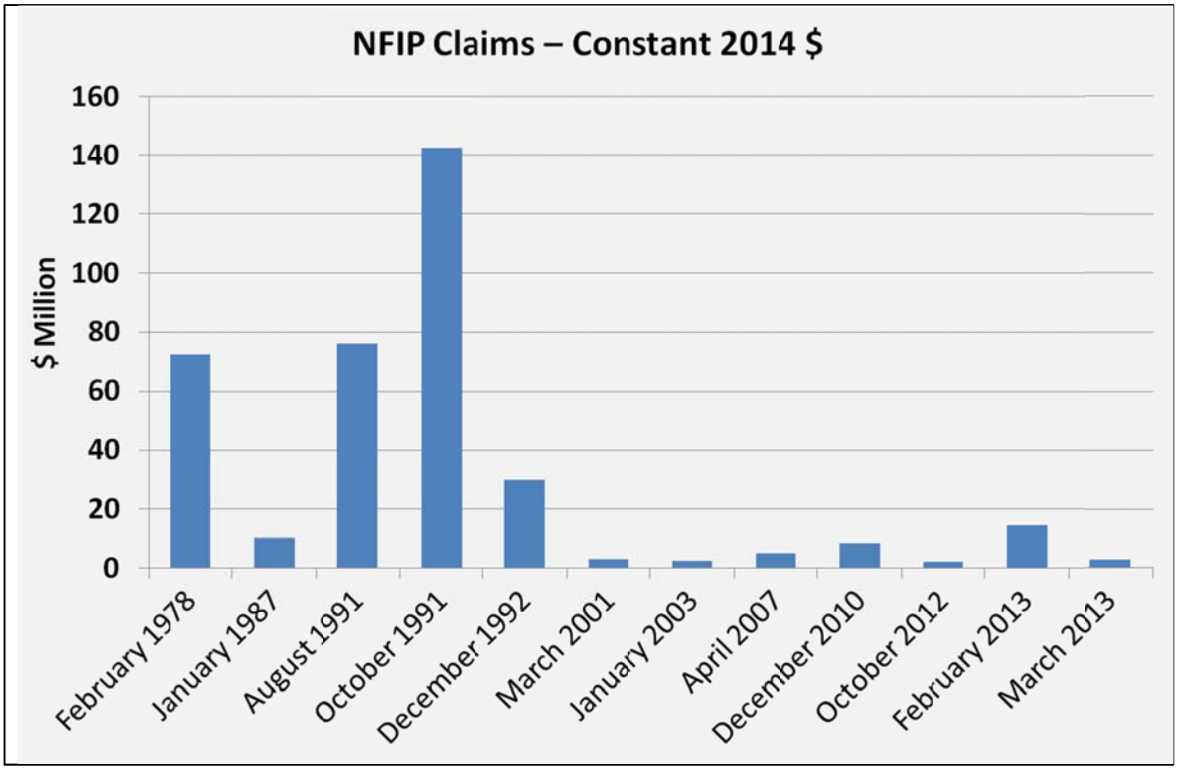

Figure 2: Massachusetts NFIP Claims in Coastal Communities (Constant 2014 dollars) Source: DCR Flood Hazard Management Program, July 2014.

Analysis of NFIP Claims Data for Individual Coastal Communities

Claims data for individual communities were also analyzed to examine the relative impact of various storms. This analysis noted a distinctly different pattern for communities with primarily northeast-facing coastlines. Those communities with northeast-facing shorelines are susceptible to significant damage on a frequent basis (sometimes even more than once in a given year) from northeasters. Communities with shorelines that do not face northeast may be subject to damage only from a specific subset of storms, particularly hurricanes. These patterns are illustrated using the distribution of damage within a northeast-facing community (Scituate) as compared to a south facing community (Wareham).

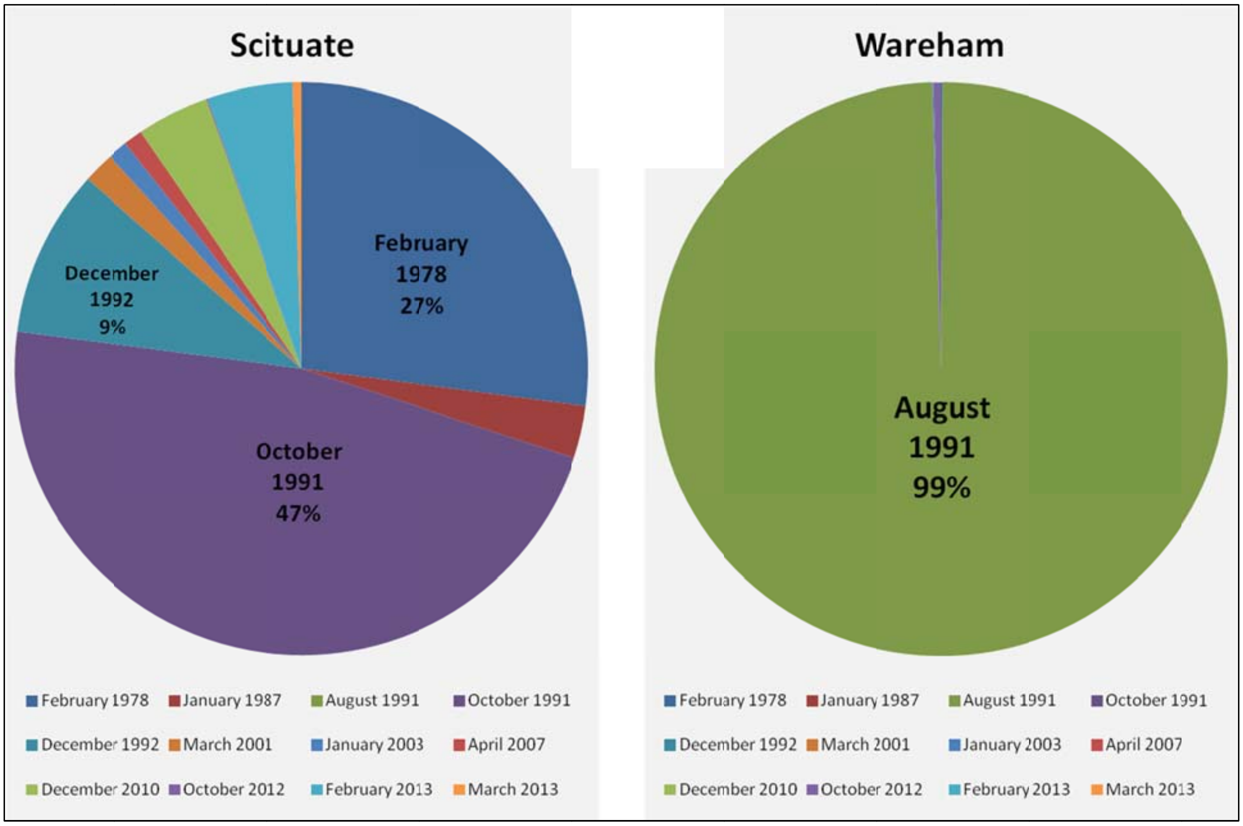

Figure 3: Distribution of claims by event in selected communities (constant 2014 dollars). Source: DCR Flood Hazard Management Program, July 2014.

Conclusions from NFIP Claims Data

In summary, a few conclusions can be made from the NFIP claims data regarding the damage from flooding as a result of coastal storms, which would also be true of the damage from coastal erosion:

- The frequency and magnitude of damage differs greatly with shoreline orientation.
  - Northeast-facing shorelines are susceptible to significant damage on a frequent basis, sometimes more than once in a given year.
  - Other areas may be subject to damage only from a specific subset of storms—particularly hurricanes.
- The coastal events with the highest damage claims occurred in 1978, 1991, and 1992.
- In recent years, significant storm damage has occurred on a more frequent basis but not to the magnitude of the 1978, 1991, and 1992 storms.

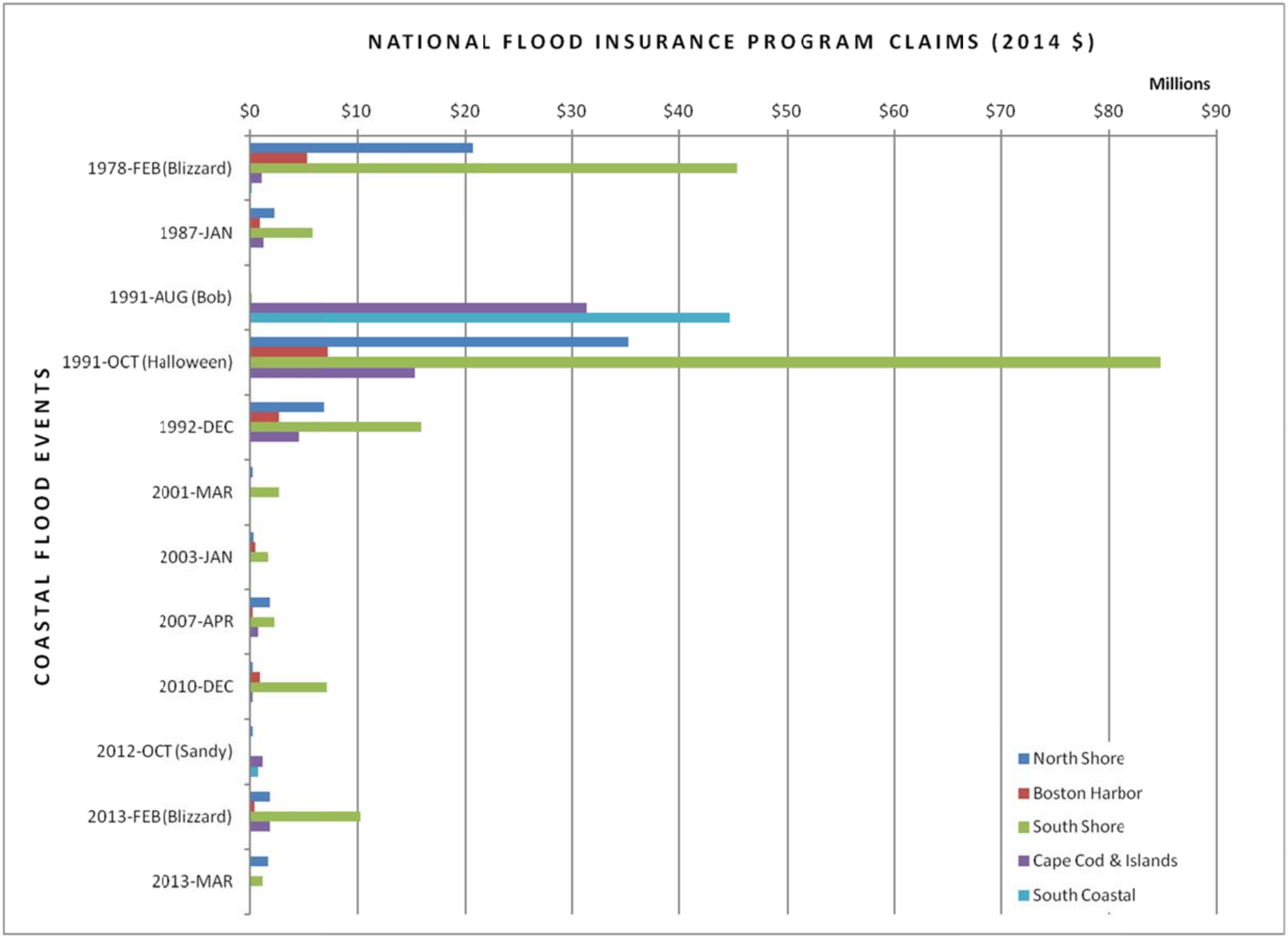

Figure 4: National Flood Insurance Program Claims (in constant 2014 dollars) by coastal flood event and region.

Task 2A and 2B: Assist the Commission in making a reasonable estimate of the value of damages likely to occur in the next 10 years by using Science/Technical Working Group best advice on erosion estimates in the next 10 years and developing and applying method to estimate impacts.

Coastal Erosion Risk Assessment: 2013 MA State Hazard Mitigation Plan

To assess all natural hazards that have occurred or could occur in Massachusetts, the State Hazard Mitigation Plan (SHMP), updated in 2013 and maintained by MEMA and DCR in coordination with interagency partners, contains a complete Threat Hazard Identification and Risk Assessment (THIRA) and vulnerability assessment. This plan is reviewed and submitted to FEMA for approval every 3-5 years.

For the Coastal Erosion Hazard, as with others, an assessment of the exposure of the state-owned and leased facilities was conducted with data provided by Department of Commonwealth Asset Management & Maintenance (DCAMM) and the Office of Leasing. Using ArcMap GIS software, the selected Massachusetts Department of Environmental Protection (DEP) coastal resource areas (wetland types) were overlaid with the state facility data to estimate the number of state facilities exposed to coastal erosion. The estimates for state building replacement costs in those zones are $82 million.

To determine the exposure of the general building stock exposed to coastal erosion, Hazus-MH[1] analysis was used. This analysis determined the default general building stock inventory (through 2000 U.S. Census block centroids) that are within identified MassDEP coastal resource areas (wetland types) and that are vulnerable to coastal erosion. Based on this analysis conducted for the 2013 SHMP update, it is estimated that more than $7.2 billion of building (structure and content) replacement cost value is exposed to the coastal erosion hazard.

> PLEASE NOTE: The replacement cost value of building stock exposed to coastal erosion determined by Hazus-MH is the full replacement value of the property exposed to the potential loss. This estimate is considered high because coastal erosion generally occurs in increments of inches to feet per year along the coastline (individual storms could result in much more erosion) and would not occur across the entire coastal resource area at the same

[1] Hazus-MH is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods and hurricanes. Hazus uses Geographic Information Systems (GIS) technology to estimate physical, economic and social impacts of disasters. It graphically illustrates the limits of identified high-risk locations due to earthquake, hurricane and floods. For more information visit: www.fema.gov/hazus

Figure 3: Summary of the building inventory exposed to the coastal erosion hazard by County. NOTE: These values represent the value of all buildings within coastal resource areas vulnerable to coastal erosion (barrier beach, coastal beach, coastal dune, coastal bank, rocky intertidal shore, salt marsh, and tidal flat) and not what would sustain damages in future coastal events during the next 10 year period.

REPLACEMENT COST VALUE EXPOSED TO THE COASTAL EROSION HAZARD			
Total Building and Content Statewide		**Replacement Cost Value in MassDEP coastal resource areas (wetland types)**	
County	**Replacement Cost Value**	**Value**	**% of Total**
Barnstable	$47,450,250,000	**$1,310,985,000**	2.8
Berkshire	$20,566,219,000	**—**	—
Bristol	$74,946,506,000	**$293,940,000**	0.4
Dukes	$4,894,499,000	**$64,469,000**	1.3
Essex	$100,099,771,000	**$1,697,707,000**	1.7
Franklin	$10,130,548,000	**—**	—
Hampden	$67,212,508,000	**—**	—
Hampshire	$20,961,384,000	**—**	—
Middlesex	$244,161,008,000	**—**	—
Nantucket	$3,610,072,000	**$55,594,000**	1.5
Norfolk	$111,344,832,000	**$609,038,000**	0.5
Plymouth	$70,614,087,000	**$2,460,079,000**	3.5
Suffolk	$115,439,212,000	**$764,897,000**	0.7
Worcester	$112,858,251,000	**—**	—
Total	**$1,004,289,147,000**	**$7,256,709,000**	**0.7**

Estimating Damage Over the Next Ten Years

Given the limitations of the available data in the State Hazard Mitigation Plan regarding vulnerability to erosion hazards, this Working Group requested assistance from the Science and Technology Working Group regarding the most appropriate methodology to use in estimating the expected erosion over the next ten years. Members of the Erosion Impacts Working Group participated in a meeting of the Science & Technology Working Group on July 30, 2014. That Working Group is testing a methodology that may more accurately estimate the amount of erosion that is likely to occur in the next ten years. The Erosion Impacts Working Group is waiting for the results of the test applications of this methodology.

Once we have an estimate of the erosion likely to occur in the next ten years, spatial analysis can be conducted to develop an estimate of potential losses due to coastal erosion.

Task 3: Assist the Commission by providing preliminary suggestions as to potential Commission recommendations or strategies related to continued or new efforts and methods to characterize and assess financial impacts of storm damage to property and infrastructure located on bank, beach, and dune resources.
Preliminary Recommendations to the Commission

The Erosion Impacts Working Group provides the following preliminary recommendations to the Coastal Erosion Commission as necessary measures to better estimate the damage caused by coastal erosion:

- Establish inter-agency agreements with Federal Partners (e.g., U.S. Geologic Survey, U.S. Army Corps of Engineers) for disaster damage reports (detailed post-disaster assessments summarizing damages).
- Install more tide gauges to supply more data points across the MA coastline.
- Enhance the ability to segregate erosion damage from other hazards (such as flooding or wind damages).
- Work with insurance and business organizations on behalf of the more than 70% of the MA coastline that is privately owned, to better understand damage caused by erosion.

MASSACHUSETTS EMERGENCY MANAGEMENT AGENCY (MEMA)

OVERVIEW OF PROCESS TO DETERMINE ELIGIBILTY FOR FEDERAL DISASTER ASSISTANCE

In the days and weeks following the emergency response to severe storms, the Massachusetts Emergency Management Agency (MEMA) may look to cities, towns and State agencies to assess the impacts to help determine whether federal disaster assistance may be warranted. Immediately following the emergency response phase of saving lives and protecting property, the Massachusetts Emergency Management Agency will turn its attention to longer-term recovery issues, including evaluating whether the state and any of its cities and towns are eligible for federal financial assistance under a presidential disaster declaration.
As part of this process, MEMA will work with state and municipal emergency management partners to determine eligibility for federal assistance under the following disaster assistance programs:

- **Public Assistance (PA)** as part of a Major Disaster Declaration resulting from a Severe Winter Storm;
- **Individual Assistance (IA)** as part of a Major Disaster Declaration resulting from a Severe Winter Storm; and
- **Low interest loans** to individuals, families and businesses as part of a Small Business Administration (SBA) Disaster Declaration.

This information is intended to provide a general overview of the damage assessment process, and the types of federal disaster assistance that may be made available if the required thresholds and criteria are met. This memorandum is not intended to be an exhaustive list of all of the requirements associated with administration of these federal programs, but rather an introduction to the process. Should federal disaster assistance be provided, MEMA will coordinate more detailed applicant briefings for local officials and state agencies to explain program requirements, provide additional guidance, and detail the reimbursement process.

<u>Initial Damage Assessments (IDA)</u>

The first step in determining the state's potential eligibility for federal disaster assistance under any of these programs is to initiate the Initial Damage Assessment (IDA) process. MEMA will send IDA forms to all municipal emergency management directors and state agencies in the damage area, with a request that the forms be completed and returned to MEMA over the following ten days. The IDA forms ask for initial estimates of storm related costs and damages in the following categories:

- Debris clearance and removal, including overtime and equipment costs associated with clearing downed trees, limbs and poles from roadways, sidewalks and public infrastructure;

- Emergency response and protective measures, including first responder overtime and equipment costs, fuel costs, shelter costs, etc.
- Repair and replacement costs associated with storm damage to roads, bridges, seawalls, piers, culverts, towers, government owned buildings, and other public infrastructure;

The IDA form also will ask local Emergency Management Directors to identify privately owned homes and businesses that were damaged or destroyed during the storm, and to estimate the extent of the damage (affected, minor, major, destroyed), and, if known, whether the repair or replacement costs will be covered by insurance.

Emergency management directors and state agencies are familiar with the IDA process - - it has been utilized in each of the natural disasters that have hit the state over the past few years. As part of this IDA process, MEMA may host a technical assistance conference call for emergency management directors, other municipal officials, and state agencies, to provide guidance and answer questions on the IDA process.

The IDA process is not onerous. MEMA understands and expects that rough estimates will be provided and that it is too soon to ask for solid cost figures. MEMA, in collaboration with FEMA, uses the results of the IDA's to evaluate the likelihood of the state being eligible for disaster assistance under some or all of the four disaster assistance programs mentioned earlier.

Preliminary Damage Assessments

Once the results of the IDAs have been analyzed, MEMA, in conjunction with FEMA, may conduct more detailed Preliminary Damage Assessments (PDAs) to verify reported costs and further determine if there is any likelihood that the state will be eligible to request federal disaster assistance under some or all of the assistance programs mentioned earlier. The PDA process builds on the IDA's and gathers more detailed cost and damage information.

The PDA process entails sending damage assessment teams, comprised of state and federal technical experts, to those communities and state agencies that have reported the most significant storm related costs and damages on the IDA forms. PDA's will not be conducted in each and every community – generally assessments are completed for those areas that reported the most significant costs with the goal of exceeding federal damage dollar thresholds as quickly as possible in support of a request for federal disaster assistance. During these field visits, the MEMA/FEMA PDA teams will view damage and debris, as well as examine local and state financial records, for the purpose of better quantifying the impacts of the storm and gathering the cost and damage information. This information will be used to determine the state's eligibility for disaster assistance and, if appropriate, will be included in the Governor's request for disaster assistance.

Depending on the scope, magnitude and extent of the disaster event, the PDA process can take anywhere from several days to several weeks to complete.

Disaster Assistance Thresholds

Each of the disaster assistance programs mentioned earlier has cost or damage thresholds that must be met as part of the state's application for federal disaster assistance. Those thresholds, and the assistance that is available under each program, are briefly summarized below.

Public Assistance (PA) under a Major Disaster Declaration Resulting from a Severe Winter Storm.

- Under the PA program, FEMA will reimburse cities and towns, state agencies, and certain non-profits for up to 75% of their eligible storm related costs, including emergency protective measures, debris removal, and repair of damage to roads, sidewalks, bridges, seawalls, piers, culverts, towers, government owned buildings, and other public infrastructure. FEMA's PA program will only consider damage and repair costs directly attributable to this storm event, and is not intended to address pre-disaster damage or deferred maintenance issues.
- FEMA PA assistance is provided on a county-by-county basis. If a county receives a PA disaster declaration, then reimbursement is provided to all cities and towns in that county, and to state agencies for their storm related costs that were incurred within the county. To receive PA assistance, total eligible storm related costs within the county must exceed a population based threshold that is established by FEMA. The applicable county thresholds are listed in the table below.

COUNTY	THRESHOLD (FFY14)
Barnstable	$755,608
Berkshire	$459,266
Bristol	$1,918,997
Dukes	$57,872
Essex	$2,601,056
Franklin	$249,802
Hampden	$1,622,215
Hampshire	$553,280
Middlesex	$5,260,797
Nantucket	$35,602
Norfolk	$2,347,975
Plymouth	$1,732,216

COUNTY	THRESHOLD (FFY14)
Suffolk	$2,527,080
Worcester	$2,794,932

- Once counties are identified as having met or exceeded individual county PA cost thresholds, the aggregate costs of these counties are calculated to determine if the statewide cost threshold has also been met. These counties can be deemed eligible under the PA program only if the statewide threshold, currently $9,101,204, is met or exceeded.

Individual Assistance (IA) under a Major Disaster Declaration

- The IA program provides disaster assistance to individuals, families and businesses that incurred storm related costs resulting from damage to their homes and businesses. Assistance available under the IA program may include:

    - Rental payments for temporary housing for those whose homes are uninhabitable. Initial assistance may be provided for up to three months for homeowners and at least one month for renters. Assistance may be extended if requested after the initial period based on a review of individual applicant requirements. *(Source: FEMA funded and administered.)*
    - Grants for home repairs and replacement of essential household items not covered by insurance to make damaged dwellings safe, sanitary and functional. *(Source: FEMA funded and administered.)*
    - Grants to replace personal property and help meet medical, dental, funeral, transportation and other serious disaster-related needs not covered by insurance or other federal, state and charitable aid programs. *(Source: FEMA funded at 75 percent of total eligible costs; 25 percent funded by the state.)*
    - Unemployment payments up to 26 weeks for workers who temporarily lost jobs because of the disaster and who do not qualify for state benefits, such as self-employed individuals. *(Source: FEMA funded; state administered.)*
    - Small Business Administration (SBA) low-interest loans to cover residential losses not fully compensated by insurance. Loans available up to $200,000 for primary residence; $40,000 for personal property, including renter losses. Loans available up to $2 million for business property losses not fully compensated by insurance. *(Source: U.S. Small Business Administration.)*
    - Loans up to $2 million for small businesses, small agricultural cooperatives and most private, non-profit organizations of all sizes that have suffered disaster-related cash flow problems and need funds for working capital to recover from the disaster's adverse economic impact. This loan in combination with a property loss loan cannot exceed a total of $2 million. (*Source: U.S. Small Business Administration.)*

    - Loans up to $500,000 for farmers, ranchers and aquaculture operators to cover production and property losses, excluding primary residence. *(Source: Farm Service Agency, U.S. Dept. of Agriculture.)*
    - Other relief programs: Crisis counseling for those traumatized by the disaster; income tax assistance for filing casualty losses; advisory assistance for legal, veterans' benefits and social security matters.
- Unlike the PA program which has fairly clear and objective damage/cost thresholds, the FEMA IA program has subjective eligibility thresholds. Generally, to qualify for IA disaster assistance, the state must show that hundreds of homes (primary residences) and businesses suffered significant damage or were destroyed and that insurance either is not available to the survivors or is inadequate. The IDA and subsequent PDA processes are intended to identify and quantify homes and businesses with significant damage. However, seasonal homes are not eligible and are not counted during the IDA and PDA processes.

SBA Disaster Program

- Even if the President does not issue a disaster declaration that provides FEMA Public Assistance or Individual Assistance, the Small Business Administration (SBA) may issue its own SBA Disaster Declaration if there are 25 or more homes and businesses in a county that each have suffered uninsured losses greater than 40% of total replacement cost. Under an SBA Disaster Declaration, low interest loans may be available to any individual, family or business that suffered storm related damages and meets loan eligibility requirements. SBA may also provide disaster loan assistance to communities in contiguous counties.
- The SBA also has an Economic Injury disaster program. Under this program, low interest loans are available to eligible businesses if there are at least five businesses whose business income will decrease by at least 40% as a result of a disaster.

Summary

Immediately following a disaster event, MEMA will determine whether to initiate a two-part process to determine whether the state and any of its counties are eligible for some or all of the disaster programs summarized above. The first part of the process entails municipal and state officials submitting Initial Damage Assessment (IDA) forms to MEMA.

Once the IDA forms are returned to MEMA and the results analyzed, MEMA and FEMA may conduct joint site/field visits as part of a Preliminary Damage Assessment (PDA) if the IDA results suggest that there is a likelihood of the state meeting the relevant thresholds under the different disaster assistance programs. It is important to note that once the assessment teams reach the statewide per capita indicator for the PA program, the PDA process often stops and the Governor makes a request for a Presidential Disaster declaration. As a result, PDA figures may not represent the true magnitude and economic impact of a given disaster.

Depending on the scope, magnitude and extent of the disaster event, the IDA & PDA processes can take anywhere from several days to several weeks to complete. In a catastrophic event, an expedited request for a Presidential disaster declaration from the Governor may be processed prior to conducting a formal disaster assessment; however, a PDA must be completed as soon as possible to assist with program planning and disaster assistance implementation.

Legal and Regulatory Working Group
Report to the Coastal Erosion Commission

Working Group Members:
Lealdon Langley, MA Department of Environmental Protection (MassDEP), Co-Chair
Robert Boeri, MA Office of Coastal Zone Management (CZM), Co-Chair
Jack Clarke, Mass Audubon*
Anne Herbst, Town of Hull*
Doug Packer, Town of Newbury*
Rebecca Haney, CZM
Elizabeth Kouloheras, MassDEP
Jim Sprague, MassDEP
Alex Strysky, MEPA Office

*Commission Member

Introduction

The 2014 Budget Bill included a section that established a Coastal Erosion Commission. This commission is charged to "investigate and document the levels and impacts of coastal erosion in the Commonwealth" and "develop a strategy and recommendations to reduce, minimize, or eliminate the magnitude and frequency of coastal erosion and its adverse impacts on property, infrastructure, public safety, and beaches and dunes."[1]

The Commission established three Working Groups at their first meeting on March 27, 2014. The tasks assigned to the Legal and Regulatory Working Group were as follows:

1. Assist the Commission by summarizing current rules, regulations and laws governing / related to coastal erosion.
2. Assist the Commission by providing input and feedback evaluating the current rules, regulations and laws governing the materials, methodologies and means for coastal erosion protection and how they are applied.
3. Assist the Commission by providing preliminary suggestions as to potential Commission recommendations or strategies related to possible changes, expansions, reductions and laws which would improve the ability of municipalities and private property owners to guard against or reduce or eliminate the impacts of coastal erosion without undue adverse environmental impacts.

The Legal and Regulatory Working Group met on May 22, 2014, June 19, 2014, and on July 28, 2014. The following report summarizes our progress on the assigned tasks.

[1] Acts of 2013, Chapter 38, Section 200

Task 1: Assist the Commission by summarizing current rules, regulations and laws governing / related to coastal erosion

In 2003, the Massachusetts Office of Coastal Zone Management (CZM) prepared the document titled *Environmental Permitting in Massachusetts* (see http://www.mass.gov/eea/docs/czm/fcr-regs/ma-env-permit-guide-2003.pdf). This document offers brief descriptions of the major environmental permits required for projects proposed to be located in the Commonwealth's coastal zone. It remains the most concise listing of Massachusetts statutes and regulations, with narratives that describe the permitting options to be considered. Work is underway to update the statutes, regulations, and programs in this guide to reflect changes that have taken place since 2003. When the updates are complete, a revised guide will be released.

Task 2: Assist the Commission by providing input and feedback evaluating the current rules, regulations and laws governing the materials, methodologies and means for coastal erosion protection and how they are applied.

The Working Group reviewed and evaluated current rules, regulations, and laws and has the following findings and recommendations:

1. Since the adoption of the current MA State Building Code in 2009, new best practices for reducing damage have been identified by the International Code Council for incorporation into the International Building Code and by the Federal Emergency Management Agency as part of their post-storm damage assessment program. The current MA Building Code needs to be updated to require implementation of these best practices to minimize damage to buildings and infrastructure in coastal storm events and avoid increasing coastal erosion.

2. The current regulatory framework lacks effectiveness in encouraging appropriately sited and designed beach nourishment or offshore sand mining for beach nourishment. The recently released 2015 *Massachusetts Ocean Management Plan* recognizes the growing demand for beach nourishment material and identifies potential locations for small-scale pilot projects for offshore sand excavation for beach nourishment, subject to further review of site-specific conditions. Implementation of the pilot projects proposed in the Plan serves as an important option for maintaining and increasing the ability of coastal beach and dune systems to protect landward areas from storm damage while protecting offshore habitat and resources. The current practice of offshore disposal of sand dredged from maintenance of navigation channels results in higher long-term cost to the Commonwealth, the loss of valuable sand resources for beach nourishment, and increased coastal property and infrastructure damage.

3. MassDEP created an Advisory Work Group to help address the lack of performance standards for the Wetland Resource Area, Land Subject to Coastal Storm Flowage (LSCSF). The objectives of the Advisory Work Group is to utilize the group's expertise and current research literature to help: (1) define the policy problems that arise at the intersection of climate change and LSCSF, (2) develop a framework and assessment of interests implicated by the initiative, and (3) identify potential means to address those interests in the LSCSF regulations. The implementation of guidance and performance standards for Land Subject to Coastal Storm Flowage (LSCSF) is necessary to change development practices in the flood plain that likely result in increased storm damage and coastal erosion. The LSCSF Advisory Work Group recommendations should address mechanisms to protect the beneficial functions of the floodplain and other coastal wetland resource areas to avoid or mitigate storm damage, including the effects of sea level rise.

4. Sea-level rise needs to be factored in to project siting, design and permitting. Since the enactment of the Global Warming Solutions Act of 2008, sea level rise has been factored into the MEPA review of coastal projects. This has included an analysis of the project site and proposed infrastructure and an assessment of vulnerabilities to flooding and storm surge based on existing conditions and potential conditions based on a range of sea level rise scenarios. As part of this review, measures that support adaptation and resiliency of the project have been identified to withstand a higher frequency and greater severity of storms. These include, but are not limited to assessment of alternative site designs and stormwater management, elevation of structures and location of infrastructure above the floodplain. Most regulations do not include the need to plan for and address this as part of the permitting process.

5. The existing regulations under the Wetlands Protection Act now include special provisions for the testing of new technology, including the short-term placement of temporary installations. Recent amendments to the regulations provide for a streamlined permitting process for the short-term testing of qualifying innovative water-dependent technology, including new renewable energy technologies, in areas subject to Wetlands Protection Act permitting, Chapter 91 licensing, and 401 Water Quality Certification requirements. These amendments have been interpreted broadly to include pilot projects, other than renewable energy projects, that would be small in scale and temporary in duration.

The Working Group believes that proposed regulations, with the reforms discussed above, are working to protect the beneficial functions of coastal resources and allow for innovative new technologies to be tested for the purposes of reducing coastal erosion and protecting coastal infrastructure. However, the recommendations provided under Task 3 are designed to be incorporated into reforming the regulations to further reduce the impacts of coastal erosion.

Task 3: Assist the Commission by providing preliminary suggestions as to potential Commission recommendations or strategies related to possible changes, expansions, reductions and laws which would improve the ability of municipalities and private property owners to guard against or reduce or eliminate the impacts of coastal erosion without undue adverse environmental impacts.

The Legal and Regulatory Working Group, after a thoughtful and considered process, offer the following recommendations to the Commission:

1. Continue to ensure that coastal development avoids erosion-prone areas or, if necessary, minimize impacts from coastal erosion through implementation of performance standards for development on coastal dunes, barrier beaches, coastal banks, coastal beaches, and salt marshes.
    - Incorporate the soon to be released (2015) CZM/MassDEP document *Applying the Massachusetts Coastal Wetlands Regulations – A Practical Guide for Conservation Commissions to Protect the Storm Damage Prevention and Flood Control Functions of Coastal Resource Areas* into project planning and review, and provide training for local and state personnel regarding implementation

2. Ensure that coastal development includes climate change adaptation measures:
    - Adopt the 2015 International Building Codes for structures in floodplains, including freeboard requirements for buildings in "A zones", in addition to current requirements for "V zones". This would enhance the effectiveness of the state building code and improve management in floodplains
    - Evaluate the applicability, benefits, concerns and legal authority for coastal high hazard area set-backs. According to National Oceanic and Atmospheric Administration (NOAA), two-thirds of coastal states have some type of shorefront no-build areas (setback, rolling easement, and zoning)
    - Incorporate assessment of sea-level rise impacts during regulatory review of coastal projects and evaluate alternatives that eliminate/reduce impacts to coastal resource areas and provide appropriate mitigation. MEPA presently considers sea-level rise in its evaluation of projects and EEA is currently assessing various models for the range of sea level rise for the appropriate range to be incorporated into reviews. Additional guidance or standard methods for evaluating sea-level rise would be valuable for MEPA and all permitting agencies
    - The Commission, with input from the Land Subject to Coastal Storm Flowage Advisory Work Group, should provide guidance to MassDEP as to the appropriate LSCSF performance standards that should be promulgated
    - Establish outreach training for the appropriate local, state, and federal representatives to assure that implementation of any changes to regulations that result from these recommendations are applied correctly

3. Through planning, policies, regulations, and coordination with state and federal agencies, encourage beach nourishment as a means of protecting coastal properties. The following recommendations are proposed to be included in the 2014 Update to the Ocean Plan.

    - Recommend working with local, state, and federal legislative parties to conference with USACE to change federal legislation currently requiring the "least cost option" as the base plan when working with federal navigation projects, to require beach nourishment and sediment reuse as the base plan. This change would improve the availability of compatible sand for beach nourishment
    - Develop enforceable component in MassDEP regulations in concert with federal partners to ensure beach nourishment using compatible sand when generated by these projects

4. Support the development of offshore sand excavation sites for beach nourishment. The development of these sites should include the following recommendations, some of which are incorporated into the Draft Massachusetts Ocean Management Plan – September 2014.

    - Consult with MADMF and NMFS to establish support for sand excavation and beach nourishment activities while minimizing impacts to important fish resources and providing appropriate mitigation. Currently, state and federal fisheries regulations are perceived as an impediment to these projects (Winthrop Shores).
    - Identify potential sand extraction site(s) within the Ocean Management Planning Area and federal waters, and consult with MADMF and NMFS regarding fisheries regulations pertaining to use of those sites
    - Consultation with MADMF, MANHESP, NMFS, and USFWS to develop policy and regulations, if applicable, allowing for beach nourishment to extend below MHW to optimize the width and slope of a nourished beach for longevity, shoreline protection and bird habitat while minimizing impacts to fisheries and bird habitat. A Memorandum of Understanding to streamline the process should be developed among the appropriate agencies

5. Establish testing and evaluation protocols for the review of pilot projects using new and innovative technologies for shoreline protection not previously used in Massachusetts, as allowed by the soon to be promulgated revised wetlands protection regulations. These protocols should include:

    - Establishment of a standing technical advisory working group to review the new and innovative technologies for environmental benefits that avoid adverse shoreline erosion effects
    - Robust pre- and post-monitoring studies

- A mechanism where pilot projects which show appropriate environmental benefits while avoiding adverse shoreline erosion can be incorporated into regulations with performance standards to streamline their use in future applicable locations
- Establishment of a tiered approach to permitting allowing small scale projects, such as rock sills used to protect or create salt marsh, to proceed directly to permitting
- Establishment of success/failure criteria
- Removal of and mitigation for failed pilot projects

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Science and Technology Working Group

Report to the Coastal Erosion Commission

Science and Technology Working Group Members:

Rebecca Haney, MA Office of Coastal Zone Management (CZM), Co-Chair
E. Robert Thieler, US Geological Survey, Co-Chair*
Pat Hughes, Town of Brewster*
Patricia Bowie, CZM
Marc Carullo, CZM
Jim Mahala, MA Department of Environmental Protection
Margot Mansfield, CZM
Kevin Mooney, Department of Conservation and Recreation
Dan Sampson, CZM

*Commission Members

Introduction

The 2014 Budget Bill included a section that established a Coastal Erosion Commission. This Commission is charged with investigating and documenting the levels and impacts of coastal erosion in the Commonwealth and developing strategies and recommendations to reduce, minimize, or eliminate the magnitude and frequency of coastal erosion and its adverse impacts on property, infrastructure, public safety, and beaches and dunes.

The Commission established three Working Groups at their first meeting on March 27, 2014: the Science and Technical Working Group; Erosion Impacts Working Group; and Legal and Regulatory Working Group. The tasks assigned to the Science and Technology Working Group are:

1. Assist the Commission in characterizing the Commonwealth shoreline by:
    - A. Providing an overview / summary of coastal geology and coastal processes, describing generally how sediments move, accumulate, and transport in nearshore coastal systems.
    - B. Characterizing the landforms, habitats, and developed lands at the immediate, exposed shoreline for coastal Massachusetts.
    - C. Describing ongoing efforts to inventory and track coastal shoreline engineered structures.
2. Assist the Commission in making a reasonable assessment of coastal erosion.
    - A. Describing and quantifying, where possible, past erosion trends and estimates of shoreline change.
    - B. Providing best advice on how to estimate erosion in next 10 years.
3. Assist the Commission in evaluating methodologies and means which may be used to guard against and reduce or eliminate the impacts of coastal erosion.
    - A. Developing a summary of shoreline management practices, effectiveness, and adverse impacts.
4. Assist the Commission by providing preliminary suggestions as to potential Commission recommendations or strategies related the science and technical aspects of reducing impacts of coastal erosion.
    - A. Providing recommendations regarding methodologies to map coastal hazard variables as indicators for determining higher hazard areas.
    - B. General recommendations pertaining to the science and technical aspects of reducing impacts of coastal erosion.

The Science and Technology Working Group met on July 30, 2014, September 3, 2014, and on September 19, 2014. The following report summarizes our work on the assigned tasks.

Task 1A: Assist the Commission in characterizing the Commonwealth shoreline by providing an overview / summary of coastal geology and coastal processes, describing generally how sediments move, accumulate, and transport in nearshore coastal systems.

The natural forces of wind and waves continuously shape the shorelines of Massachusetts, seeking to achieve a dynamic equilibrium between land and sea. These dynamic environments shift and change in response to relative shoreline shape and position, the availability of sediment, periodic increases in energy (wind and waves), and continuously rising sea levels. The loss (erosion) and gain (accretion) of coastal land is a visible result of the way shorelines are reshaped.

The source of sand that created and continues to feed the beaches, dunes, and barrier beaches in Massachusetts comes primarily from the erosion of coastal banks (also called bluffs). For example, the material eroded from the Atlantic-facing bluffs of the Cape Cod National Seashore supplies sand to downdrift beaches on Cape Cod (Fitzgerald, et. al., 1994).

Erosion, transport, and the accretion are continuous interrelated processes. Every day, wind, waves, and currents move sand, pebbles, and other small sediments along the shore (alongshore) or out to sea. Shorelines also change seasonally, tending to accrete during the summer months when sediments are deposited by relatively low energy waves and erode dramatically during the winter months and during coastal storms when sediments are moved offshore by high energy waves (Davis, 1997). As sea level continues to rise, inundation from coastal storms will extend further inland, causing greater erosion and flooding impacts to private and public infrastructure (Burkett & Davidson, 2012).

While erosion and flooding are necessary and natural, they do have the potential to damage coastal property and related infrastructure, particularly when development is sited in unstable or low-lying areas. Erosion and flooding are dynamic and powerful processes that can expose septic systems and sewer pipes; release oil, gasoline, and other toxins into the marine environment; sweep construction materials and other debris out to sea; or even lead to the collapse of buildings. Public safety is further jeopardized when these damages result in the contamination of water supplies, shellfish beds, or other resources.

Where engineered structures are used to stabilize shorelines, the natural process of erosion is interrupted, which can change the amount of sediment available and causing erosion to adjacent areas. Under conditions of reduced sediment supply, the ability of coastal resource areas, such as dunes and beaches, to protect landward areas from storm damage and flooding is diminished (Nordstrom, 2000). In addition, some of the Commonwealth's greatest attractions–beaches, dunes, barrier beaches, salt marshes, and estuaries—are threatened and will slowly disappear as the sand sources that feed and sustain them are eliminated.

The challenge, therefore, is to site coastal development in a manner that allows natural physical coastal processes, such as erosion to continue. Coastal managers, property owners, and developers will be better prepared to meet this challenge by understanding the magnitude and causes of erosion and applying appropriate management techniques that will maintain its beneficial functions—effectively working with the forces of erosion and not against them.

In order to inform decisions regarding shoreline management, coasts can be divided up into compartments called littoral cells. Each cell contains a complete cycle of transport, including sediment sources, transport paths and sinks. Sources of sediment contributing to the system include eroding coastal banks and dunes, sinks are often inlets or bays, and transport paths can include alongshore and onshore/offshore. A sediment budget can be estimated for each littoral cell to help understand the volume of sediment coming from the sources, the amounts being sequestered in the sinks, as well as calculations of the volume, rate and direction of sediment movement along the shoreline. Littoral cells have been mapped for Cape Cod (Berman, 2011), and the south shore from Hull to the Cape Cod Canal (ACREI, 2005). Sediment budgets have been produced for small sections of the Massachusetts shoreline, such as portions of inner Cape Cod Bay (Giese et al., 2014), the Outer Cape coast (Giese et al., 2011), and the area from the Westport River to Allens Pond in Dartmouth (ACI, 1997). Although this Working Group did not develop state-wide sediment budgets, we recognize that this information for the entire coast would greatly improve coastal manager's ability to understand the historic erosion trends and predict how the shoreline may respond to various shoreline management strategies.

For additional details on the various types of shoreline management practices, their effectiveness, adverse impacts, and relative costs, see Task 3A (page 41).

For recommendations regarding additional needs for the mapping and assessment of coastal processes, see Task 4B (page 53).

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Task 1B: Assist the Commission in characterizing the Commonwealth shoreline by characterizing the landforms, habitats, and developed lands at the immediate, exposed shoreline.

Coastal landforms, habitats, developed lands, and shore-parallel coastal engineered structures were identified at the immediate, exposed shoreline that encompasses 57 Massachusetts communities. The purpose of this exercise was to gain an understanding of the land cover and land uses potentially at risk from coastal erosion. Results will better inform coastal managers by: 1) providing a baseline from which to monitor landscape trends, and 2) identifying patterns for evaluating adaptation and mitigation strategies for a particular location or region.

This effort was aided by the CZM-USGS Massachusetts Shoreline Change Project, 2013 Update, which produced a contemporary shoreline (ca. 2007-2009) interpreted from digital orthophoto images and lidar-based digital elevation models, and integrated the shoreline with site-specific knowledge in a GIS environment. The contemporary shoreline represents a mean higher high water (MHHW) line in the more exposed areas of the shoreline and generally excludes harbors and estuaries; sections of back barrier beach were included where wave and tide processes could have an effect on shoreline movement, as determined by the Massachusetts Shoreline Change Project (see Figure 1). Maps depicting the shoreline extents used for this project (referred to here as "assessed shoreline") are included in Science and Technology Working Group Report - Appendix A.

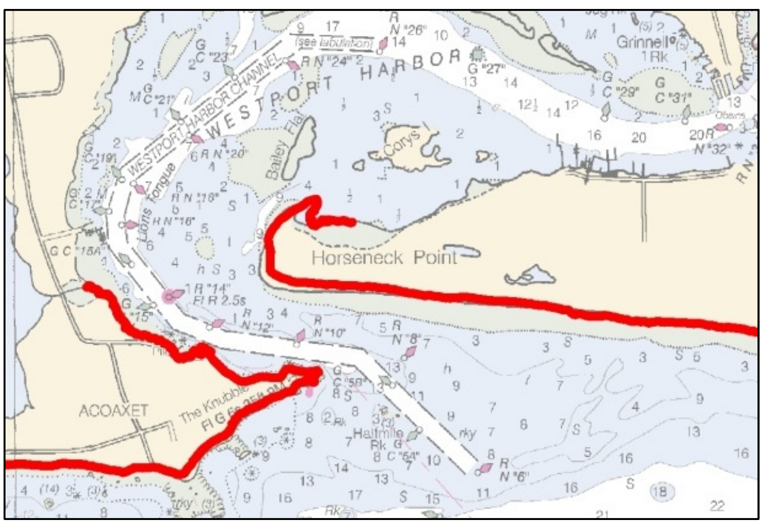


Figure 1. Assessed shoreline (red) and NOAA chart for the area around Westport Harbor. Note the assessed shoreline wraps around Horseneck Point, but does not extend east up the harbor.

Transects used to measure shoreline change rates in the Massachusetts Shoreline Change Project were adapted for this exercise to divide the shoreline into assessment units (i.e., linear segments). These transects generally occur every 50 meters along the assessed shoreline, therefore most assessment units are approximately 50 meters in length. The Massachusetts Shoreline Change Project is described in greater detail under Task 2A and on the CZM website at www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/shoreline-change.

The following GIS data layers—depicting coastal landforms, habitats, developed lands, and shore-parallel coastal engineered structures—form the basis from which we characterized the shoreline:

- Massachusetts Department of Environmental Protection (MassDEP) Wetlands
- Massachusetts Office of Geographic Information (MassGIS) 2005 Land Use
- Massachusetts Coastal Zone Management (CZM) Inventory of Privately Owned Coastal Structures (2013)
- Massachusetts Department of Conservation and Recreation and CZM Inventory of Publicly Owned Coastal Structures (2006-2009)

Brief descriptions and web links to additional specifications for each GIS data layer can be found in Science and Technology Working Group Report - Appendix A.

A number of different approaches were developed and tested to achieve the primary objective of characterizing land and water along the shoreline. A transect approach using existing data was ultimately selected for its efficiency, repeatability, and scale (e.g., assessment unit = ~ 50 m shoreline segments). A common approach to characterizing land cover/land use along a linear feature (e.g., shoreline) is to buffer that feature a specified distance and summarize the resulting area. That approach could yield useful information, but unlike the transect approach, it does not provide characterizations for discrete locations along the linear feature. The methods used to characterize the immediate, exposed shoreline for this project are explained in greater detail in Science and Technology Working Group Report - Appendix A.

Among the different land cover/land use data sources, 57 categories, or classes, were identified as occurring along the immediate, exposed shoreline. Select classes were aggregated to arrive at 11 distinct bins and classes by which to summarize data (see Science and Technology Working Group Report - Appendix A, Table 1). Results for each community with assessed shorelines are presented in Science and Technology Working Group Report - Appendix A. Data were also processed for a statewide representation as depicted in Figure 2 below. Additionally, community results were presented at the Coastal Erosion Commission regional workshops in poster format (see Figure 3).

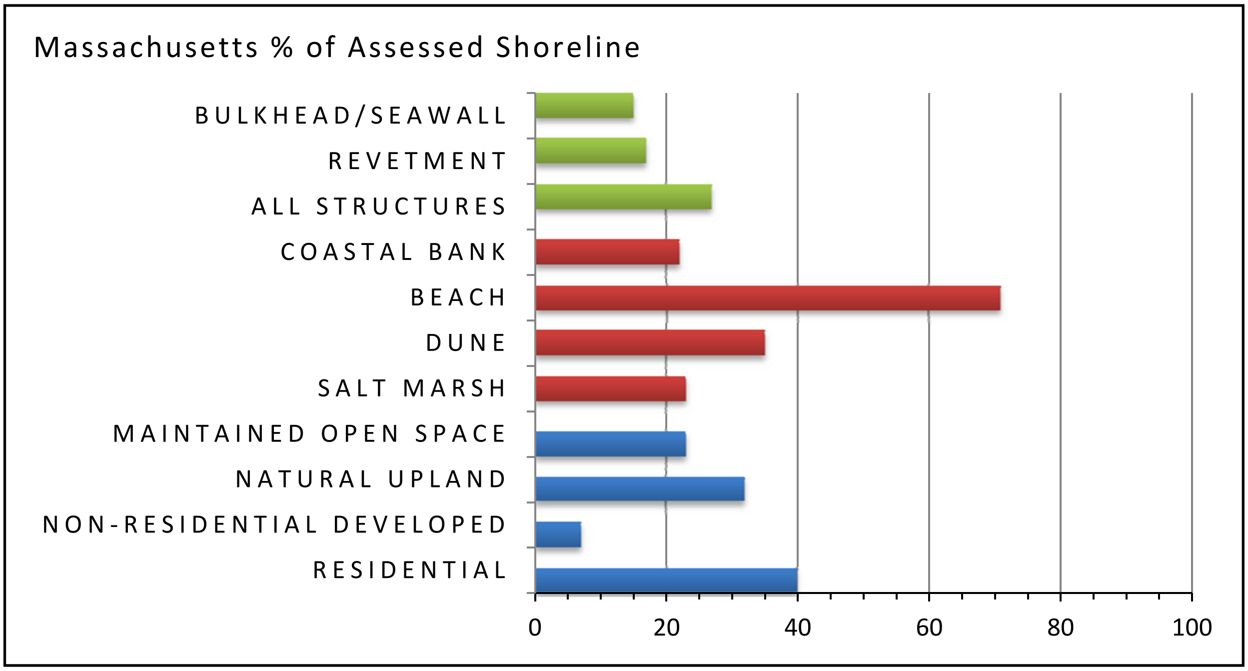


Figure 2. Chart depicting the percent of each class or bin that occurs along the assessed length of Massachusetts shoreline. Multiple classes could occur at each shoreline segment.

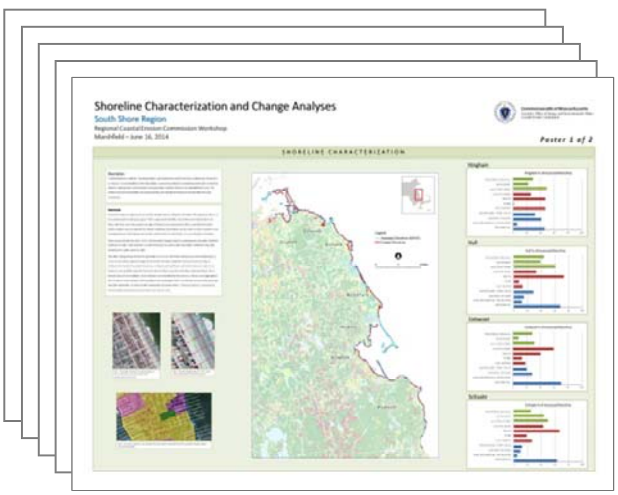


Figure 3. A poster series depicting shoreline characterization and change analyses was presented at each regional workshop.

Data Limitations

The shoreline characterization dataset primarily relies on the delineation and classification of land use/land cover features as presented in a number of source datasets. It is important to note that particular limitations may exist when asking specific questions of the shoreline characterization data. The following are points for consideration:

- The assessed shoreline generally excludes harbors and estuaries.
- The shore-parallel coastal engineered structures data layers were mapped and classified at a higher resolution than were land use and wetlands data layers.

- The source imagery from which the DEP Wetlands polygons were delineated are not tide-controlled, resulting in potential under- or over-representation of beaches, depending on the tide (i.e., beaches delineated from imagery captured at or near a high tide could be under-represented, while beaches delineated at or near low tide may be over-represented with inclusion of the wet beach. A distinction between dry beach and wet beach cannot be made using the DEP Wetlands data layer.
- DEP Wetlands polygons were delineated and interpreted from circa 1990-1993 source imagery.
- MassGIS Land Use polygons were delineated and interpreted from 2005 source imagery.

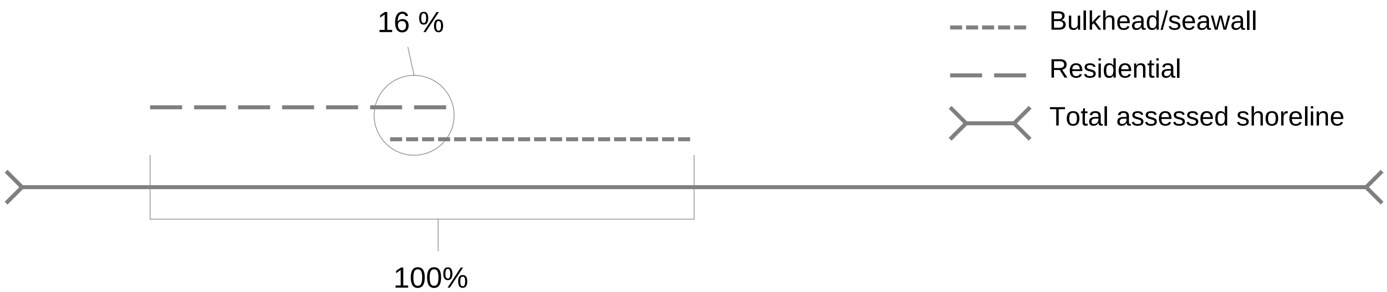
Considerations for Additional Data Processing and Analysis

The data presented here offer only a small piece of what can be achieved with more data processing and analysis. If additional information is desired moving forward, these approaches can be further developed and applied with varying degrees of effort. They include the following.

- **Co-occurrence Matrix**
    - Identifies patterns in the landscape where two or more features co-exist.
    - May be used to look for patterns at the parcel, community, or regional levels.

Table 1. Co-occurrence matrix showing the percentage for which corresponding classes or bins occur along the assessed shoreline in Fairhaven. For example, bulkheads/seawalls and residential areas co-occur along 16% of the shoreline where one or both are present, as illustrated in the graphic below.

	B/S	RVT	RES	NRD	MOS	BEA	DUN	BNK
BULKHEAD/SEAWALL (B/S)	-	-	-	-	-	-	-	-
REVETMENT (RVT)	1	-	-	-	-	-	-	-
RESIDENTIAL (RES)	16	6	-	-	-	-	-	-
NON-RESIDENTIAL DEVELOPED (NRD)	7	1	8	-	-	-	-	-
MAINTAINED OPEN SPACE (MOS)	0	1	5	1	-	-	-	-
BEACH (BEA)	11	4	26	7	5	-	-	-
DUNE (DUN)	2	0	8	2	2	14	-	-
BANK (BNK)	0	2	5	0	2	4	0	-



- **Landward Class Ordering**
  A process has been developed to order classes for each shoreline segment as they occur along the transect, moving from the subtidal zone to upland (see Figure 4). This ordering could be used to better describe the local landscape, such as where salt marsh occurs seaward of beach, or to look for anomalies, such as where a coastal dune occurs seaward of a coastal engineered structure.
- **Class Extent**
  A process has also been developed to measure class width along each transect. This extends the utility of these data in providing more than just presence or absence information about each class. Figure 4 shows a transect with class intersection points, whereby class widths can be calculated and reported. Beach width is 24 meters in this example.
- **Shoreline Change Analysis**
  By incorporating shoreline change data, additional patterns can be identified and explored. For instance, the shoreline characterization data, using landward class ordering, were used to summarize long-term and short-term shoreline change rates derived from the Massachusetts Shoreline Change Project for seven classes: beach, beach with dune, beach with bank, beach with shore-parallel coastal engineered structure, bank, salt marsh, and structure. Results of this analysis are referenced under Task 2A and presented in Science and Technology Working Group Report - Appendix B.

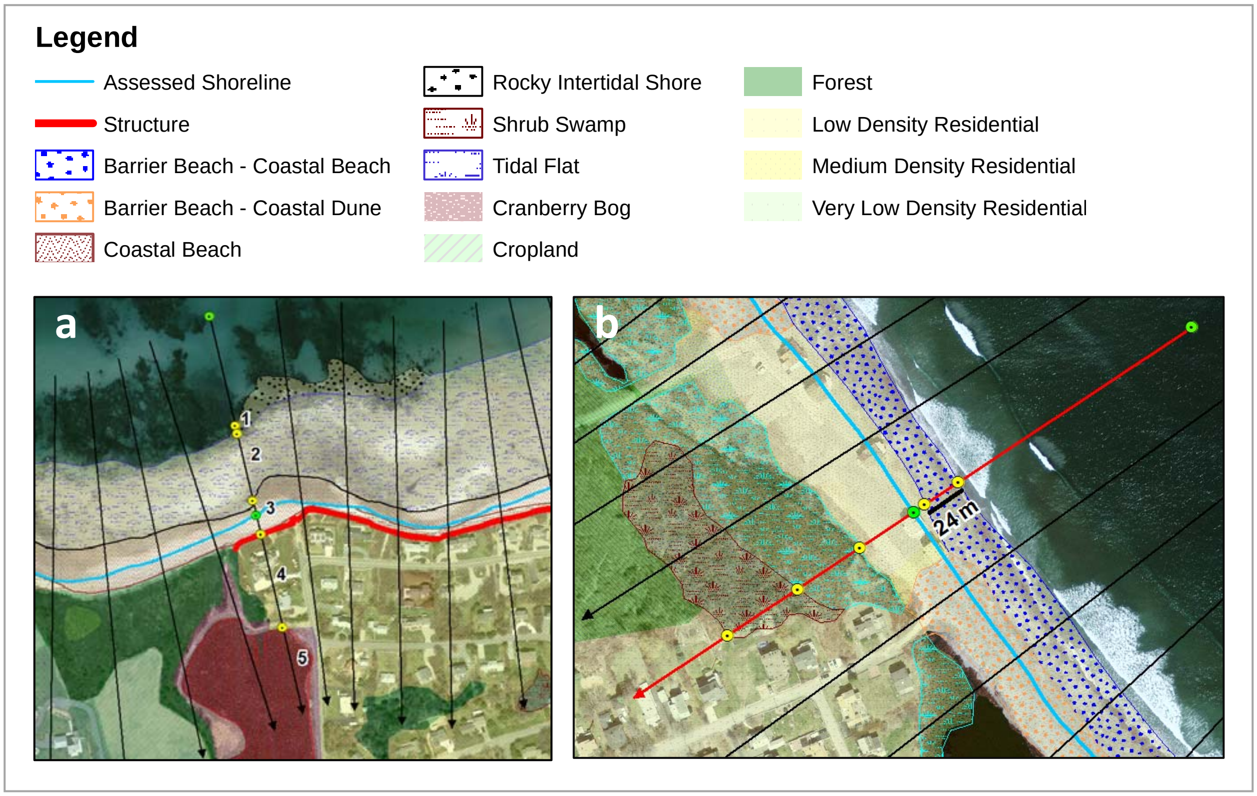


Figure 4. (a) Example of a transect with five corresponding classes, ordered landward from 1 to 5, and (b) example of a transect where beach width equals 24 m.

Task 1C: Assist the Commission in characterizing the Commonwealth shoreline by describing ongoing efforts to inventory and track coastal shoreline engineered structures.

The Massachusetts ocean-facing coastline, which is approximately 1,100 miles long, was used as the extent of the project area for mapping publicly owned and privately owned coastal engineered structures.

Publicly Owned Coastal Engineered Structures

An inventory of all publicly owned shoreline stabilization structures was completed for the Commonwealth of Massachusetts in 2009. The project was initiated by the Infrastructure Plan Working Group of the Coastal Hazards Commission, which focused primarily on shoreline stabilization structures and their ability to resist major coastal storms and prevent damage from flooding and erosion. Since ownership and maintenance are major issues for these structures, the goal of the infrastructure project was to research, inventory, survey, and assess existing publicly owned coastal infrastructure along the shoreline from the New Hampshire border to the Rhode Island border, including the islands. The study identified publicly owned shore protection structures through research of local, state, and federals records. Each structure was located, recorded, and described prior to field work. Field inspections were conducted by civil engineers who performed visual condition inspections and collected photographs of each structure. A detailed report was prepared for each coastal community identifying each publicly owned coastal engineered structure, including type, material, height, length, elevation, Federal Emergency Management Agency Flood Insurance Rate Map flood zone designation(s), condition, priority rating, estimated repair or reconstruction cost, and any records regarding the design and permits that were obtained for the structure. The condition of each structure was rated A through F, indicating a scale ranging from Excellent to Critical, respectively. The structures were also given a priority rating, based on the perceived immediacy of action needed and the presence of potential risks to inshore structures if problems were not corrected. The Summary Report, reports for each community, and all data are available in the online Massachusetts Ocean Resources Information System (MORIS) at www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/seawall-inventory.

Continuing this effort, the Department of Conservation and Recreation initiated a project to update the inventory of publicly owned structures in 2013. The final project update will include identification of all work performed on publicly owned structures since the previous inventory, detailed assessments of publicly owned structures that were missed in the previous inventory, updated condition assessments for all structures, updated cost estimates for repairs and reconstruction, detailed reports for each coastal community, and the applicable GIS data that can be incorporated into MORIS. The updated reports are expected to be completed by December 2015.

Privately Owned Coastal Engineered Structures

An inventory of privately owned coastal engineered structures was completed for the Massachusetts Office of Coastal Zone Management (CZM) in 2013. These structures were delineated using remote sensing techniques to extract information regarding structure location, type, material, length, elevation, and height. Various data sources were used to locate the coastal structures and determine their attributes, including: 2008/2009 USGS color orthophotographs, Light Detection and Ranging (lidar) terrain datasets available on MassGIS, Massachusetts Oblique Imagery (Pictometry), Microsoft Bing Maps, Tax Assessor Parcel records, and Chapter 91 license data. The final report, *Mapping and Analysis of Privately-Owned Coastal Structures along the Massachusetts Shoreline*, the appendices regarding extracted elevations and structure ID generation, and a geodatabase of all project data are available at: http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/seawall-inventory/.

Table 2. Summary of the miles of coastline armored by shore-parallel coastal engineered structures, broken down by region.

CZM Region	Shoreline Length (miles)	Private Structure Length (miles)	Public Structure Length (miles)	Percent Armored
North Shore	160	50	24	**46%**
Boston Harbor	57	12	21	**58%**
South Shore	129	28	29	**44%**
Cape Cod & Islands	615	66	11	**13%**
South Coastal	154	49	7	**36%**
TOTAL	**1,115**	**205**	**92**	**27%**

Task 2A: Assist the Commission in making a reasonable assessment of coastal erosion by describing and quantifying, where possible, past erosion trends and estimates of shoreline change.

Massachusetts Shoreline Change Project

The data presented in this section originate from the Massachusetts Shoreline Change Project (www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/shoreline-change), launched by CZM in 1989. The Project illustrates how the shoreline of Massachusetts has shifted between the mid-1800's to 2009. Using data from historical and modern sources, up to eight shorelines depicting the local high water line have been generated with transects at 50-meter intervals along the ocean-facing shore. For each of these 26,000+ transects, data are provided on the net distance of shoreline movement, shoreline change rates, and uncertainty values. The information provided by the Shoreline Change Project shows the historical migration of Massachusetts shorelines and erosional hot spots.

Averages of long-term (approximately 150 years) and short-term (approximately 30 years) erosion and accretion rates provide general summaries of shoreline trends for each community's coastal zone, and localized shoreline trends for designated public beaches. The long-term shoreline change data covers the period from the mid-1800s to 2009; the short-term data spans from 1970-2009. Due to the multitude of natural and human-induced factors that influence shoreline positions over time, care must be used when applying the information to a specific property or section of coastline—correct interpretation of the data requires knowledge of coastal geology and mapping and other factors that affect shoreline position and change rates. To interpret and apply the shoreline change data, both general shoreline trends and long- and short-term rates must be analyzed and evaluated in light of current shoreline conditions, recent changes in shoreline uses, and the effects of human-induced alterations to natural shoreline movement. In areas that show shoreline change reversals (i.e., where the shoreline fluctuates between erosion and accretion) and areas that have been extensively altered by human activities (e.g., seawalls and jetties), professional judgment and knowledge of natural and human impacts are typically required to properly interpret and incorporate the data into project planning and design. In no case should the long-term shoreline change rate be used exclusively—it is important to first understand and assess the short-term rate, the uncertainty associated with each shoreline position, the patterns of erosion and accretion, and other contributing factors.

The shorelines used for the project were derived from different historical maps, aerial photographs, and lidar (light detection and ranging) topographic data sources. Each shoreline was assigned an uncertainty value based on an estimate of errors inherent in the source material and method used to delineate the local high water line (Thieler et al., 2013). These estimates of total shoreline position uncertainty, which range from 38.1 feet (11.6 meters) for 1800s shorelines to 4.17 feet (1.27 meters) for lidar-derived shorelines, should be considered when analyzing shoreline movement over time.

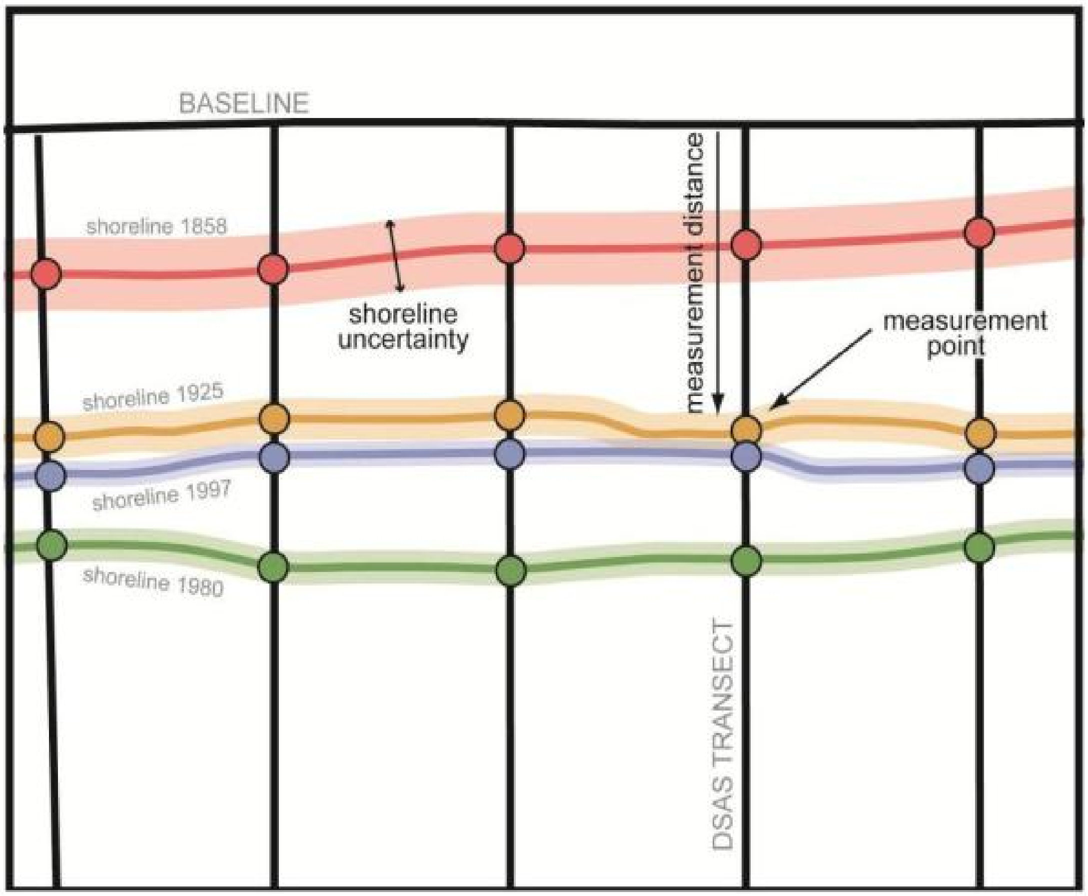


Figure 5. Shoreline Measurement Points. This diagram shows the relation between the measurement baseline, the transects generated by the Digital Shoreline Analysis System (DSAS) software, shoreline measurement points, and shoreline positional uncertainty. (From Thieler et al., 2009)

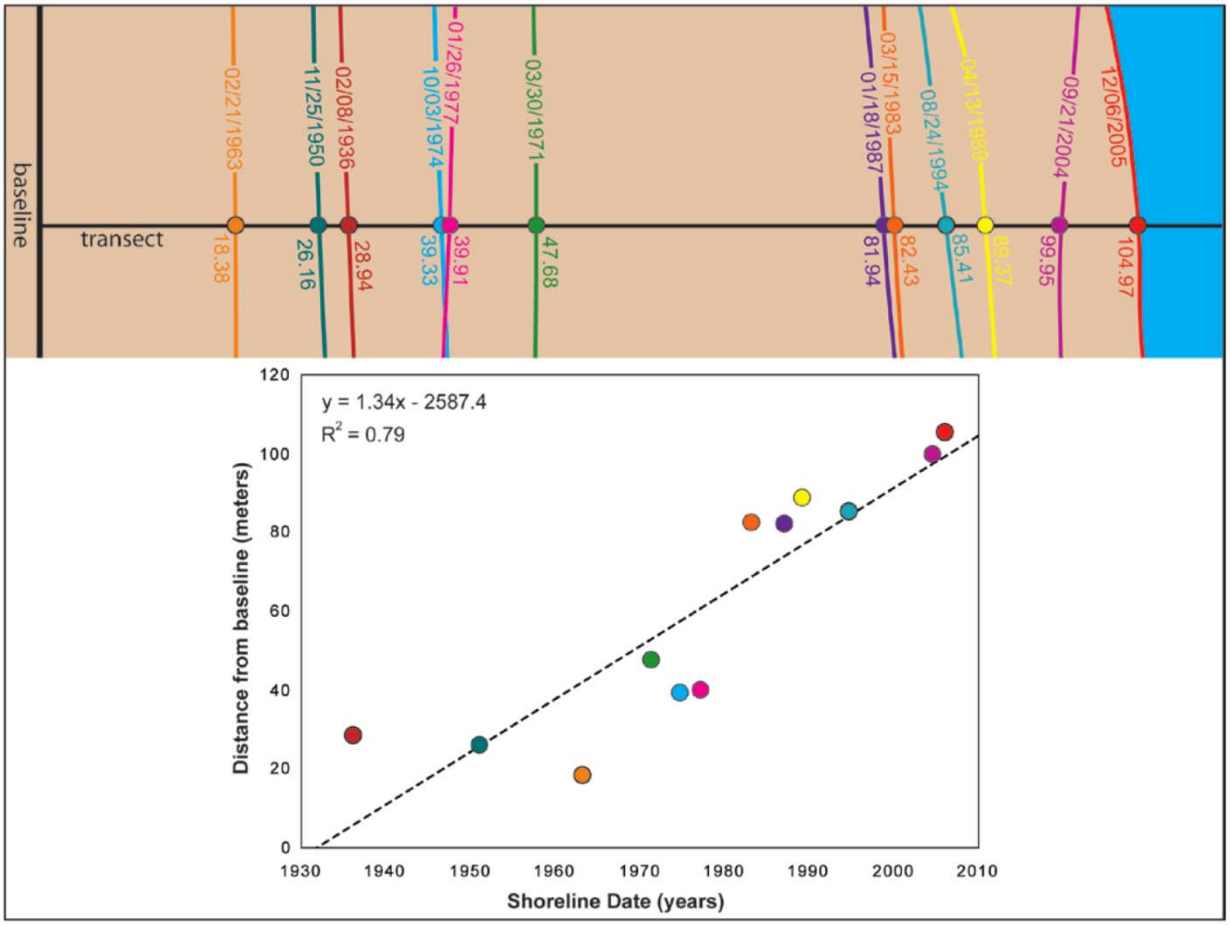


Figure 6. Example of Applying Linear Regression to Calculate Shoreline Change Rates. A linear regression (line of best fit) is applied to each transect to account for multiple shorelines when calculating a rate for that transect. High variability in shoreline position over time increases the uncertainty of the rate of shoreline change relative to the value for the linear trend in linear regression calculations. This increases the potential for rates of shoreline change that are statistically insignificant. In many locations, the short-term trend is calculated with only three to four shorelines. Because uncertainty generally decreases with an increasing number of shoreline data points, the small number of shorelines in the short-term calculation can result in higher uncertainty. (From Thieler et al., 2009)

Past Erosion Trends and Estimates of Shoreline Change

To address the charge from the Commission, a few different methods were explored to analyze and present shoreline change trends. Using the MassDEP 1:12000 Wetlands layer, a first cut was to locate and remove from further analysis rocky intertidal shorelines, on the premise that in this setting shoreline movement is constrained by bedrock or similar stable coastal type (e.g., rocky headlands). Since there is potential for erosion of bluff/banks that overlie rocky intertidal and low bedrock outcrops, and preliminary results did not reveal any significant differences when average rates were computed per town, they were not removed from the final analysis.

In an effort to characterize trends for the entire Commonwealth, shoreline change rates were averaged for each community and are depicted in Table 3. Communities on Cape Cod which have shorelines facing multiple directions, subject to different physical processes, (e.g., Barnstable's north shore is primarily subject to the effects of northeasters, while it's south shore is primarily subject to the effects of hurricanes) are further broken down based on sub-region (e.g., Cape Cod Bay, Cape Cod South). Figure 7 shows the 20 communities with the highest rates of erosion (for both long- and short-term rates). Table 4 list these communities with their rates and standard deviation (where a higher standard deviation equates to greater variability about the mean).

It is important to note that the short- and long-term rates of erosion often average out the episodic changes that occur, both seasonally and as a result of coastal storm events. (The uncertainty expressed in Table 3 and Table 4 covers cross shore error, but not alongshore variation in averaging. It is possible there may be a town with a very high erosion rate and very high accretion rate that would average to near 0.) Based on knowledge of the coastline and storm damage reports collected by the Massachusetts Coastal Storm Damage Assessment Team, the working group has identified several locations as "hot spots" where the combination of erosion, storm surge, flooding, and waves have caused significant damage to buildings and/or infrastructure during coastal storm events over the past few years (Table 5).

In preparation for the Coastal Erosion Commission regional public workshops, a series of charts organized by CZM regions were created to demonstrate the long- and short-term erosion and accretion trends per community (Figures 1-10 in Science and Technology Working Group Report - Appendix B). These charts show the normalized data, representing those transects that depicted either an erosional or accretion trend.

Average Short-Term and Long-Term Shoreline Change Rates

Table 3. Average Short-Term and Long-Term Shoreline Change Rates for the Commonwealth. Average short-term and long-term rates are presented in feet/year for each community, with the respective standard deviation (where a higher standard deviation equates to greater variability about the mean). Negative values indicate erosion; positive values indicate accretion. Rates for Cape Cod communities with shorelines facing multiple directions are provided below the rate for the entire community (Cape sub-regions are denoted as CCB = Cape Cod Bay, NS = Nantucket Sound, OCC = Outer Cape Cod, bordering the Atlantic Ocean, BB = Buzzards Bay).

Town	Town Sub-region	Short-Term Rate		Long-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Aquinnah		-0.3	2.8	-0.5	1.6
Barnstable	Entire town	0.4	5.2	-0.4	2.2
	CCB	1.1	7.2	-0.2	2.3
	NS	-0.3	2.1	-0.7	2.0
Beverly		-0.3	0.7	-0.1	0.3
Boston		0.3	2.0	0.2	1.7
Bourne	Entire town	-0.3	1.1	-0.1	0.7
	CCB	2.3	1.8	-0.5	0.3
	BB	-0.4	0.9	-0.1	0.7
Brewster		0.2	5.2	-0.6	1.3
Chatham	Entire town	0.5	48.6	1.6	9.4
	OCC	0.6	51.0	1.9	9.7
	NS	-0.1	2.5	-1.7	4.4
Chilmark		-1.8	1.9	-2.1	2.0
Cohasset		0.6	2.4	0.1	0.7
Dartmouth		-0.8	2.8	-0.2	0.6
Dennis	Entire town	-0.5	3.3	-0.8	2.9
	CCB	-0.7	4.0	-1.3	2.8
	NS	-0.1	1.6	0.2	2.8
Duxbury		0.2	3.7	-0.6	0.8
Eastham	Entire town	-3.5	5.4	-2.5	1.7
	CCB	-1.7	5.2	-1.9	2.0
	OCC	-5.7	4.7	-3.3	0.7
Edgartown		-2.4	9.6	-2.2	3.7
Fairhaven		-0.8	0.9	-0.4	0.5
Falmouth	Entire town	-0.5	1.4	-0.3	0.7
	NS	-1.1	1.1	-0.7	0.9
	BB	-0.3	1.5	-0.1	0.4
Gloucester		-0.2	2.2	-0.1	0.4
Gosnold		0.6	1.3	-0.2	0.4
Harwich		0.1	1.9	0.8	1.7
Hingham		-0.9	1.9	-0.1	0.5
Hull		-0.2	1.8	0.0	0.5
Ipswich		-3.6	11.0	-0.4	2.1
Kingston		-0.3	1.0	-0.2	0.4
Lynn		-0.8	1.1	0.4	1.0
Manchester		-0.2	0.7	0.1	0.3
Marblehead		-0.3	0.6	-0.1	0.4

Town	Town Sub-region	Short-Term Rate		Long-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Marion		0.1	1.0	-0.3	0.4
Marshfield		0.1	2.5	0.1	1.0
Mashpee		-0.7	2.6	-1.0	1.6
Mattapoisett		-0.2	1.0	-0.4	0.4
Nahant		-0.2	1.8	-0.1	0.5
Nantucket		-2.7	7.3	-2.2	4.9
New Bedford		1.6	1.8	0.9	1.2
Newbury		-2.4	3.1	-0.2	1.7
Newburyport		3.6	8.8	1.8	4.2
Oak Bluffs		-0.7	1.5	-0.5	1.2
Orleans	Entire town	-5.3	6.5	-2.2	3.2
	CCB	-1.7	3.5	-2.8	1.3
	OCC	-5.7	6.7	-2.1	3.3
Plymouth		0.1	3.3	-0.4	0.8
Provincetown	Entire town	0.2	3.9	1.0	2.1
	CCB	-1.4	3.0	0.9	1.8
	OCC	0.6	4.2	1.1	2.2
Quincy		-0.2	3.4	0.0	1.0
Revere		0.7	1.1	0.4	0.9
Rockport		-0.1	1.5	-0.1	0.6
Rowley		-3.3	3.3	-1.3	0.9
Salem		-0.3	0.6	0.2	1.0
Salisbury		-3.7	1.9	0.0	0.8
Sandwich		2.3	4.1	0.2	2.1
Scituate		-1.3	2.0	-1.0	1.7
Swampscott		-0.9	1.1	-0.1	0.3
Tisbury		-0.9	1.1	-0.3	0.8
Truro	Entire town	-2.4	2.7	-0.9	1.4
	CCB	-1.6	2.3	0.1	1.3
	OCC	-3.0	2.8	-1.6	0.9
Wareham		0.7	1.6	-0.3	1.0
Wellfleet	Entire town	-2.3	3.2	-1.6	1.8
	CCB	-2.0	3.6	-1.2	2.0
	OCC	-3.1	1.7	-2.8	0.3
West Tisbury		-1.0	2.2	-2.3	2.7
Westport		-1.0	1.3	-0.6	0.6
Weymouth		-0.7	2.8	0.1	0.4
Winthrop		0.4	1.9	0.4	1.1
Yarmouth	Entire town	-0.8	3.9	-0.3	1.3
	CCB	-8.7	6.5	-2.8	1.9
	NS	0.3	1.6	0.0	0.8

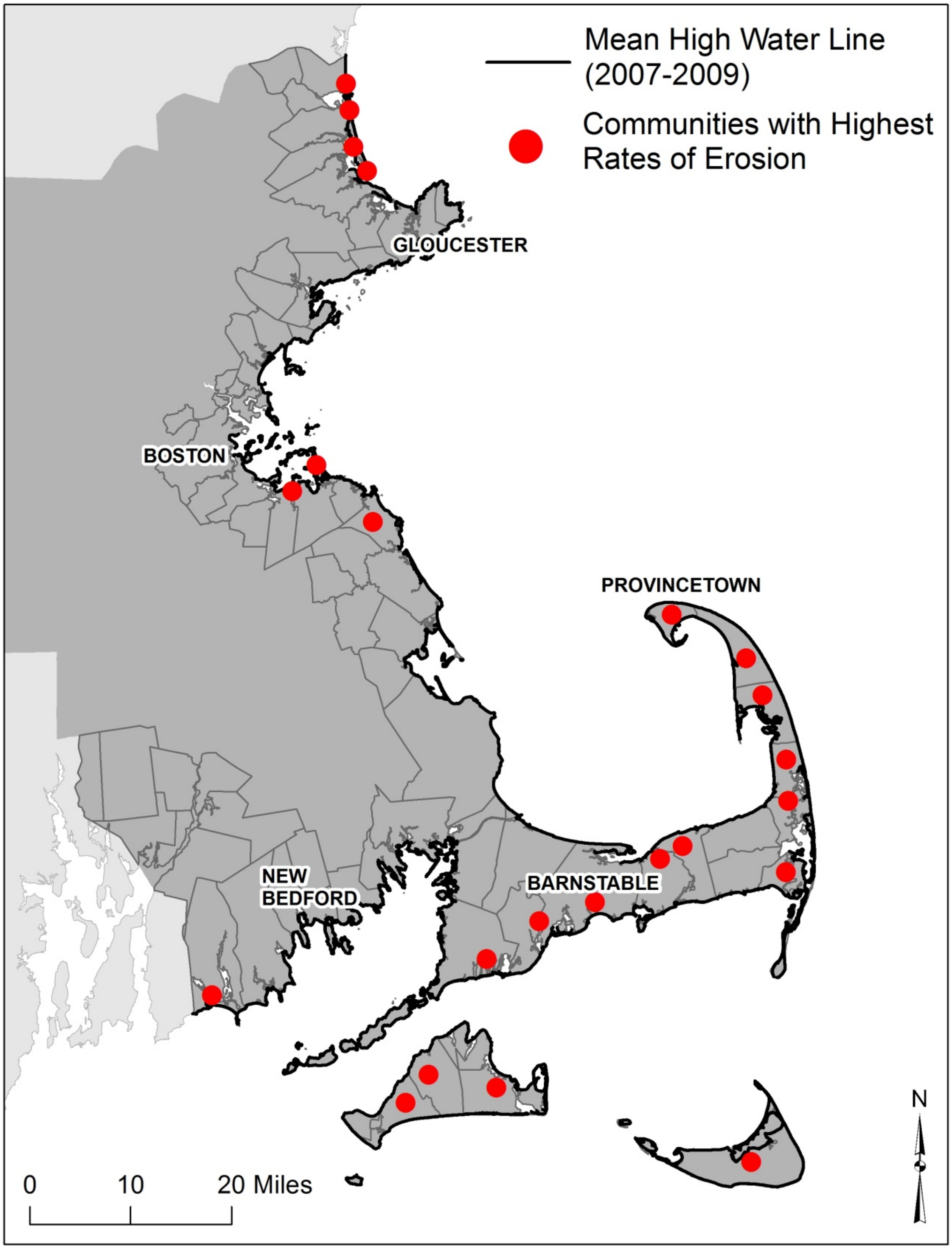


Figure 7. Communities with Highest Rates of Erosion. This figure displays the geographic range of the communities with the highest rates of both long- and short-term erosion. The long-term rates range from -3.3 ft/yr (Eastham) to -0.6 ft/yr (Westport). The short-term rates range from -8.7 ft/yr (Yarmouth) to -1.0 ft/yr (West Tisbury). See Table 3 for a list of rates for each of the top communities.

Communities with Highest Short-Term and Long-Term Rates of Erosion

Table 4. Communities with Highest Short-Term and Long-Term Rates of Erosion. Rates are presented in feet/year, each with the respective standard deviation (where a higher standard deviation equates to greater variability about the mean). Cape Cod community sub-regions are reported rather than the entire community (CCB = Cape Cod Bay, NS = Nantucket Sound, OCC = Outer Cape Cod, bordering the Atlantic Ocean, BB = Buzzards Bay).

Town	Town Sub-region	Short-Term Rate		Town	Town Sub-region	Long-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)			Mean (ft/yr)	Std Dev (ft/yr)
Yarmouth	CCB	-8.7	6.5	Eastham	OCC	-3.3	0.7
Eastham	OCC	-5.7	4.7	Orleans	CCB	-2.8	1.3
Orleans	OCC	-5.7	6.7	Wellfleet	OCC	-2.8	0.3
Salisbury		-3.7	1.9	Yarmouth	CCB	-2.8	1.9
Ipswich		-3.6	11.0	West Tisbury		-2.3	2.7
Rowley		-3.3	3.3	Edgartown		-2.2	3.7
Wellfleet	OCC	-3.1	1.7	Nantucket		-2.2	4.9
Truro	OCC	-3.0	2.8	Chilmark		-2.1	2.0
Nantucket		-2.7	7.3	Orleans	OCC	-2.1	3.3
Edgartown		-2.4	9.6	Eastham	CCB	-1.9	2.0
Newbury		-2.4	3.1	Chatham	NS	-1.7	4.4
Wellfleet	CCB	-2.0	3.6	Truro	OCC	-1.6	0.9
Chilmark		-1.8	1.9	Dennis	CCB	-1.3	2.8
Eastham	CCB	-1.7	5.2	Rowley		-1.3	0.9
Orleans	CCB	-1.7	3.5	Wellfleet	CCB	-1.2	2.0
Truro	CCB	-1.6	2.3	Scituate		-1.0	1.7
Provincetown	CCB	-1.4	3.0	Mashpee		-1.0	1.6
Scituate		-1.3	2.0	Falmouth	NS	-0.7	0.9
Falmouth	NS	-1.1	1.1	Barnstable	NS	-0.7	2.0
West Tisbury		-1.0	2.2	Brewster		-0.6	1.3
Westport		-1.0	1.3	Duxbury		-0.6	0.8
				Westport		-0.6	0.6

Coastal Processes "Hot Spots"

Table 5. Coastal processes "Hot Spots." The areas listed are known locations where the combination of erosion, storm surge, flooding, and waves have caused increased damage to buildings and/or infrastructure during coastal storm events over the past five years. The areas are listed from north to south.

COMMUNITY	LOCATION
Salisbury	Salisbury Beach
Newburyport	Plum Island
Newbury	Plum Island
Hull	Nantasket Beach
Hull	Crescent Beach
Scituate	Glades
Scituate	Oceanside Drive
Scituate	Lighthouse Point
Scituate	Peggotty Beach
Scituate	Humarock Beach (northern half)
Marshfield	Fieldstone to Brant Rock
Marshfield	Bay Ave
Plymouth	Saquish
Plymouth	Long Beach (southern end)
Plymouth	White Horse Beach
Plymouth	Nameloc Heights
Sandwich	Town Neck Beach
Dennis	Chapin Beach
Nantucket	Siasconset
Edgartown	Wasque Point
Oak Bluffs	Inkwell Beach
Gosnold	Barges Beach
Westport	East Beach

Combining Shoreline Characterization and Shoreline Change Rates

The results from the shoreline characterization (discussed under Task 1B) were used to further analyze shoreline change rates for each community. This was done to demonstrate the long-term and short-term erosion or accretion trends for seven shoreline types (classes) per community. The shoreline types used in this exercise are defined in Table 6. Beach, dune, bank, and salt marsh classes were derived from the DEP 1:12000 Wetlands data layer via the shoreline characterization exercise described under Task 1B. Shore-parallel structures were derived from the Massachusetts Coastal Structures Inventory database.

Definition queries and other geospatial analysis techniques were used to select transects where each of these shoreline types occur. Shoreline change rates by shoreline type for Massachusetts are presented in Table 7. An example of the average shoreline change rates by shoreline type for five communities is presented in Table 8 (see Science and Technology Working Group Report - Appendix B for the full list of communities).

Shoreline Types

Table 6. Shoreline Types. Definitions of the seven shoreline classes used to produce average shoreline change rates by shoreline type for each community.

Beach	Beach is present; dune, bank, and structure(s) are absent; salt marsh may be present, but not seaward of beach.
Beach w/Dune	Beach and dune are present; bank and structure(s) are absent; salt marsh may be present, but not seaward of beach.
Beach w/Bank	Beach and bank are present; dune and structure(s) are absent; salt marsh may be present, but not seaward of beach.
Beach w/Structure	Beach and structure(s) are present; other classes may be present as well.
Bank	Bank is present; beach is absent.
Salt Marsh	Salt marsh is present; beach, bank, and dune may be present, but not seaward of salt marsh.
Structure	Structure(s) is present; beach is absent; other classes may be present as well.

Shoreline Change Rates by Shoreline Type for Massachusetts

Table 7. Example of Shoreline Change Rates by Shoreline Type for Select Towns. Average shoreline change rates by shoreline type for five select communities. See Science and Technology Working Group Report - Appendix B for the full list of communities.

Shoreline Type	Long-Term Rate		Short-Term Rate	
	Mean (ft/yr)	**Std Dev (ft/yr)**	**Mean (ft/yr)**	**Std Dev (ft/yr)**
Beach	-0.67	1.99	-0.78	5.66
Beach w/ Dune	-0.43	4.25	-1.41	10.74
Beach w/ Bank	-1.24	1.87	-1.43	3.68
Beach w/ Structure	-0.23	1.08	-0.48	7.27
Bank	-0.07	0.91	-0.12	1.55
Salt Marsh	-0.69	1.67	-1.37	4.47
Structure	0.02	0.87	-0.12	1.22

Example of Shoreline Change Rates by Shoreline Type for Select Towns

Table 8. Example of Shoreline Change Rates by Shoreline Type for Select Towns. Average shoreline change rates by shoreline type for five select communities. See Science and Technology Working Group Report - Appendix B for the full list of communities.

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Brewster	Beach	-0.81	0.95	1.46	1.20
	Beach w/ Dune	-0.36	0.81	0.23	3.34
	Beach w/ Bank	-0.10	0.25	2.37	1.82
	Beach w/ Structure	-0.36	0.81	0.23	3.34
	Structure	-0.16	0.00	0.46	0.00
Hull	Beach	-0.12	0.39	-0.72	2.21
	Beach w/ Dune	0.08	0.38	1.13	1.15
	Beach w/ Bank	0.03	0.30	-2.62	2.67
	Beach w/ Structure	0.08	0.38	1.13	1.15
	Bank	0.39	0.87	-0.04	1.43
	Structure	0.38	0.86	0.02	1.10
Newbury	Beach w/ Dune	-0.06	1.68	-2.30	2.05
	Beach w/ Structure	-0.06	1.68	-2.30	2.05
	Structure	1.46	2.16	1.79	2.43
Plymouth	Beach	-0.68	0.78	-0.31	1.78
	Beach w/ Dune	0.06	1.06	1.44	5.60
	Beach w/ Bank	-0.48	0.57	-0.17	1.94
	Beach w/ Structure	0.06	1.06	1.44	5.60
	Bank	-0.15	0.82	0.14	1.41
	Structure	0.12	1.14	-0.03	1.24
Winthrop	Beach	2.84	2.59	0.85	1.38
	Bank	-0.15	0.21	-0.10	0.25
	Structure	0.05	0.54	0.18	1.32

Accounting for the Influence of Shoreline Stabilization Structures on Erosion Trends
The Massachusetts shoreline has a long history of human alteration in the form of shoreline stabilization structures, such as seawalls and revetments. Approximately 27 percent of the Commonwealth's shoreline is armored with shore-parallel structures (RPS ASA, 2013). Where the shoreline has been armored with structures, the shoreline change data may reflect the effects of the structures. For example, a shoreline that retreated for decades until a seawall was built may have a long-term rate of change that does not reflect the more recent constrained shoreline movement imposed by the seawall (Thieler et al., 2013).

As part of this analysis to provide a more accurate estimate of recent shoreline change, the following exercise was conducted to account for the influence of shore-parallel structures, both private and public, on shoreline change trends (shore-perpendicular structures were not included in this analysis). The most recent shoreline (2007-2009) was buffered according to the maximum positional uncertainty. The USGS positional uncertainties for the most recent shorelines are 4.2 feet (1.27 meters) for the 2007 shoreline; 14 feet (4.4 meters) for the 2008 shoreline; and 16 feet (4.9 meters) for the 2009 shoreline. Thus, with additional photo interpretation, a 20 foot buffer was applied to the most recent shoreline data layer to account for these positional uncertainties. The locations of shore-parallel structures were extracted from the Massachusetts Coastal Structures Inventory database. Similar to the shoreline buffering, each structure type was buffered according the maximum positional uncertainty and additional photo interpretation (30 feet for revetments and 5 feet for bulkheads and seawalls). Where these buffers of the shoreline and the shore-parallel structure overlap, the corresponding transects were flagged as those without a dry beach (See Figure 8 below for examples). These flagged transects also represent areas where the shoreline is physically restricted from moving landward. Of the 26,000+ transects, 21 percent fall into this category of restricted landward shoreline movement (Figures 11-12 in Science and Technology Working Group Report - Appendix B).

It is important to consider that even where the shoreline has essentially been fixed due to armoring (the 21 percent of the shoreline discussed above), the shoreline is still subject to erosion. Vertical erosion (a lowering of the beach elevation) may occur where the shoreline position has been "fixed" by structures. This process of beach lowering will not be captured by shoreline change analysis.

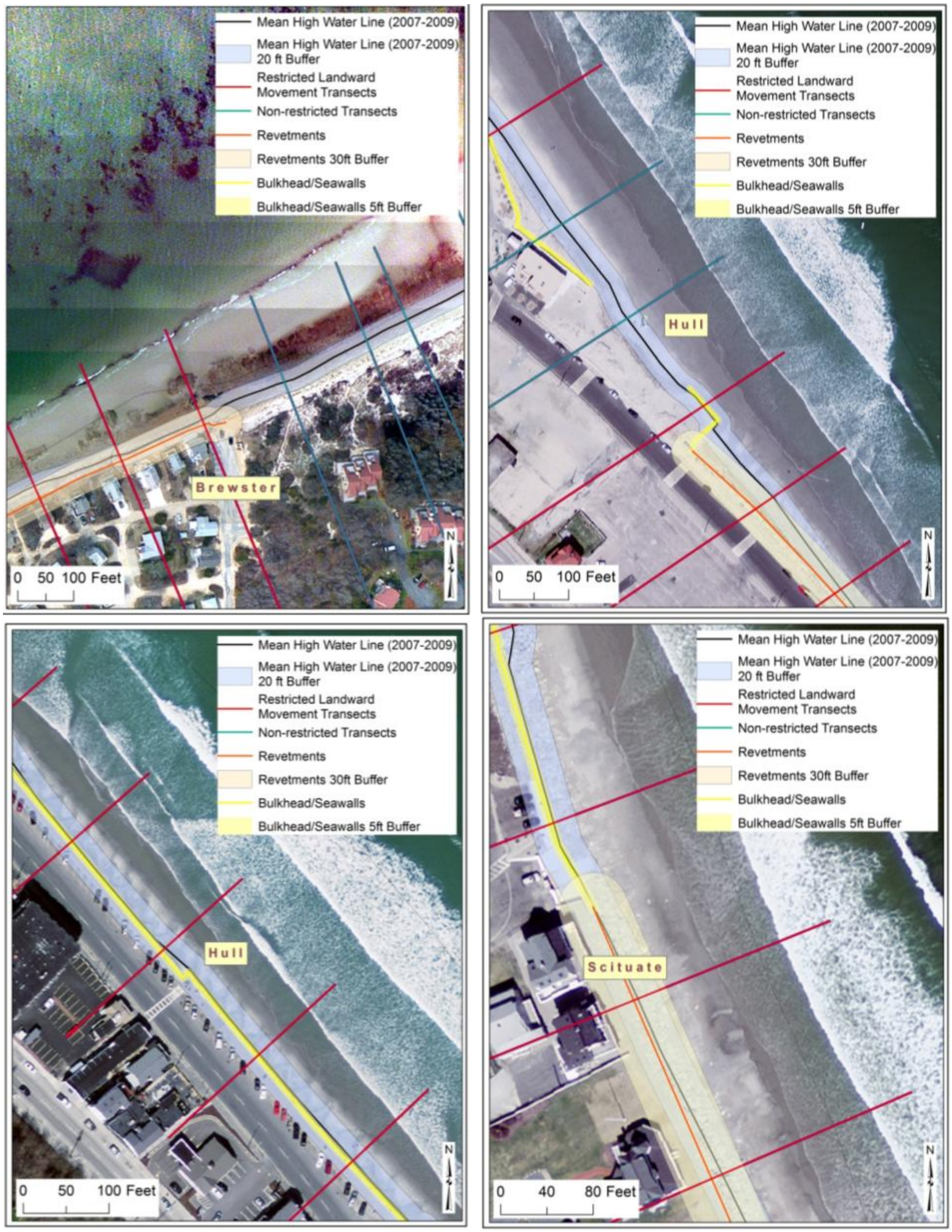


Figure 8. Examples of Transects Associated with a "Fixed" Shoreline. Examples from Brewster, Hull, and Scituate of where the modern shoreline is now "fixed" from further landward movement due to the influence of shore-parallel structures. The shoreline, however, is still subject to vertical erosion (lowering of the beach elevation).

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Task 2B: Assist the Commission in making a reasonable assessment of coastal erosion by providing the best advice on how to estimate erosion in the next 10 years.

Shoreline change forecasting

The factors that cause shorelines to change vary in time and space. This includes the geologic setting of the coast, which affects the quantity and quality of sediment available for beaches; coastal processes such as waves and currents that move the sediment; human modifications to the coast such as jetties, groins, breakwaters, seawalls, and beach nourishment; and changes in climate and sea-level that combine with these other factors to determine the location of the shoreline. Understanding past trends of shoreline movement and forecasting future trends are important scientific and management objectives worldwide due to the importance of coastal beaches for recreation, tourism, storm protection, and ecosystem services.

Common methods

Forecasting shoreline change (i.e., predicting the location of the shoreline at some future time) has been an important area of research since reliable compilations of historical shoreline positions became widely available in the 1980s and early 1990s, and coastal scientists sought to understand how the historical record could be applied to predicting the future. Current approaches to shoreline change forecasting can be divided into two general categories 1) statistics-based, and 2) process-based.

Statistics-based shoreline change forecasting relies solely on historical observations of shoreline positions, and forecasting changes based on different statistical techniques. These include simple extrapolation, binning, polynomials, eigenvectors, principal components, and B-spline functions (Fenster et al., 1993; Frazer et al., 2009; Genz et al., 2009; Anderson and Frazer, 2014). As a simple example, a shoreline position forecast can be made by computing a trend over some time interval (e.g., last 30, 50, 100, 150 years) using a trend estimation metric (Dolan et al., 1991; Thieler and Danforth, 1994; Genz et al., 2007; Thieler et al., 2009), and multiplying the trend value by the desired future time interval. Figure 9, for example, shows a long-term shoreline change trend of 1.34 meters per year (or 4.4 feet per year) of seaward progradation using a linear regression rate estimator. A simple forecast that assumes the long-term trend continues for another 10 years can be made such that 4.4 ft/yr* 10 yr+444 ft.. In other words, this forecast suggests that in 10 years the shoreline will be 44 feet farther seaward.

Process-based shoreline change forecasting uses not only historical observations of shoreline positions, but also observations and/or parameterizations of processes that are principal driver of shoreline change. Generally, we define these as models that describe a time-varying forcing-response relationship. These can range in complexity from models that relate wave energy to shoreline evolution (e.g. Miller and Dean (2004), Yates et al. (2009), Davidson et al. (2010), and Long and Plant (2012) to those that explicitly compute complex interactions between waves, water levels, currents, and sediment transport (e.g. Roelvink et al. 2009). The former methods employ data (e.g., wave characteristics, sediment grain size) and models of beach evolution applicable for seasonal to inter-annual timescales while the later are applied to much shorter time scales (hours to days) that are not as relevant here because of the computational resources needed to run the models.

Each of these approaches makes a number of assumptions that may constrain their utility, including: 1) underlying geologic (e.g., bedrock) or anthropogenic (e.g., a seawall) factors do not limit the ability of the shoreline to move; 2) sediment availability is unlimited; 3) there is a constant background trend; the processes being modeled sufficiently capture potential future changes in their form and magnitude.

Demonstration of a process-based approach to shoreline change forecasting using a Kalman filter technique

An application of shoreline change forecasting using a variation of a statistical-based model is described below. Historical shoreline information (Thieler et al., 2013) and other data are used to forecast shoreline position and position uncertainty using an assimilative approach similar to the one developed by Long and Plant (2012; see journal paper included here as an Science and Technology Working Group Report - Appendix C). A Kalman filter (Kalman, 1960) is used to combine model-derived and observed shoreline positions to both hindcast and forecast shoreline change from 1847 to 2025. In addition to the shoreline position, the time-varying uncertainty in the hindcast/forecast position is also computed. Uncertainty here is a combination of measurement noise, process noise, and the magnitude of mismatch between the model and data at each historical shoreline position (also called an observation). Measurement noise varies with each observation and is derived from two sources: 1) the type of method used to estimate the shoreline (historical maps, orthophoto images, lidar, etc.) and 2) the amount of scatter in the data about the linear regression. Process noise refers to how much change occurs in the shoreline that is not predicted by the model. In this case, we assume that shoreline change is a linear process ($y = vt+b$; where y is the shoreline position, v is the shoreline change rate, t is time, and b is the y-intercept) and resembles a linear regression through a series of shoreline observations at a particular transect (e.g., as shown in Figure 9). However, shorelines are constantly changing due to wave processes that act over time scales of days to months, so the magnitude of these changes (variability around the linear line) is considered process noise. The Kalman filter optimizes the forecast based on a combination of measurement and process noise. More measurement noise relative to process noise causes the Kalman filter to track closer to the model prediction. More process noise relative to measurement noise causes the Kalman filter to correct the model prediction to be closer to the observations.

The Kalman filter approach is initialized with values for the change rate (v) and y-intercept (b) that are determined using a linear regression through the available shoreline observations for each cross-shore transect and then estimates the shoreline position and rate on a yearly interval. Process noise (unresolved, wave-driven shoreline change) was estimated by running an equilibrium shoreline change model (e.g., Yates et al., 2009) forced with seven years of wave conditions offshore of Outer Cape Cod at NDBC buoy 44018 (i.e., the full period of data available for this buoy) and previously published model coefficients (Yates et al., 2009). Note that these model coefficients have not been calibrated for this particular beach because there is not sufficient data, but the model was used to get an initial estimate of the amount of wave-driven storm and seasonal variability that may be expected (e.g., variability in the shoreline position about the linear model).

Figure 10 shows two locations on the Massachusetts coast where the Kalman filter technique is demonstrated. Table 9 and Figures 11-14 show three example transects along Plum Island, Massachusetts, that illustrate the results of the Kalman filter approach at this location. For each figure, the Kalman filter prediction and uncertainty is shown and compared with the observations and the result from a simple linear regression through the available data points. Note that the Kalman filter approach is not intended to 'match' the observations at each time. The Kalman filter models the long-term trend, rather than a shoreline position at any given time, which includes the impacts of wave-driven processes. However, the uncertainty bounds, which are computed using both the measurement and process noise, should encompass each of those data points.

For transect 356, the 2025 Kalman filter estimated shoreline position is close to the position estimated using a linear regression. For transect 396, the Kalman filter forecasts less shoreline retreat than the linear regression, but the linear regression estimate is still within the Kalman filter uncertainty bounds. For transect 406, the Kalman filter forecasts more shoreline retreat than the linear regression, and the linear regression lies outside the Kalman filter uncertainty bounds. All three transects illustrate how the uncertainty increases in time due to compounding process noise, and how the addition of an observation can reduce uncertainty. Unlike the Kalman filter, linear regression methods only provide static estimates of uncertainty that do not explicitly include process noise.

Figure 15 shows a graph of the historical shorelines, 2025 forecast, and forecast uncertainty for the studied section of Plum Island. Figure 16 shows examples of anthropogenic influences on shoreline change and how the Kalman filter forecasts and uncertainty are affected.

Table 10 and Figure 17 show a similar example for part of Scituate-Marshfield, Massachusetts, that includes shoreline segments with and without large shore-parallel engineering structures (seawall/revetment). The forecast rate uncertainties give the range of long-term regressions that could give a shoreline position within the uncertainty bounds. Table 10 also shows the average and maximum uncertainty in the 2025 shoreline position.

The Kalman filter approach to shoreline position forecasting provides uncertainty estimates that adjust with time based on available data. As shown in Figures 15 and 17, there is alongshore variability in the predictions and uncertainty, and the effect of some anthropogenic influences manifests in the uncertainty (e.g., northern end of Plum Island; Figure 16). For the Scituate-Marshfield area, three historical shorelines since 2000 were available as input for the Kalman filter method, and the prediction closely follows the cluster of most recent shorelines. Most of the larger variability is in the older shorelines so their effect on the prediction diminishes through time (e.g., Figures 11-14). The uncertainty in the Brant Rock area is about half of that observed farther north.

The overall paucity of data, however, may influence the ability of the method to capture potential increased variability or erosion along the sandy portions and decreased variability in the gravel portions of this shoreline (in the Brant Rock area). Overall, the uncertainty is a bit large and extends landward of the seawalls which is an unlikely physical outcome. In this case, forecasts can be constrained with knowledge of the position of coastal structures (e.g., information described in Chapter 2 of this report). In general, large positional uncertainty can be interpreted to indicate areas that require additional observations to constrain the forecast.

Examples of Historical and Forecast Positions and Rates of Change

Table 9. Historical and forecast positions and rates of change for three transects on Plum Island, Massachusetts.

Transect ID	1853 Position [m]	2008 Position [m]	Forecast 2025 Position [m]	Forecast Position Uncertainty [m]	Forecast Rate [m/yr]	Forecast Rate Uncertainty [m/yr]	Historical Rate [m/yr]	Historical Rate Uncertainty [m/yr]
356	-84.72	-150.47	-155.3	14.21	-0.49	0.64	-0.39	0.16
396	-61	-113.33	-117.56	11.93	-0.27	0.60	-0.33	0.11
406	-67.34	-114.31	-123.97	12.4	-0.67	0.61	-0.27	0.12

Table 10. Historical (long-term linear regression) and forecast rates of change using the Kalman filter approach for part of Scituate-Marshfield, Massachusetts.

Region	Historical Rate [m/yr]		Forecast Rate [m/yr]		Forecast Shoreline Position Uncertainty @ 2025 [m]	
	Average	Maximum	Average	Maximum	Average	Maximum
Scituate-Marshfield	-0.02 ± 0.28	-0.84 ± 0.37	-0.27 ± 0.70	-0.69 ± 0.66	± 17	± 29

Notes

Positions are relative to transect origin.
Forecast rate uncertainty gives the range of long-term regressions that could give a shoreline position within the uncertainty bounds.
Historical rates from long-term linear regression shown for comparison.

Figures

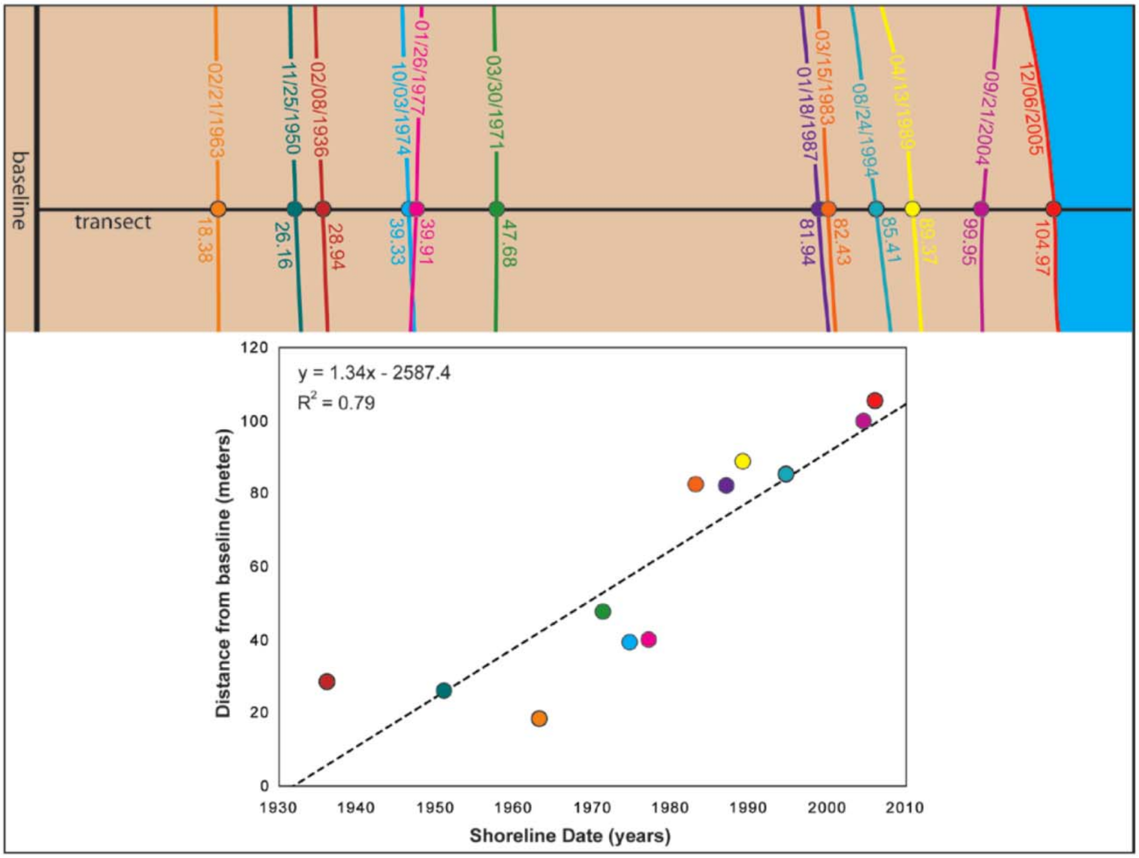


Figure 9. Top: schematic diagram showing historical shoreline positions along a measurement transect that originates from a reference baseline. Bottom: graph showing a linear regression fit to the shoreline positions, indicating a rate of change of 1.34 m/yr. (From Thieler et al., 2009.)

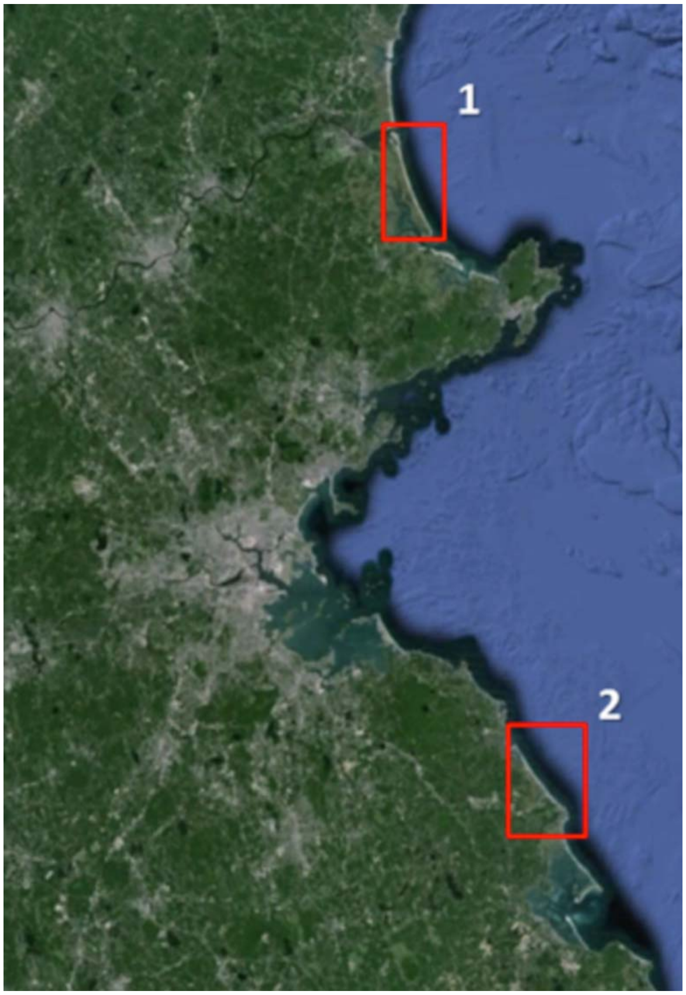


Figure 10. Map showing the Plum Island (1) and Scituate-Marshfield (2), Massachusetts study areas used to demonstrate the Kalman filter shoreline forecasting technique.

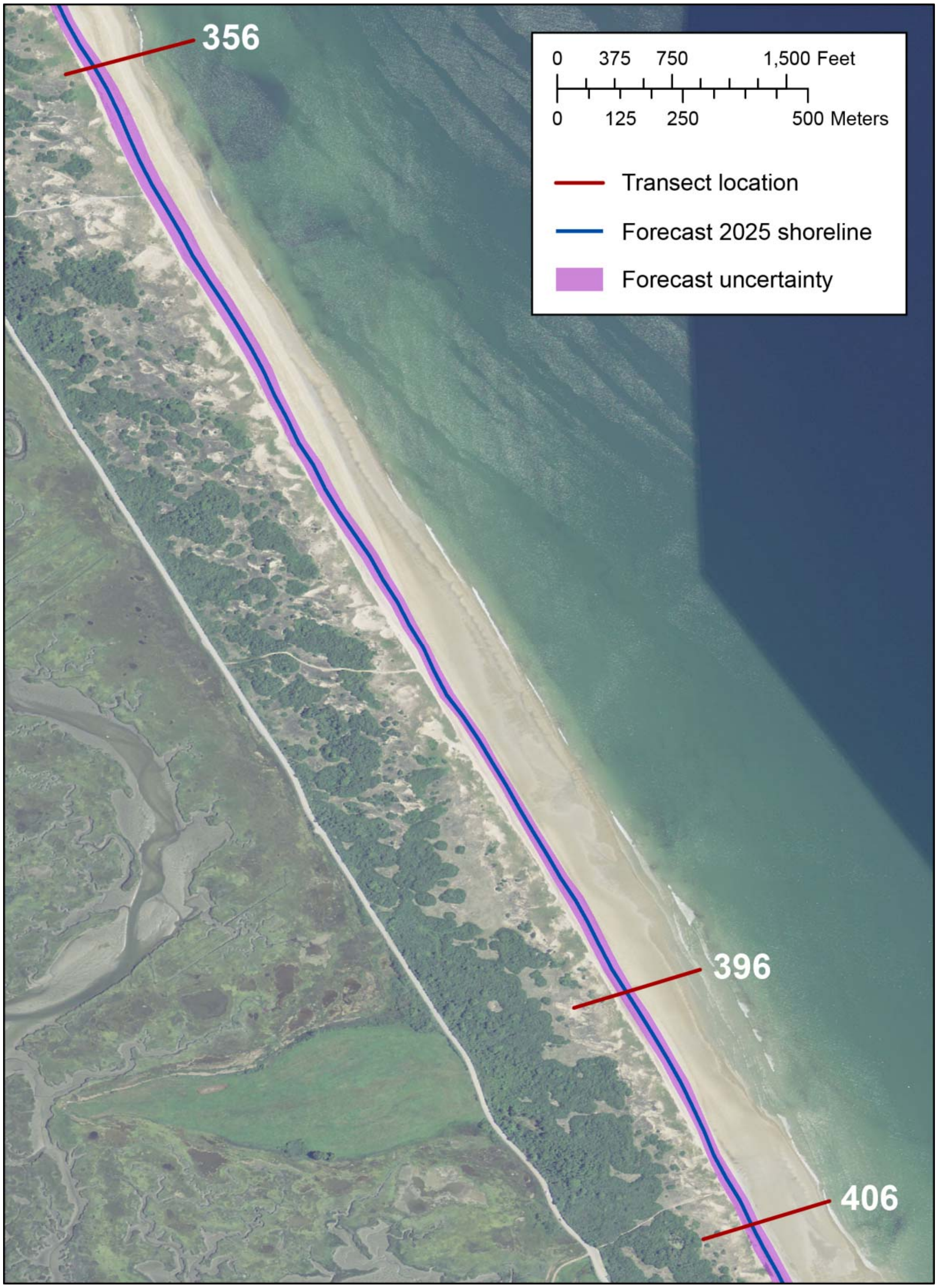


Figure 11. Map showing three example transects and alongshore variability of forecast shoreline position for a portion of Plum Island, Massachusetts using a Kalman filter approach. The transects are shown in greater detail in figures 3-5.

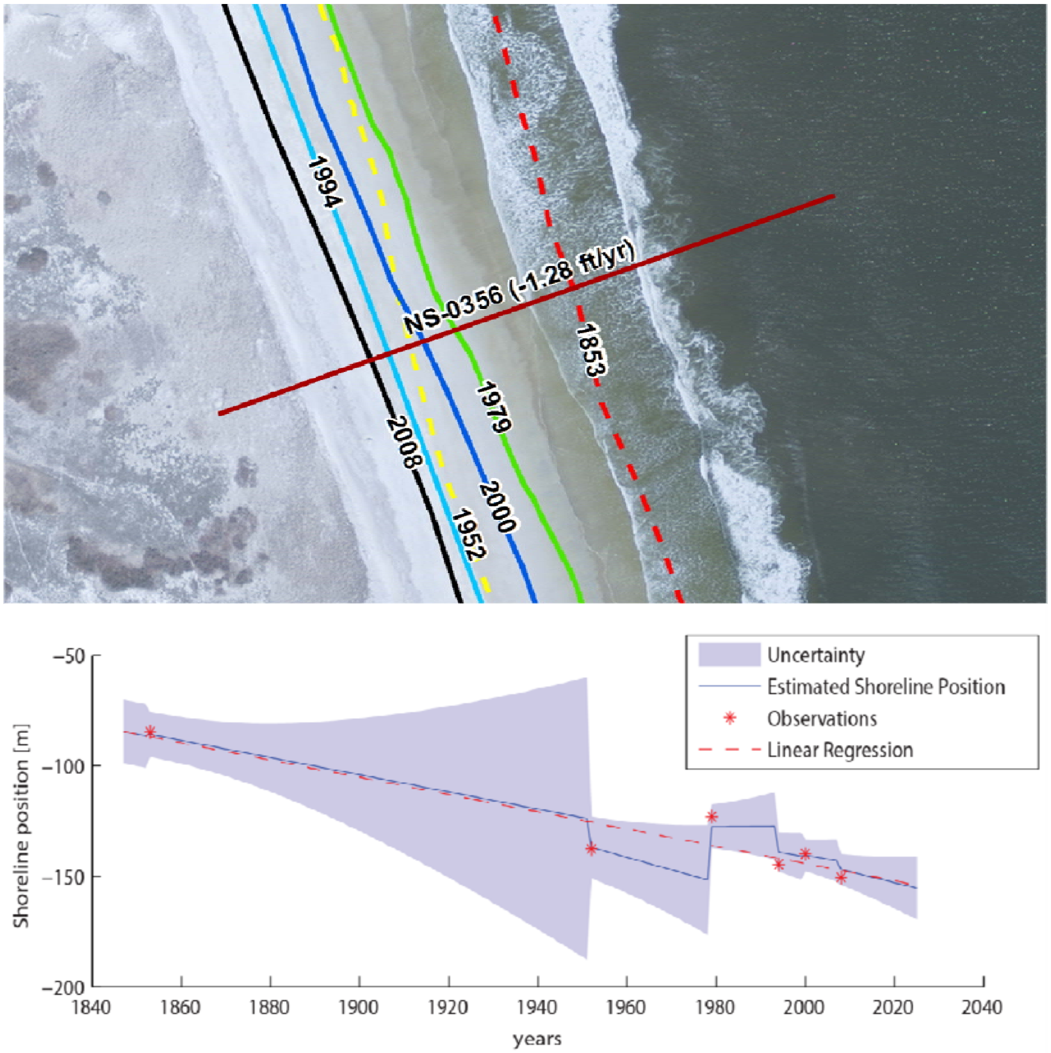


Figure 12. Map and graph showing historical and forecast shoreline positions over the time period 1853-2025 for transect 356 at Plum Island, Massachusetts. In the graph, the Kalman filter estimate (solid blue line) and linear regression estimate (red dashed line) are provided for comparison. The uncertainty bounds for the Kalman filter estimate are shaded in light blue. Historical shoreline positions are shown as red asterisks. This transect illustrates a Kalman filter forecast that is similar to a rate forecast using a simple linear regression model.

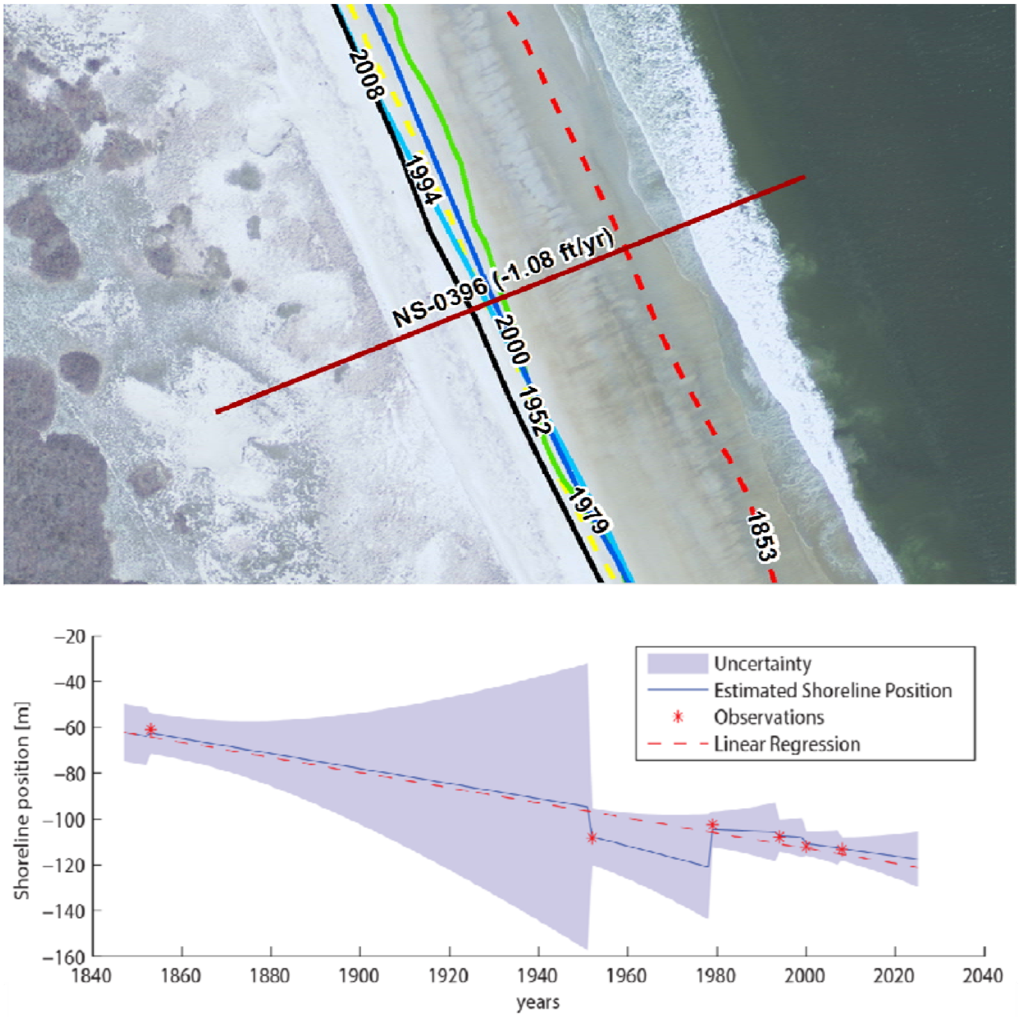
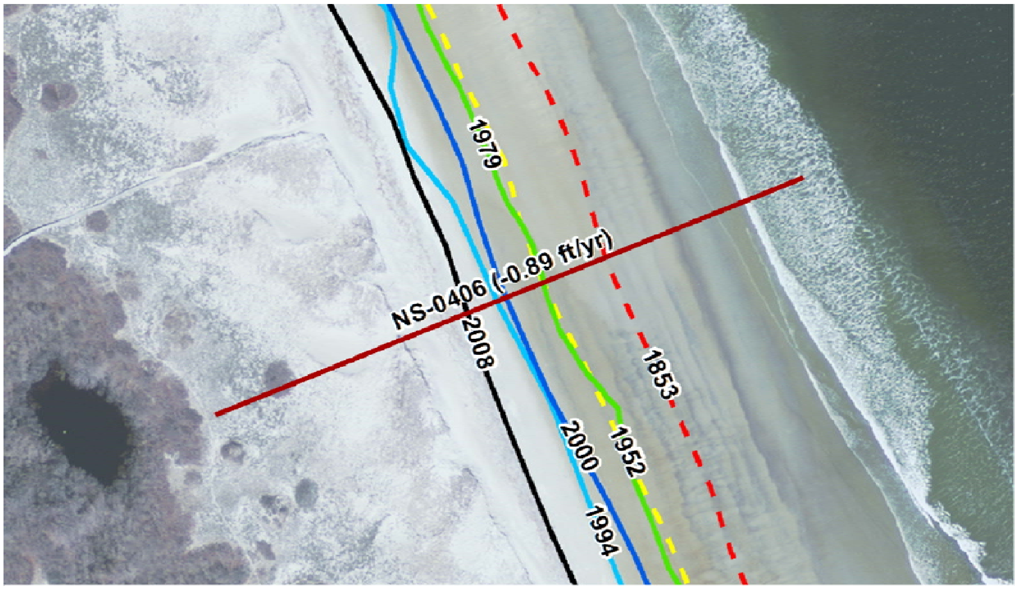


Figure 13. Map and graph showing historical and forecast shoreline positions over the time period 1853-2025 for transect 396 at Plum Island, Massachusetts. In the graph, the Kalman filter estimate (solid blue line) and linear regression estimate (red dashed line) are provided for comparison. The uncertainty bounds for the Kalman filter estimate are shaded in light blue. Historical shoreline positions are shown as red asterisks. This transect illustrates a Kalman filter forecast that is lower than a rate forecast using a simple linear regression model, but the linear regression lies within the Kalman filter uncertainty.



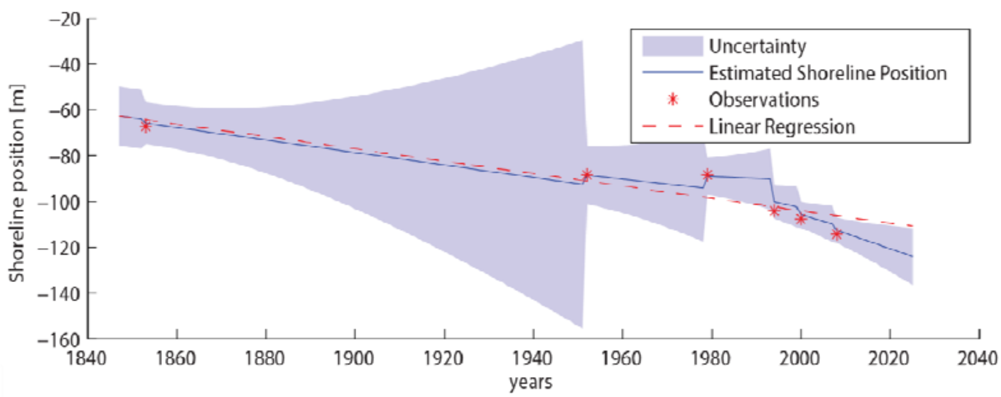


Figure 14. Map and graph showing historical and forecast shoreline positions over the time period 1853-2025 for transect 406 at Plum Island, Massachusetts. In the graph, the Kalman filter estimate (solid blue line) and linear regression estimate (red dashed line) are provided for comparison. The uncertainty bounds for the Kalman filter estimate are shaded in light blue. Historical shoreline positions are shown as red asterisks. This transect illustrates a Kalman filter forecast that is greater than a rate forecast using a simple linear regression model, and the linear regression estimate lies outside the Kalman filter uncertainty.

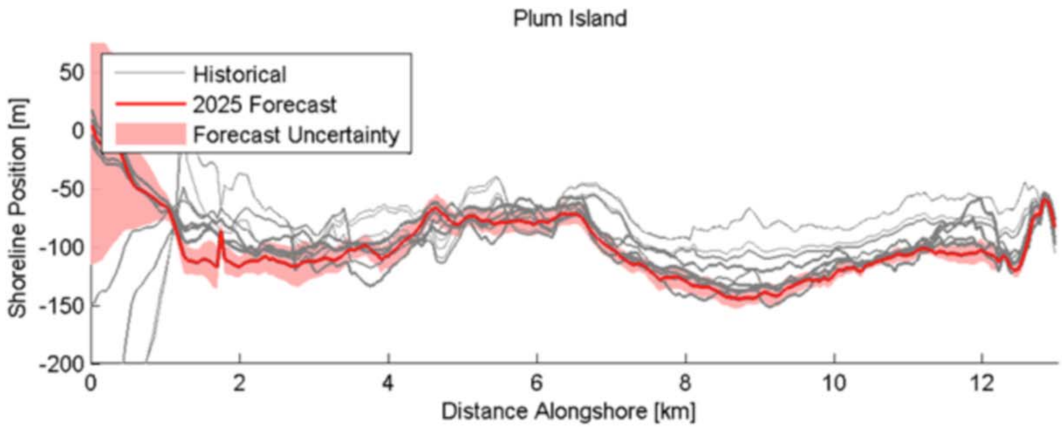


Figure 15. Graph showing historical shoreline positions, a 2025 shoreline position forecast and forecast uncertainty for part of Plum Island, Massachusetts using the Kalman filter technique.

Figure 16. Examples from Plum Island illustrating the effect of anthropogenic influences on the shoreline position and uncertainty forecasts. On the left, the construction of a jetty changed the trajectory of the shoreline after 1912, but large uncertainty still exists in how the coast will evolve. On the right, the construction of a groins identified in the Kalman filter prediction.

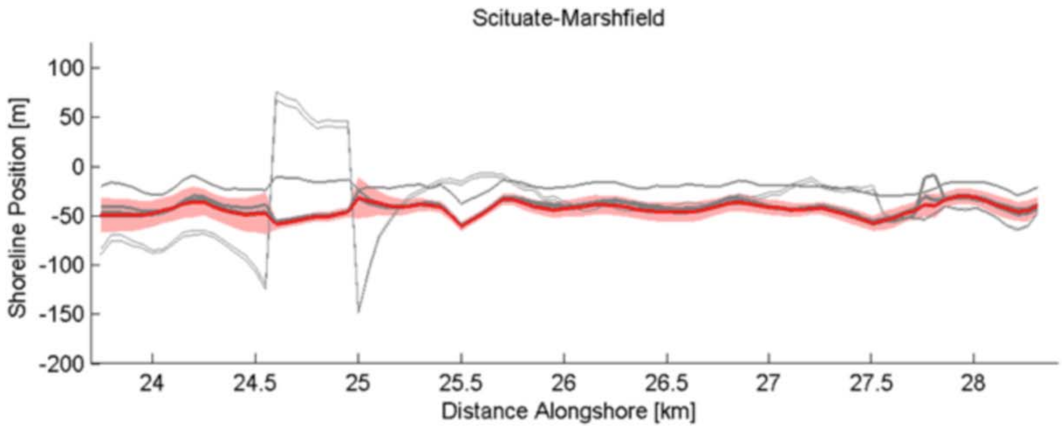


Figure 17. Graph showing historical shoreline positions, a 2025 shoreline position forecast and forecast uncertainty for part of Scituate-Marshfield, Massachusetts using the Kalman filter technique.

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Task 3A: Assist the Commission in evaluating methodologies and means which may be used to guard against and reduce or eliminate the impacts of coastal erosion by developing a summary of shoreline management practices, effectiveness, and adverse impacts

The Science and Technology Working Group developed the following summary based, in part, on the 2007 Massachusetts Coastal Hazards Commission report's Appendix C: Potential Benefits and Impacts of Protection Alternatives from, *Preparing for the Storm: Recommendations for Management of Risk from Coastal Hazards in Massachusetts*. Information developed for the StormSmart Properties Fact Sheet Series was also used for reference. Because many shore protection techniques require maintenance and mitigation to address adverse impacts to the shoreline system, information regarding the relative costs, maintenance, and mitigation has been included below to provide a better understanding of the commitment associated with each alternative.

Under the Massachusetts Wetlands Protection Act Regulations, new hard coastal engineered structures such as revetments, seawalls, and geotextile tubes (large sand-filled bags composed of high-strength synthetic fabric) are typically prohibited on all beaches and dunes. The construction of coastal engineered structures on coastal banks is only allowed when necessary to protect buildings permitted before August 10, 1978. Although coastal engineered structures may stop erosion of the area behind the structure, they can have significant adverse impacts, including the reflection of wave energy and resulting erosion of the fronting beach (Morton, 1988; Pilkey et. al., 1988). If sediment is not added to maintain the level of the beach, the erosion may undermine the structure, reducing its effectiveness and leading to costly repairs. Ongoing erosion of the beach results in loss of the dry beach at high tide, reducing the beach's value for storm damage protection, recreation, and wildlife habitat. Coastal engineered structures on coastal banks also cut off the supply of sediment to the longshore sediment system, which increases erosion of downdrift beaches, dunes, and properties. Geotextile tubes can be damaged, deflated, or destroyed, resulting in the tube or portions of the tube becoming marine debris and a hazard to recreation and navigation.

Sand fences are typically placed at the back of a beach to help capture wind-blown sand to build dunes. If relatively simple fencing composed of thin wooden slats held together with twisted wire, with at least 50% openings is used in areas where it is outside the reach of high tides and outside endangered shorebird nesting habitat, then potential impacts are limited to creating marine debris if the fence washes out in a storm event. Other materials, such as plastic and wire fencing are not recommended for use in coastal areas due to their potential impacts. For instance, so called "sturdy drift fencing," which is typically designed as a wave break and not as a mechanism for trapping blowing sand, is constructed with more robust structural elements than standard wire and slat fencing. This type of fencing can increase scour and erosion around the larger posts and can act as a physical barrier that interferes with longshore sediment transport. When destroyed in a storm, sturdy drift fencing results in significantly more marine debris on beaches, with metal bolts, screws, and nails posing a threat to public safety.

Breakwaters, mounds of rock or other modular units installed offshore and typically parallel to the shoreline, are used to create a barrier that dissipates the wave energy before it reaches the shoreline or harbor area. Rock sills are smaller versions of breakwaters, with lower elevations, that can be used closer to the shoreline. Although breakwaters and sills do dissipate some wave energy and enhance sediment deposition, they often interrupt longshore sediment transport, resulting in increased downdrift erosion. Breakwaters and sills can also deflect wave energy onto the adjacent shoreline, increasing erosion (ASCE, 1994).

Shore perpendicular structures, such as groins, are constructed on beaches to trap and retain sediment moving alongshore, thereby increasing the width of the beaches on the updrift side of the structures. Groins can be used effectively when they are filled to entrapment capacity (i.e., the beach compartment between groins or other structures is completely filled with sediment), allowing alongshore transport to resume at the same rate. If not filled to entrapment capacity during construction or repair, the interference with sediment transport will cause increased erosion of downdrift beaches. Groins can also reflect wave energy, impede lateral access along the shoreline, and cause changes in beach and nearshore habitats (ASCE, 1994). Jetties are similar to groins, but they are installed at inlets to stabilize navigation channels. They are designed to interrupt longshore sediment transport to keep navigation channels clear, but they also result in erosion of downdrift beaches. This can be mitigated by sand by-passing, which involves the excavation of sediment from the updrift side of a jettied inlet and its placement on the down-drift side of the inlet. Some temporary impacts to biologic resources associated with the excavation and placement of sediments may also occur. If carefully designed, however, the adverse impacts of jetties on the longshore sediment transport system can often be mitigated (ASCE, 1994).

Sand back-passing is similar to sand by-passing—in that it involves excavation of sediment from an area of accumulation and placement of these sediments on an adjacent beach—but the primary difference is that back-passing uses sediments that have reached a "dead-end" in the sediment transport system (i.e., where there is no potential for sediments to be naturally transported alongshore to other areas). This practice must be used carefully to ensure that sediment is only excavated from areas where it has reached that "dead-end" and that the removal of sediments will not increase storm damage to landward areas. Temporary impacts to biologic resources associated with the excavation and placement of sediments may also occur.

Non-structural techniques, such as beach and dune nourishment, artificially supply sediment to increase the volume of the natural system and enhance its ability to dissipate wave energy. Impacts may occur when the placement of sediment displaces nearshore habitat and biologic resources, such as shellfish habitat. Other non-structural techniques, such as bioengineering, can be used to stabilize eroding coastal banks using a combination of deep-rooted plants and erosion control products made of natural, biodegradable materials, such as coir rolls and natural fiber blankets. Anecdotal observations suggest that bioengineering projects on banks may absorb more wave energy than hard structures, such as seawalls and revetments, resulting in less erosion of the fronting and adjacent beaches. There is not yet a published body of literature that supports these observations. However, like hard structures, coir rolls can reduce the natural supply of sediment from coastal banks to beaches and some increased erosion may occur at the terminal ends of the project. In some low- to medium-energy environments, bioengineering can also be used to create salt marshes on fronting beaches to dissipate wave energy. The primary impact of creating new marshes on fronting beaches is the exchange of one resource type/habitat for another (MassDEP, 2007).

Sand-filled coir envelopes, layers of coir and jute fabric filled with sand, have some similarities to bioengineering. Coir envelopes, however, have different impacts and design considerations than coir rolls. Although they may reflect less energy than revetments and seawalls, sand-filled coir envelopes tend to reflect more energy than traditional bioengineering with coir rolls and vegetation. In addition, coir envelope projects typically do not involve as much planting as bioengineering projects, and therefore do not offer the same benefits of having the plants take root to help stabilize the eroding landform after the other components have biodegraded. Although the sand contained in the envelopes may at some point be available for beach nourishment as the envelopes biodegrade, coir envelopes may inhibit the overall supply of sediment and cause increased erosion at the terminal ends of the project.

Summary of Shoreline Management Techniques

The applicability of each shoreline management option varies according to the nature of the risk, local conditions, and the resources that are available to apply the shoreline management techniques. It is important to review the various options in context of achieving a more resilient and livable community. In many cases, multiple, complementary techniques may be appropriate to manage erosion impacts and improve community resilience. Blending the appropriate structural and non-structural measures with effective land-use management tools offers the best opportunity to reduce risk.

Similar types of structures have been grouped together in the table below. For example, there are L-shaped, notched and T-shaped groins. The specific type of each structure would be selected to fit the site-specific conditions.

Shoreline Management Techniques

Table 11. Summary of shoreline management techniques, appropriate environment, and relative costs. Costs are based on the StormSmart Properties Fact Sheet Project and personal communications with coastal engineers who serve on the project's Technical Advisory Committee.

SHORELINE MANAGEMENT TECHNIQUE	ENVIRONMENT	RELATIVE COSTS			
		DESIGN and PERMITTING	CONSTRUCTION	AVERAGE ANNUAL MAINTENANCE COSTS	AVERAGE ANNUAL MITIGATION COSTS
Adapting Existing Infrastructure					
Relocate Buildings	low - high energy	low	very high	none	none
Relocate Roads & Infrastructure	low - high energy	low	very high	none	none
Elevate Existing Buildings	low - high energy	low	very high	low	none
Enhancements to the Natural System					
Dune Nourishment	low - high energy	low	low	low	none
Beach Nourishment	low - high energy	low-medium	low - high	low-medium	none
Bioengineering on Coastal Banks	low - high energy	medium - high	low – medium	low - medium	low
Erosion Control Vegetation	low - high energy	low	low	low	none
Sand Fencing	low - high energy	low	low	low	low
Salt Marsh Creation	low energy	low - high	low - medium	low - medium	none
Sand By-Pass	low - high energy	low - medium	low - medium	low	none
Sand Back-Pass	low – high energy	medium – high	low – medium	low	none
Cobble Berm/Dune	low – high energy	low – high	low -medium	low- medium	none
Nearshore Coastal Engineered Structures					
Breakwater/Reef–Nearshore	low- high energy	medium – high	high – very high	low	low
Hybrid Options					
Perched Beach	low energy	Medium-high	Medium-high	low	none
Sand-Filled Coir Envelopes	low – high energy	low – medium	low – medium	medium-high	low
Shore Parallel Coastal Engineered Structures					
Dike/Levee	low - high energy	medium - high	medium - high	low	low
Rock Revetment – Toe Protection	low - high energy	medium - high	high	low	low - medium
Revetment – Full Height	low - high energy	high - very high	very high	low	medium
Geotextile tubes	low - high energy	very high	high	medium - high	medium
Gabions	low energy	high – very high	high	medium	low
Seawall	low - high energy	high - very high	very high	low	medium - high

Bulkhead	low energy	High – very high	high	low	low
Shore Perpendicular Coastal Engineered Structures					
Groin	low - high energy	very high	very high	low	low - high
Jetty	low - high energy	very high	very high	low	low - high
Offshore Coastal Engineered Structures					
Breakwater – Offshore	low - high energy	very high	very high	low	none

Cost Estimates (average cost per linear foot of shoreline)
Low: <$200
Medium: $200-$500
High: $500-1000
Very High: >$1,000

Average Annual Mitigation Costs: estimated annual costs averaged over the life of the project to compensate for the technique's adverse effects.

Glossary of Terms

Artificial Dunes: New mounds of compatible sediments constructed at the back of a beach.

Beach Nourishment: Sediment brought in from an off-site source and placed on a beach to renourish eroding shores.

Bioengineering: A shore stabilization technique that uses a combination of deep-rooted plants and erosion control products made of natural, biodegradable materials, such as coir rolls and natural fiber blankets. Natural fiber blankets are mats made of natural fibers, such as straw, burlap, and coconut husk fibers. See Coir Rolls also.

Breakwater: Mounds of rock or other modular units constructed offshore to protect a shore area, harbor, anchorage, or basin from waves.

Bulkhead: A structure or partition used to retain or prevent sliding of the land.

Cobble Berm/Dune: A mound of mixed sand, gravel and cobble, which serves the function of a coastal dune.

Coir Rolls: 12- to 20-inch diameter cylindrical rolls that are packed with coir fibers (i.e., coconut husk fibers) and are held together with mesh.

Downdrift: The direction of predominant sediment movement alongshore.

Dune Nourishment: Compatible sediment brought in from an off-site source and placed on an existing dune.

Erosion Control Vegetation: Salt-tolerant plants with extensive root systems that reduce erosion by holding sediments in place. The plants also control erosion by breaking the impact of raindrops or wave splash and physically slowing the speed and diffusing the flow of overland runoff.

Gabions: Rectangular wire baskets filled with stone or crushed rock to protect bank or bottom sediments from erosion.

Geotextile Tube: Large sand-filled geotextile bags constructed from high-strength synthetic fabric.

Groin: A narrow shoreline structure that is constructed perpendicular to the beach and designed to interrupt and trap the longshore flow of sediment, building sediments up on the updrift side at the expense of the downdrift side. Most groins are constructed of timber or rock and extend from a seawall or the backshore well onto the foreshore.

Jetty: A structure extending beyond the mouths of rivers or tidal inlets to help deepen, stabilize, and prevent shoaling of a channel by littoral materials.

Levee: 1) A ridge or embankment of sand and silt, built up by a stream on its flood plain along both banks of its channel. 2) A large dike or artificial embankment, often having an access road along the top, which is designed as part of a system to protect land from floods.

Littoral: Of or pertaining to a shore, especially of the sea. Often used as a general term for the coastal zone influenced by wave action, or more specifically, the shore zone between the high and low water marks.

Littoral Cell: A reach of the coast with its own complete cycle of sedimentation including sources, transport paths, and sinks. Littoral cells along the coast are separated from one another by protruding headlands, inlets, and river mouths that prevent littoral sediment from passing from one cell to the next. Cells may range in size from a multi-hundred meter pocket beach in a rocky coast to a barrier island many tens of kilometers long.

Longshore: Parallel to and near the shoreline; alongshore.

Nearshore: The area extending seaward from the shoreline to a water depth generally less than 10 meters.

Perched Beach: A beach that is elevated above its original level by a submerged retaining sill that traps sand.

Resilience: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.

Revetment: A retaining wall or facing of stone used to protect an embankment against erosion by wave action or currents.

Salt Marsh: Coastal wetlands regularly flooded and inundated by salt water from the tides.

Sand Back-Passing: Hydraulic or mechanical movement of sand from an accreting "dead-end" downdrift area to an eroding updrift area.

Sand Bypassing: Hydraulic or mechanical movement of sand from the accreting updrift side to the eroding downdrift side of an inlet or harbor entrance. The hydraulic movement may include natural movement, as well as movement caused by erosion.

Sand Fencing: Fencing installed to help build dunes and sometimes used to designate the boundaries of pedestrian access on dunes.

Seawall: A structure, often concrete or stone, built along a portion of a coast to prevent erosion and damage by wave action. Seawalls often retain earth behind them. Seawalls are typically more massive and capable of resisting greater wave forces than bulkheads.

Sill: A submerged structure designed to reduce the wave energy reaching landward areas.

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Task 4A: Assist the Commission by providing recommendations regarding methodologies to map coastal hazards variables as indicators for determining higher hazard areas.

Flooding, erosion, storm surge, and other natural forces along the coastline have the potential to threaten populations, development, and resources. Certain sections of the Massachusetts coastline are particularly vulnerable to coastal hazards due to differences in topography, geology, offshore physical processes, and varying patterns of human activities and development along the coast (Applied Coastal Research and Engineering, 2005). Even over short distances, differences in the landscape and natural processes can significantly influence the severity and extent of hazard impacts that a particular location may experience (Stockdon et al., 2007). As a result, managing coastal hazards requires an understanding of how impacts are distributed across the landscape and over time. Knowing which areas may be more vulnerable to coastal hazards can help inform land use planning decisions and guide shoreline management measures in more sustainable ways.

Coastal inundation mapping is a key component of assessing vulnerability and planning for future impacts (Massachusetts Office of Coastal Zone Management, 2013). The full range of coastal hazards affecting communities can be evaluated to help differentiate the relatively safe geographic areas from those that may be more vulnerable. FEMA flood zone maps identify locations that are subject to flooding from a storm that has a 1% chance of occurring in a given year (also known as a 100-year storm). However, these maps do not identify locations that are at risk to erosion and future sea level rise. Potential storm surge zones and sea level rise may extend beyond the mapped 100-year flood zone, or cause greater impacts to areas within the 100-year flood zone that currently experience frequent flooding from small storms or high tides. The inclusion of different timescales and intensities of coastal flood events may offer a more complete picture of the varying levels of vulnerability along the coast.

The Science & Technology Working Group recommends identifying *high hazard areas*–areas that are currently at risk to frequent flood inundation and erosion and at significant risk to larger storm events and future sea level rise. High-hazard area mapping will need to consider the purpose and the intended audience or users of the maps. The scale and standards to which mapping will need to conform will depend on whether the maps are for general guidance or public awareness, to help inform land use planning decisions, or to serve as a basis for making regulatory decisions. Likewise, coastal managers, land owners, planners, scientists/engineers, and regulators will use the maps differently and need information presented at different scales. It is important to note that current data sources cannot accurately depict high hazard areas at the parcel-level scale.

The Working Group recommends a two-pronged approach to identify high hazard areas:

1) Produce a comprehensive overlay of potential flood inundation from a range of coastal hazards scenarios, including different timescales and intensities (New York State Department of State, Risk Assessment Methodology). The following data layers can be used to create a map depicting areas of potential inundation, with the caveat that the data will

need to be carefully examined to determine how combining these layers will affect map accuracy and uncertainty:

a. FEMA Flood Zones
b. Sea Level Rise Scenarios
c. Sea, Lake, And Overland Surges From Hurricanes (SLOSH) Storm Surge Inundation Zones
d. Shallow Coastal Flooding Areas (illustrates the extent of flood-prone coastal areas based on predicted water levels exceeding specific tidal heights as issued by the National Weather Service Weather Forecast Office)
e. Density and Type of Development
f. Repetitive FEMA Flood Claims

2) Characterize the geologic and geographic variables that are not currently accounted for in inundation maps but have the potential to significantly increase the vulnerability of development and infrastructure to coastal hazards. (See, for example, the CZM South Shore Coastal Hazards Characterization Atlas). Segments of the shoreline could be color-coded to correspond to varying levels of vulnerability associated with each variable. An example that illustrates where the physical effects of sea level rise might be the greatest due to local variability in geologic and offshore physical processes is the U.S. Geological Survey's Coastal Vulnerability Assessment of Cape Cod National Seashore to Sea-Level Rise (see example in Figure 1). Variables that could be used to characterize coastal hazard vulnerability in a similar color-coding scheme along the Massachusetts shoreline include, but are not limited to:

a. Elevation: Determine elevations of coastal dunes, banks, or the back beach relative to increased water levels during storms as an indicator of areas that may be subject to erosion, overwash, or inundation.
b. Wave Climate: Identify the distribution of wave energy along the Massachusetts coast.
c. Dry Beach Width: Assess the width of the beach as an indicator for relative beach stability and potential protection to landward areas from storm wave attack.
d. Shoreline Type (Geomorphology): Delineate the dominant coastal landforms that govern coastal geological processes. Areas identified as barrier beaches are typically more susceptible to storm overwash, therefore natural landward migration of these features should be anticipated.
e. Historical Shoreline Change Rate: Illustrate historical rates of shoreline change (erosion vs. accretion) along the entire Massachusetts coast. Storm effects may be exacerbated on highly eroding shorelines, extending flood zones farther landward, whereas shorelines that are accreting may be less prone to severe effects.
f. Coastal Slope: Illustrate relative vulnerability to inundation and the potential rapidity of shoreline retreat based on coastal slope. Low-sloping coastal regions generally retreat faster than steeper regions. To calculate coastal slope, obtain topographic and bathymetric elevations extending landward and seaward of shoreline.
g. Beach Slope: Determine how the beach slope (measured between the dune, or berm, and mean high water line) influences the amount of wave run-up.
h. Coastal Engineered Structures: Inventory the presence of coastal engineered structures, since they can impact the way the shoreline responds to storm events.

Though coastal engineered structures may reduce the effects of storm-generated waves, locations may be at increased risk to wave overtopping effects if the structures are in poor condition, deteriorating, or not built to withstand current or anticipated storm water levels.

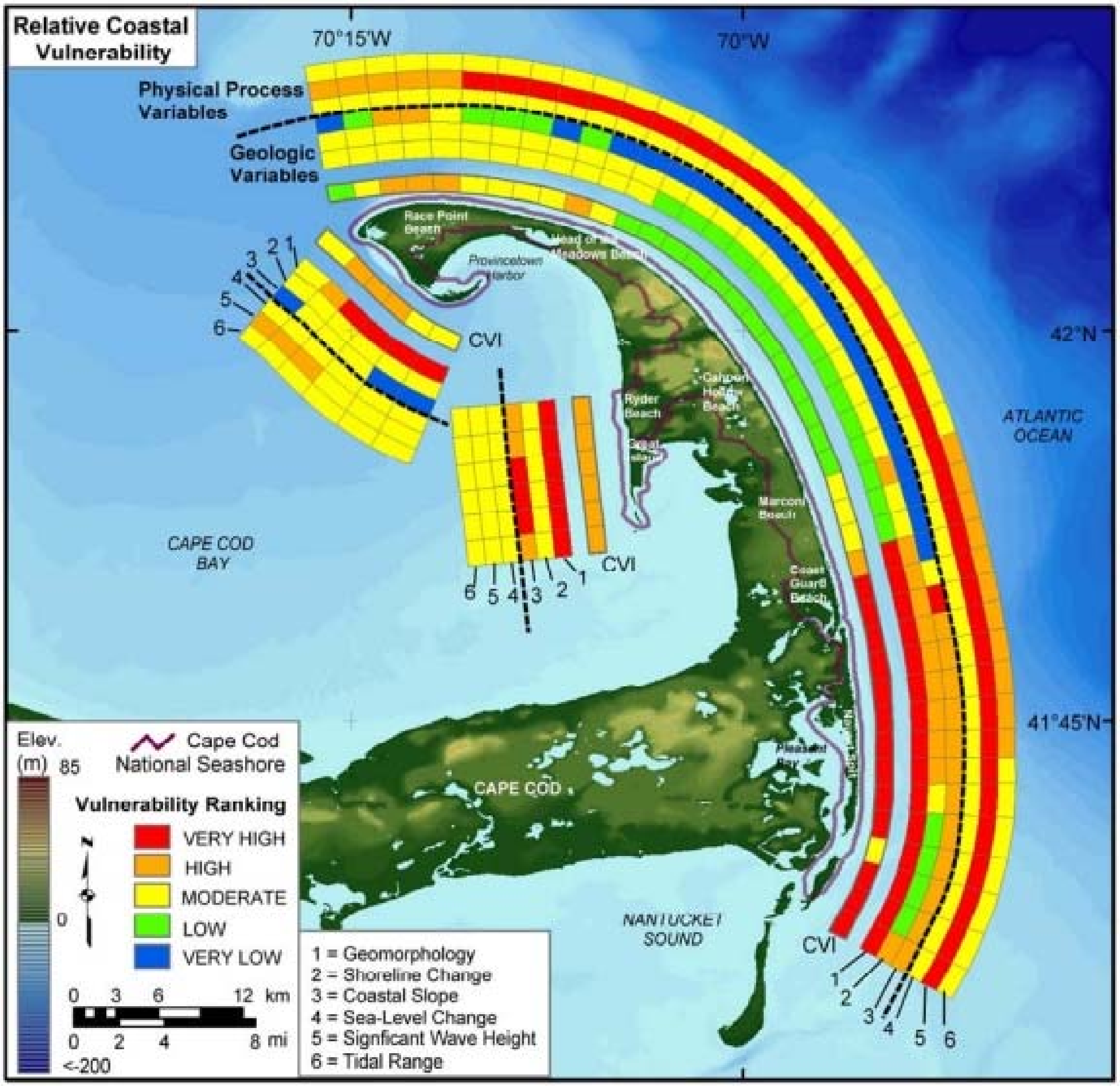

Figure 18. Relative coastal vulnerability for the Cape Cod National Seashore. The coastal vulnerability index (CVI) is a summary of the vulnerability of the individual geologic and physical process variables. (Hammar-Klose et al., 2003).

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Task 4B: Assist the Commission by providing general recommendations pertaining to the science and technical aspects of reducing impacts of coastal erosion.

Preliminary Recommendations to the Commission

1. Identify knowledge gaps in hazard assessments, shoreline position/condition forecasting, and storm impacts, and the potential effects of these gaps on policy and decision making. Actions include:
   - Evaluating whether sufficient knowledge of future impacts exists on which to base policy and planning.
   - Evaluating whether topical information is lacking (e.g., physical setting, coastal processes, infrastructure and property valuation).
   - Evaluating where spatial information (e.g., locations along the Massachusetts coast) is lacking.

2. Improve the ability to understand coastal erosion impacts and potential responses at appropriate spatial scales by looking at larger sections of the coastline. Actions include:
   - Littoral cell mapping, regional sediment budget and management studies.
   - Assessing long-term and cumulative effects of shoreline management techniques, including impacts to adjacent properties and natural resources (physical and biological).
   - Assessing the economic value of Massachusetts beaches.

3. Develop criteria to evaluate impacts and alternatives to repairs or reconstruction of publicly owned coastal engineered structures. Actions include:
   - Clearly defining what is being protected (buildings, utilities, natural resource area, etc.) and determining whether repair or reconstruction increases or decreases hazard exposure.
   - Performing alternatives and benefit/cost analysis, including no action, relocation, upgrades to the structure, and mitigation, and determining potential impacts over the structure's lifetime.
   - Monitoring the performance and impacts of the structure to improve the basis for decision making.

4. Improve the use of sediment resources for beach nourishment. Actions include:
   - Identifying offshore sources of sediment for beach nourishment through the Ocean Management Planning process.
   - Expanding the Barnstable County Dredge Program model to other areas.
   - Increasing the use of sediment by-passing and back-passing.

Science and Technology Working Group - Appendix A

Shoreline Characterization Methods, Figures, and Tables

Science and Technology Working Group Appendix A: Shoreline Characterization Methods, Figures, and Tables

Methods

Coastal landforms (e.g., dune, beach, and bank), habitats (e.g., forest, salt marsh, and rocky intertidal shore), developed lands (e.g., high-density residential, commercial, and industrial), and shore-parallel coastal engineering structures (e.g., bulkheads/seawalls and revetments) are hereby collectively referred to as "classes."

An introduction to the transect approach employed for shoreline characterization can be found under Task 1B. To characterize the shoreline and define the assessment units, this approach utilizes existing data, from: 1) a contemporary shoreline (ca. 2007-2009), and 2) shore-parallel transects, both from the CZM-USGS Massachusetts Shoreline Change Project, 2013 Update. More information about the Massachusetts Shoreline Change Project can be found at http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/shoreline-change/, including the USGS Open-File Report, *Massachusetts Shoreline Change Mapping and Analysis Project, 2013 Update.*

Data Sources

GIS data layers depicting coastal landforms, habitats, and developed lands include the following:

- *Massachusetts Department of Environmental Protection (DEP) Wetlands*
  http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/depwetlands112000.html
  Polygon features in this data layer describe different types of wetland resource areas. They were interpreted from 1:12,000 scale, stereo color-infrared (CIR) photographs by staff at the University of Massachusetts Amherst. The images covering coastal Massachusetts were captured in 1990, 1991, and 1993. The interpretation was field checked by the DEP Wetlands Conservancy Program. A recent draft update of this data layer was created by the DEP Wetlands Conservancy Program based on multispectral images captured in April 2005 (0.5 m spatial resolution, 1:5,000 digital stereo pairs using a color infrared band). The draft updated data layer was obtained, but not used for shoreline characterization. It has not been published as of this writing.

- *Massachusetts Office of Geographic Information (MassGIS) 2005 Land Use*
  http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/lus2005.html
  Land cover/land use polygons were created using semi-automated methods, based on 0.5 m spatial resolution, digital orthophoto images captured in April 2005. The minimum mapping unit (MMU) is generally 1 acre, but an MMU as low as 0.25 acres may be found in some

areas; e.g., in urban areas where assessor parcels were used to enhance the mapping of multi-family residential areas.

Of the 27 wetland classes mapped in the DEP Wetlands data layer, 25 were found at the immediate, assessed shoreline. Of the 33 land cover/land use classes mapped by MassGIS, 29 were found at the immediate, assessed shoreline. Complete lists of classes described by these data layers are provided in Tables 1 and 2 below.

GIS data layers depicting shore-parallel coastal engineering structures include the following:

- *Massachusetts Coastal Zone Management (CZM) Inventory of Privately Owned Coastal Structures (2013)* http://www.mass.gov/eea/docs/czm/stormsmart/seawalls/private-coastal-structures-2013.pdf
  Line features that represent coastal engineered structures (e.g., seawalls, jetties, and revetments) were identified and mapped using remote sensing techniques and high-resolution imagery. The inventory included an identification of the location, length, type, material, and elevation of structures that were not mapped in previous phases of the Massachusetts Coastal Infrastructure Inventory and Assessment Project (with the presumption that they are privately owned).

- *Massachusetts Department of Conservation and Recreation and CZM Inventory of Publicly Owned Coastal Structures (2006-2009)*
  http://www.mass.gov/eea/docs/czm/stormsmart/seawalls/public-inventory-report-2009.pdf
  Publicly owned coastal structures were mapped by civil engineers using GPS units in the field. These line feature data were attributed with condition ratings and estimated repair or reconstruction costs.

Together these two sources of data include a total of four classes of coastal engineered structures: breakwaters, bulkheads/seawalls, groins/jetties, and revetments. Only two classes, bulkheads/seawalls and revetments, were used for this exercise since interest was in characterizing structures that are both shore-parallel and constructed along the shoreline. Visit the CZM StormSmart Coasts Inventories of Seawalls and Other Coastal Structures web page for more information: http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/seawall-inventory/.

Processing Steps

The general steps taken to complete the shoreline characterization exercise are as follows. GIS points were created at the intersections of the contemporary shoreline and transects, as shown in Figure 1. The shoreline was split at these points for further processing. Midpoints were generated along the shoreline segments (between transects), as depicted by the green points in Figure 2. This figure also shows an example of an approximately 50 m shoreline segment (green line). This segment represents one assessment unit used to characterize the seaward and landward classes found along its transect. Shoreline segments (i.e., assessment units) have a one-to-one relationship with transects—i.e., each segment is associated with a unique transect.

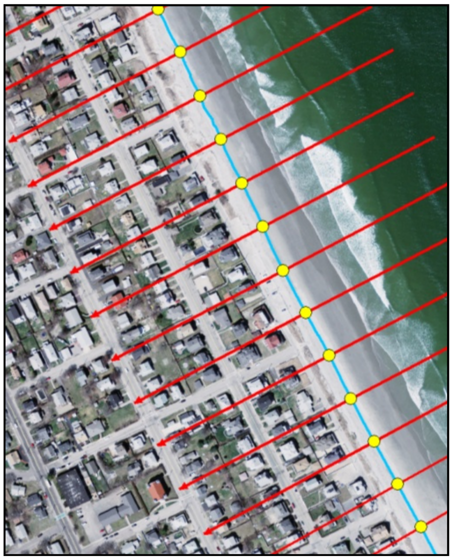


Figure 1. (left image) Points (yellow) were generated at the intersection of transects and the contemporary shoreline.

Figure 2. (right image) Shoreline segments of ~ 50 m were split using intersection midpoints (green points).

As described above, class data and shoreline-transect data were sourced from a number of different data layers. Each data layer required some level of processing to prepare it for shoreline characterization. Described here is one unique challenge that arose from MassGIS 2005 Land Use data layer production.

Wetland polygons from the DEP Wetlands data layer were added to the MassGIS 2005 Land Use data layer during production, replacing any underlying interpreted land cover/land use polygons. The reason for this was that wetland polygons were interpreted at a reasonably large scale and they provided the best available digital data on wetland coverage and shoreline delineation. The DEP Wetlands data layer includes a number of classes, such as Coastal Beach, Coastal Dune, Salt Marsh, etc. Where these classes occur within a barrier beach system, they are referenced as separate classes (e.g., Barrier Beach-Salt Marsh vs. Salt Marsh). The DEP Wetlands data layer also includes a class named Barrier Beach System (BBS), which represents areas where wetland classes do not occur (e.g., developed lands) within a barrier beach system. For instance, a residential community on Plum Island, a barrier island, is mapped as Barrier Beach System with no land cover/land use interpretations--a result of using the MassDEP Wetlands polygons in the MassGIS 2005 Land Use data production. Without the ability to go back to intermediate 2005 Land Use data, a surrogate had to be used to fill in the data gaps created by the Barrier Beach System wetland polygons. Where BBS occurs, the MassGIS 1999 Land Use data layer was used. BBS areas occur in a number of communities, though typically as small areas, with the exception being the residential community at the north end of Plum Island.

Classes from the three pre-processed data layers representing coastal landforms, wetlands, other undeveloped lands, developed lands, and shore-parallel coastal engineered structures were spatially joined to the transect data layer (see Figure 3). This means that information about each class polygon intersected by a particular transect was passed onto that transect. Data were further processed to result in approximately 26,500 unique transects attributed with the presence or absence of each of the 62 original classes. Transect data were then spatially joined to their corresponding shoreline segments, resulting in the final assessed shoreline with class attributes.

A series of pre-processing steps were required to generate summary statistics of classes by community. Select classes were aggregated into bins, whereas others were reported as individual classes to focus on those of greatest interest. A list of classes and their corresponding bins can be found in Tables 1 and 2. Maps of the assessed shoreline and coastal engineered structures by community/region are presented in Figures 4a-4h. Results for 11 classes and bins are presented for each of the 57 communities assessed in Table 3 and Figure 5a-5o.

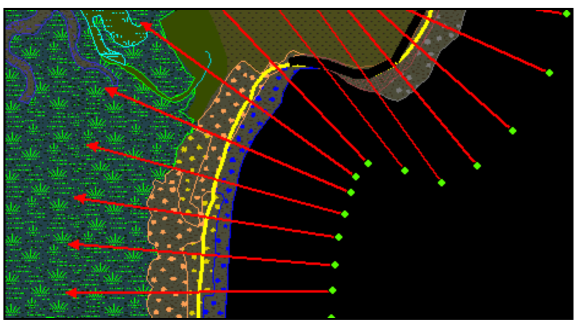


Figure 3. Transects intersecting land cover/land use, wetlands, and shore-parallel coastal engineering structures.

Map Figures and Tables

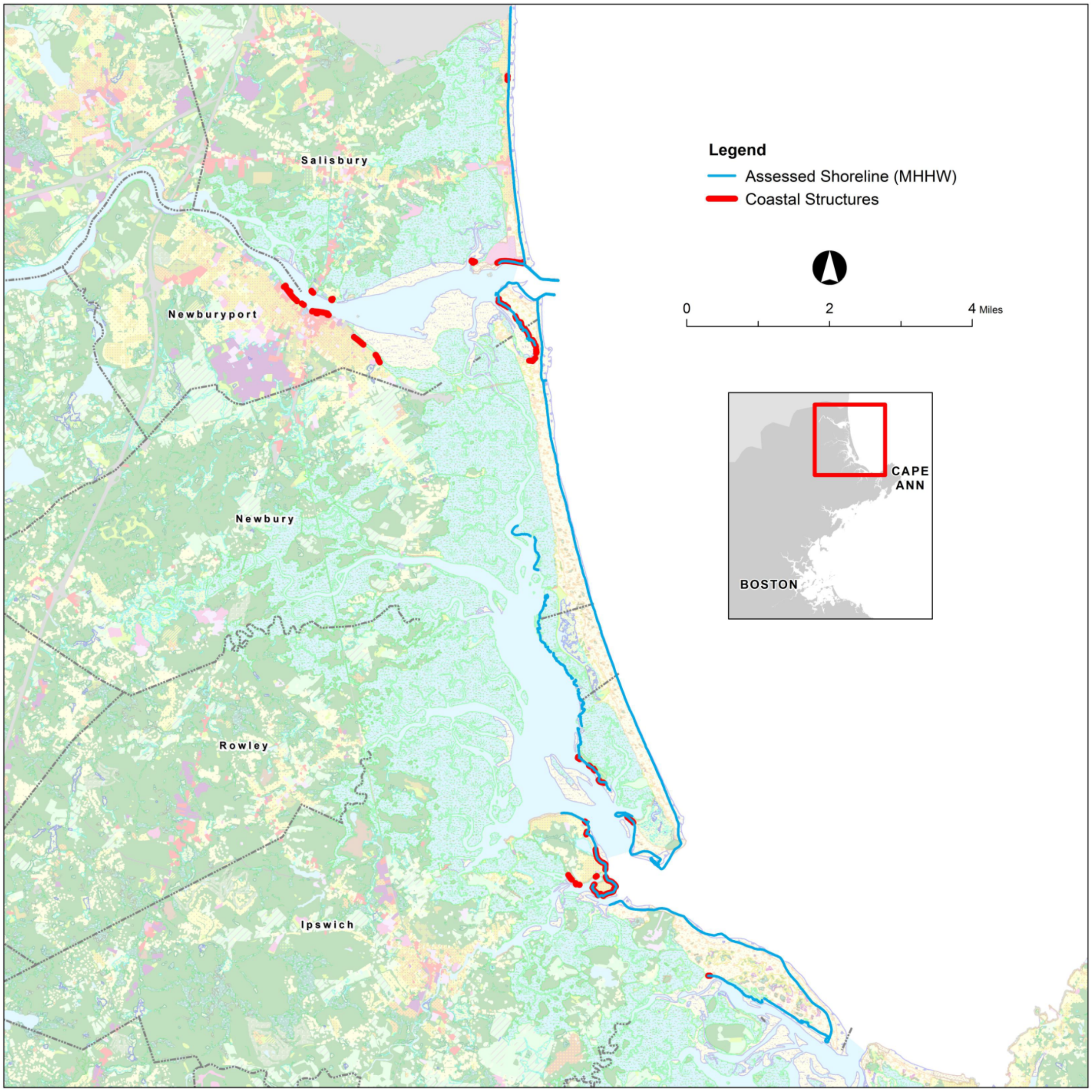


Figure 4a. Map of assessed shoreline (blue) and coastal engineering structures (red) for Salisbury, Newburyport, Newbury, Rowley, and Ipswich (North Shore Region).

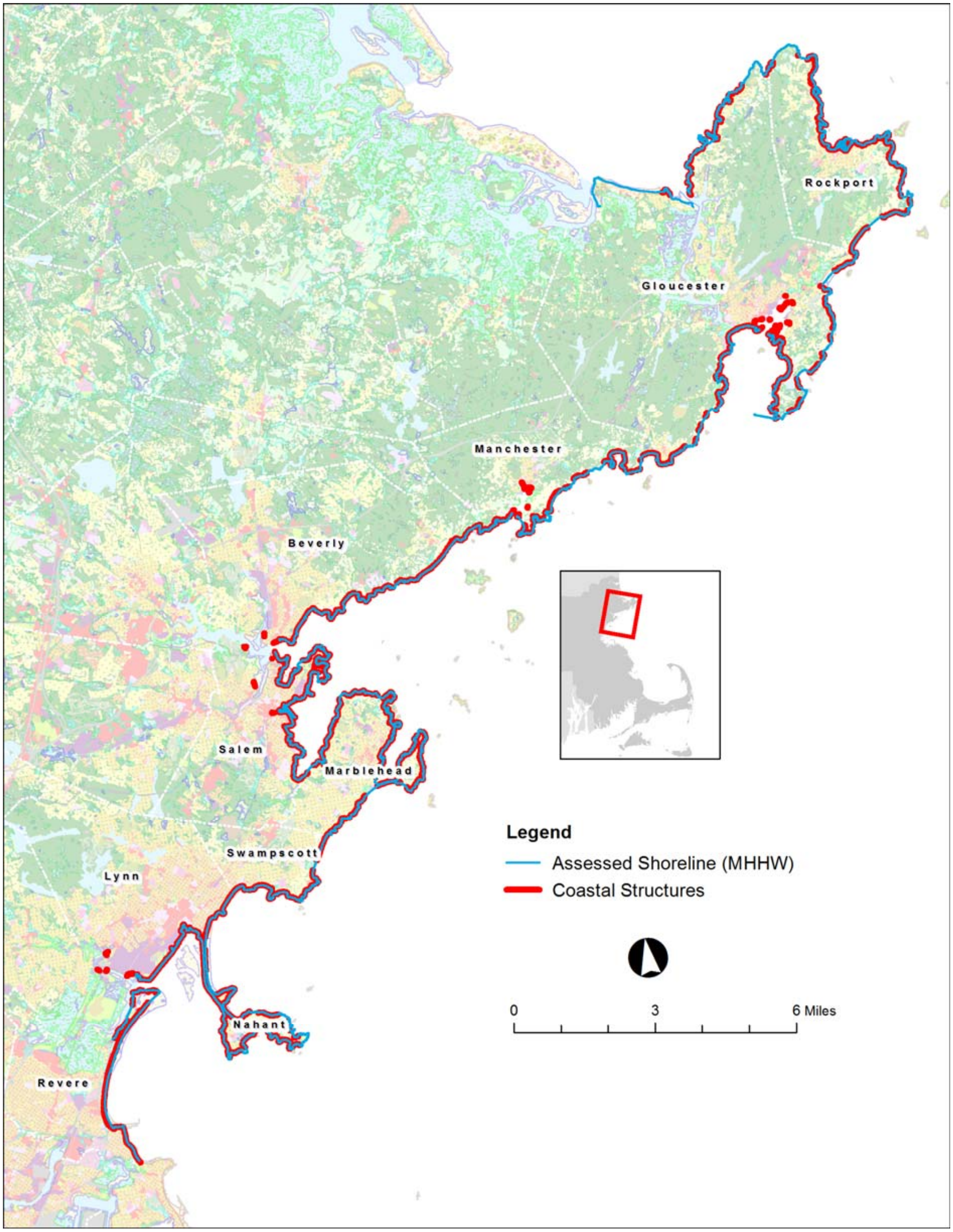


Figure 4b. Map of assessed shoreline (blue) and coastal engineering structures (red) for Gloucester, Rockport, Manchester, Beverly, Salem, Marblehead, Swampscott, Lynn, Nahant, and Revere (North Shore Region).

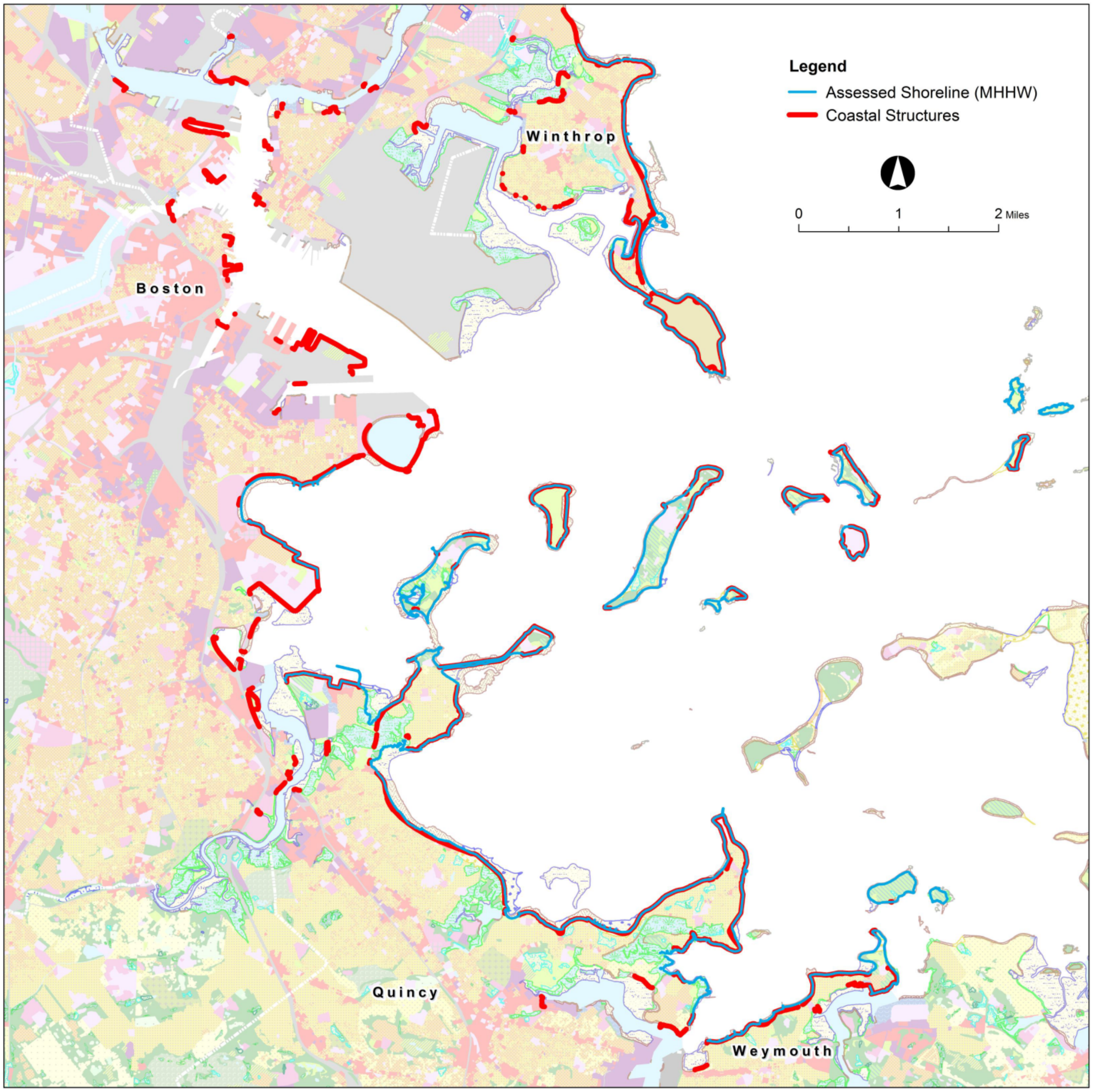


Figure 4c. Map of assessed shoreline (blue) and coastal engineering structures (red) for Winthrop, Boston, Quincy, and Weymouth (Boston Harbor Region).

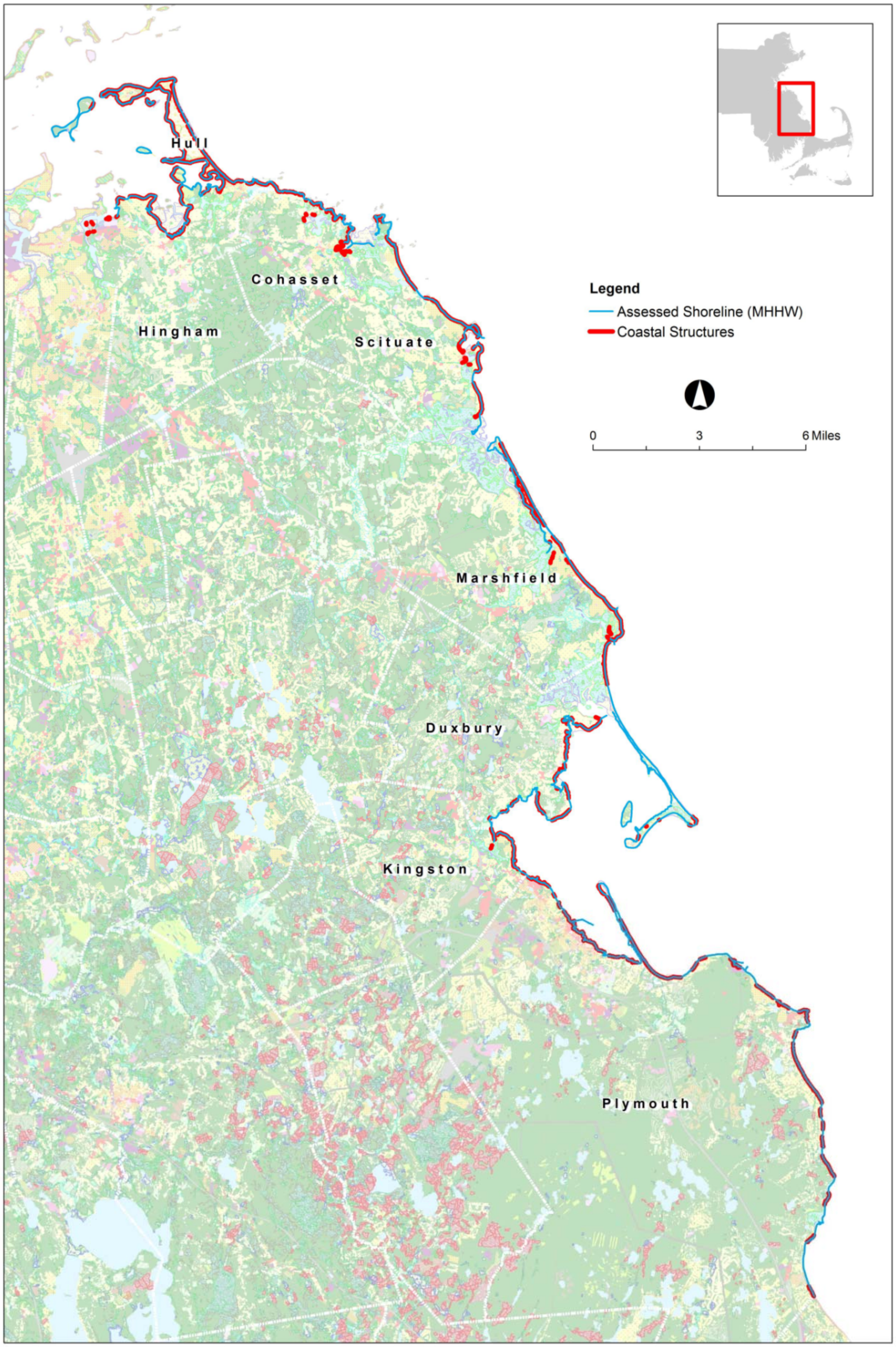


Figure 4d. Map of assessed shoreline (blue) and coastal engineering structures (red) for Hingham, Hull, Cohasset, Scituate, Marshfield, Duxbury, Kingston, and Plymouth (South Shore Region).

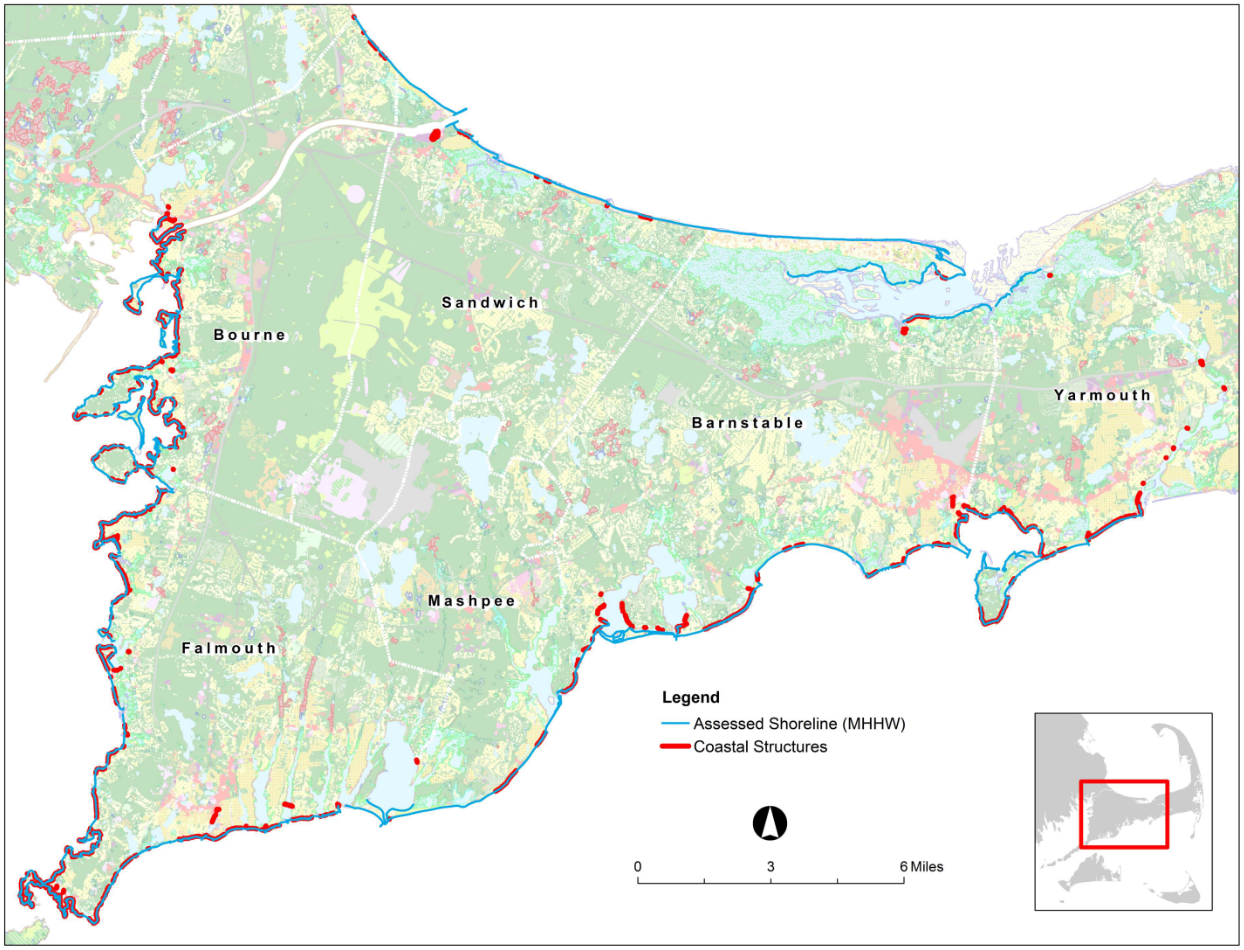


Figure 4e. Map of assessed shoreline (blue) and coastal engineering structures (red) for Bourne, Sandwich, Falmouth, Mashpee, Barnstable, and Yarmouth (Cape Cod & Islands Region).

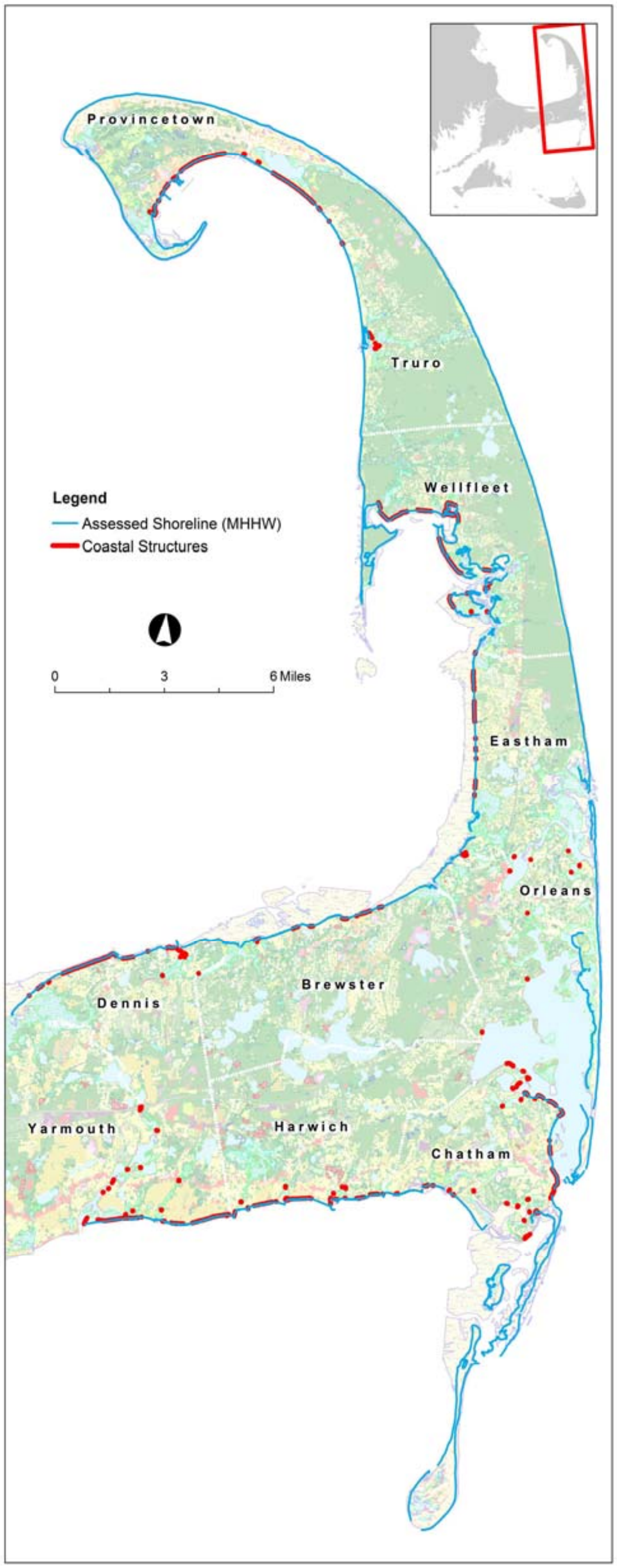
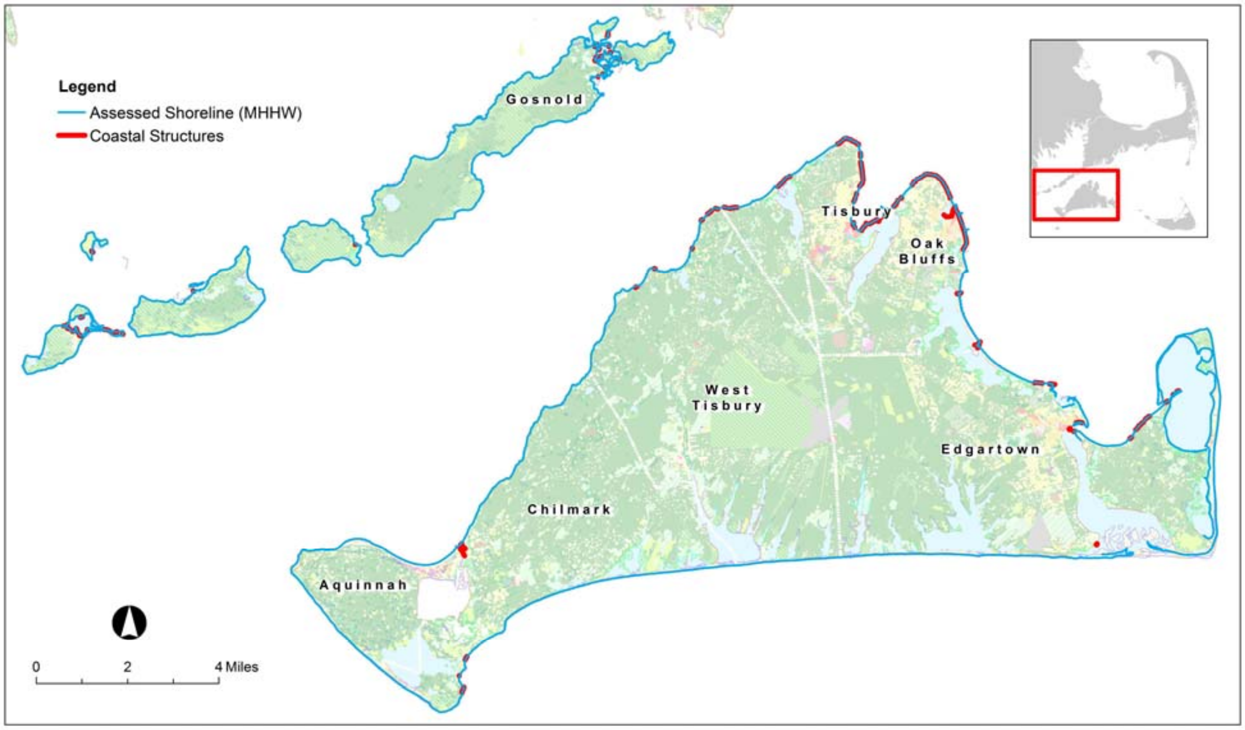


Figure 4f. Map of assessed shoreline (blue) and coastal engineering structures (red) for Dennis, Brewster, Harwich, Chatham, Orleans, Eastham, Wellfleet, Truro, and Provincetown (Cape Cod & Islands Region).



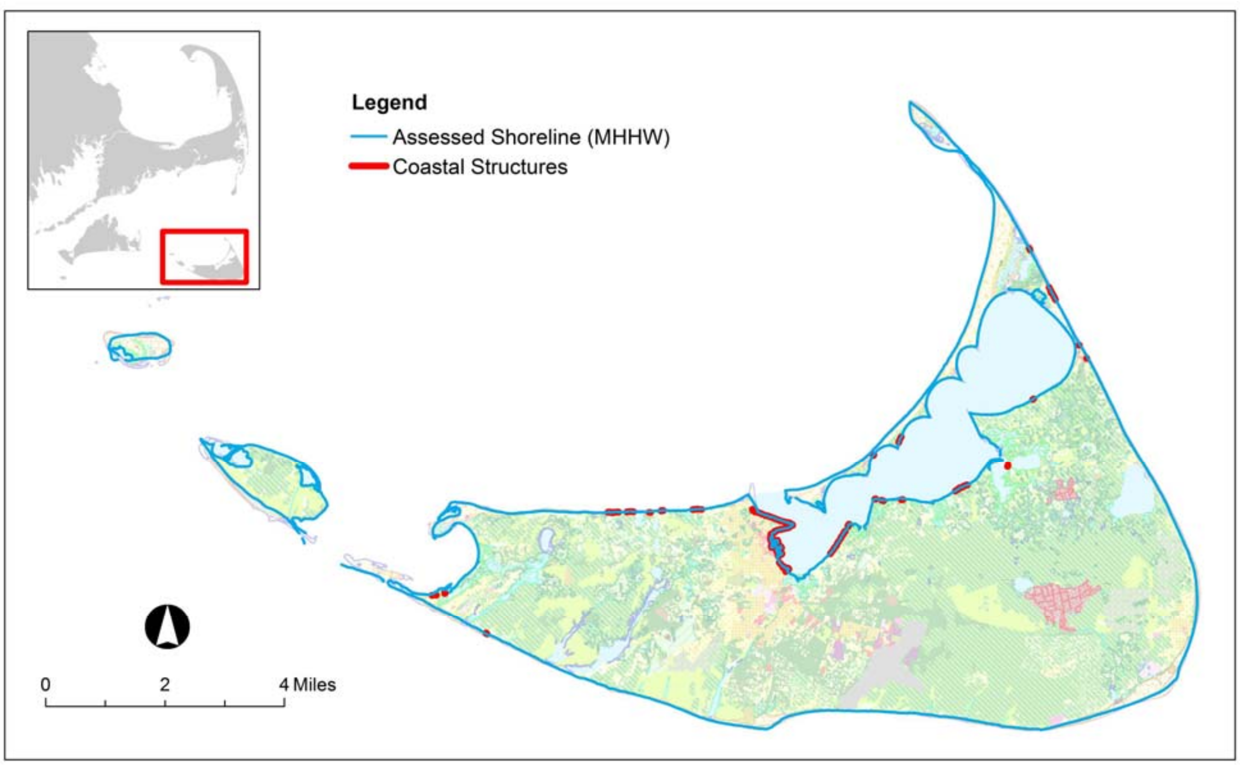
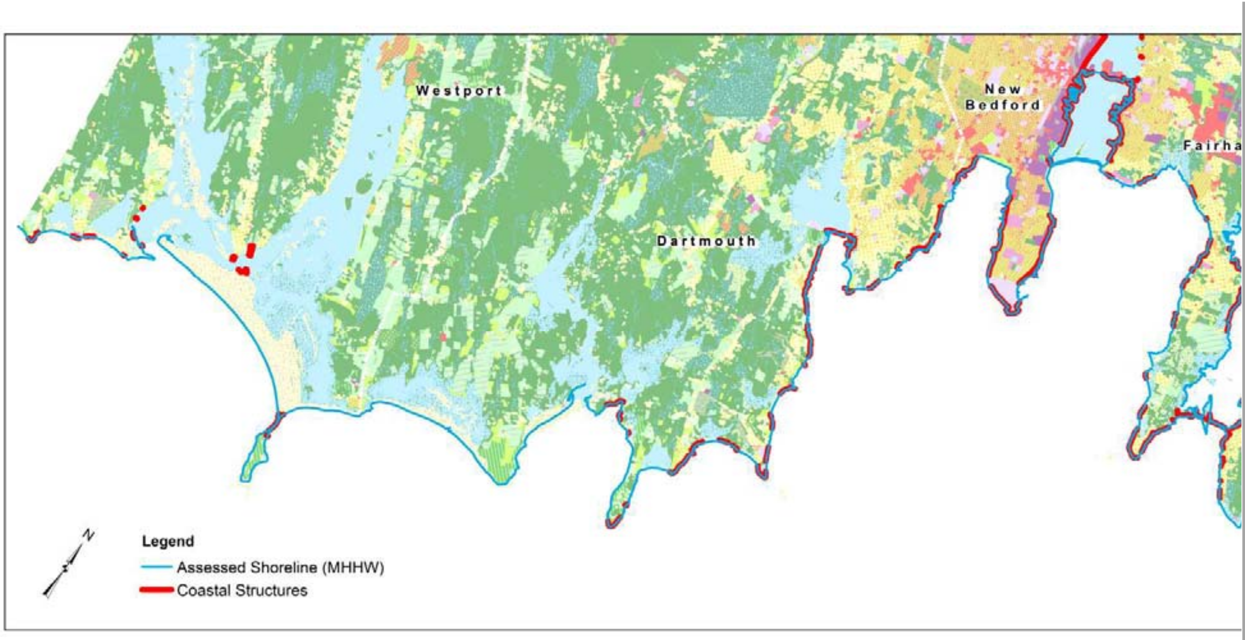


Figure 4g. Map of assessed shoreline (blue) and coastal engineering structures (red) for Edgartown, Oak Bluffs, Tisbury, West Tisbury, Chilmark, Aquinnah, Gosnold, and Nantucket. (Cape Cod & Islands Region).



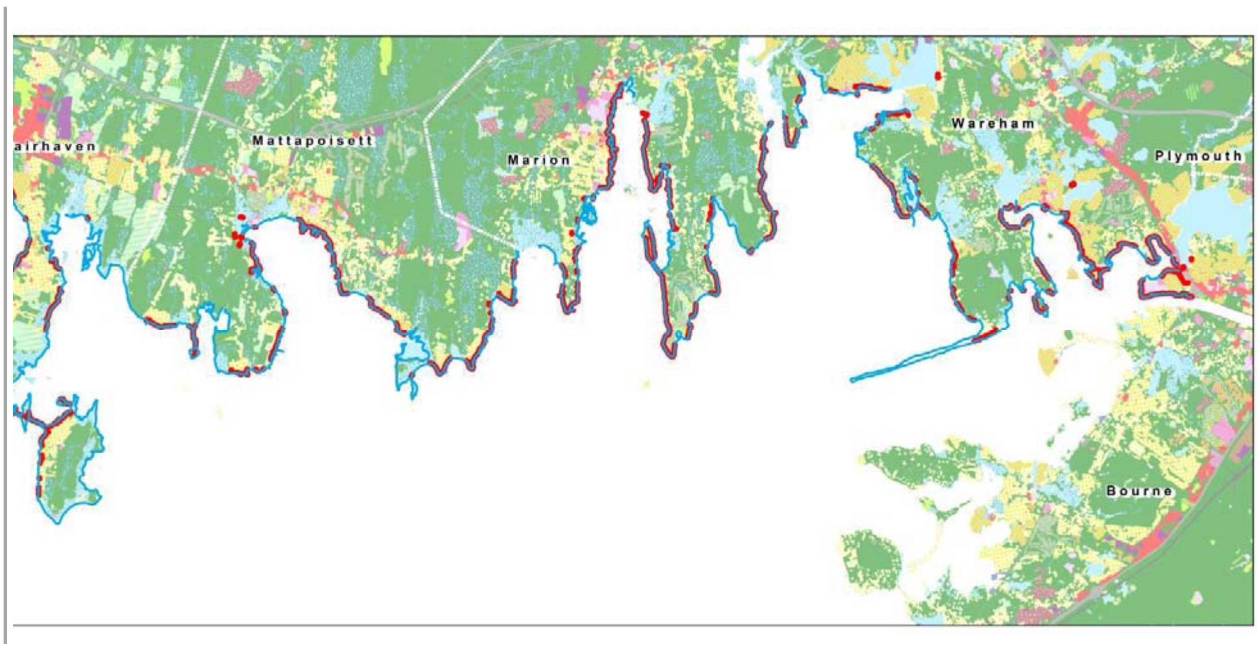


Figure 4h. Map of assessed shoreline (blue) and coastal engineering structures (red) for Westport, Dartmouth, New Bedford, Fairhaven, Mattapoisett, Marion, and Wareham (Buzzards Bay Region).

Table 1. List of MassGIS 2005 Land Use classes and corresponding aggregations (bins).

	MassGIS 2005 Land Use Class	Shoreline Characterization Class or Bin
1	Brushland/Successional	Natural Upland
2	Cemetery	Maintained Open Space
3	Commercial	Non-Residential Developed
4	Cropland	Maintained Open Space
5	Forest	Natural Upland
6	Golf Course	Maintained Open Space
7	High Density Residential	Residential
8	Industrial	Non-Residential Developed
9	Junkyard	Non-Residential Developed
10	Low Density Residential	Residential
11	Marina	Non-Residential Developed
12	Medium Density Residential	Residential
13	Multi-Family Residential	Residential
14	Non-Forested Wetland*	NULL
15	Nursery	Maintained Open Space
16	Open Land	Maintained Open Space
17	Participation Recreation	Maintained Open Space
18	Saltwater Sandy Beach*	NULL
19	Saltwater Wetland*	NULL
20	Spectator Recreation	Non-Residential Developed
21	Transitional	Non-Residential Developed
22	Transportation	Non-Residential Developed
23	Urban Public/Institutional	Maintained Open Space
24	Very Low Density Residential	Residential
25	Waste Disposal	Non-Residential Developed
26	Water*	NULL
27	Water-Based Recreation	Maintained Open Space
28	Pasture	Maintained Open Space
29	Forested Wetland*	NULL
30	Mining	Maintained Open Space
31	Cranberry Bog	Maintained Open Space
32	Powerline/Utility	Maintained Open Space

* MassGIS Land Use classes with NULL values were overriden by DEP Wetland classes.

Table 2. List of DEP Wetlands classes and corresponding aggregations (bins).

	DEP Wetlands Class	Shoreline Characterization Class or Bin
1	Barrier Beach-Coastal Beach	Beach
2	Barrier Beach-Coastal Dune	Dune
3	Barrier Beach System	<Reclassified using MassGIS 1999 Land Use>
4	Coastal Bank Bluff Or Sea Cliff	Coastal Bank
5	Coastal Beach	Beach
6	Coastal Dune	Dune
7	Rocky Intertidal Shore	NOT REPORTED
8	Salt Marsh	Salt Marsh
9	Shallow Marsh Meadow Or Fen	NOT REPORTED
10	Shrub Swamp	NOT REPORTED
11	Tidal Flat	NOT REPORTED
12	Wooded Swamp Deciduous	NOT REPORTED
13	Wooded Swamp Mixed Trees	NOT REPORTED
14	Wood Swamp Coniferous	NOT REPORTED
15	Deep Marsh	NOT REPORTED
16	Cranberry Bog	NOT REPORTED

(1) Wetland classes with NOT REPORTED values were included in this exercise, but not reported in this document.

(2) Coastal Bank was divided into two categories: 1) Coastal Bank, and 2) Coastal Bank-Presumed Rocky, but reported simply as Coastal Bank in this document.

Table 3. Percent of assessed shoreline for each class or bin by community. Multiple classes could occur at each shoreline segment.

Community	Class or Bin										
	Bulkhead/Seawall	Revetment	All Structures	Coastal Bank	Beach	Dune	Salt Marsh	Maint Open Space	Natural Upland	Non-Residential Dev	Residential
Aquinnah	0	0	0	28	100	70	5	19	54	3	15
Barnstable	7	11	17	8	80	69	32	19	18	2	31
Beverly	59	25	67	44	47	10	7	27	28	18	82
Boston	24	31	44	50	71	11	7	64	22	15	8
Bourne	12	18	28	21	65	22	31	13	46	8	58
Brewster	1	12	13	14	92	71	29	3	47	1	66
Chatham	1	3	4	5	90	75	23	4	5	1	11
Chilmark	0	1	1	32	78	34	2	17	65	0	11
Cohasset	28	8	31	59	40	13	18	20	28	0	70
Dartmouth	9	24	30	11	81	32	21	34	48	8	48
Dennis	14	31	43	22	97	62	19	14	32	15	60
Duxbury	9	9	17	6	59	37	55	12	21	3	47
Eastham	2	10	11	42	84	34	28	21	30	1	30
Edgartown	3	1	4	4	87	62	21	16	27	1	18
Fairhaven	17	7	23	5	37	16	54	16	21	10	41
Falmouth	19	37	49	16	80	34	13	19	37	6	64
Gloucester	24	15	35	66	26	12	2	28	28	5	67
Gosnold	0	2	3	19	86	13	16	21	76	1	6
Harwich	13	26	35	16	99	67	17	10	19	14	75
Hingham	29	22	49	26	47	1	47	32	41	6	46
Hull	44	39	61	33	73	8	13	29	15	12	68
Ipswich	5	9	14	11	79	69	26	6	17	1	12
Kingston	12	59	67	12	66	0	42	22	30	0	87
Lynn	65	66	100	8	27	2	0	68	0	59	24
Manchester	30	14	43	63	27	4	4	11	33	3	76
Marblehead	60	15	65	38	28	2	3	22	25	8	84
Marion	19	30	43	11	39	5	50	27	47	1	50
Marshfield	37	25	51	8	66	23	32	13	2	4	82
Mashpee	5	11	16	18	92	25	23	43	15	2	31

Community	Class or Bin										
	Bulkhead/Seawall	Revetment	All Structures	Coastal Bank	Beach	Dune	Salt Marsh	Maint Open Space	Natural Upland	Non-Residential Dev	Residential
Mattapoisett	14	24	37	11	46	17	46	19	38	3	57
Nahant	31	32	58	44	36	11	1	36	8	14	55
Nantucket	4	1	4	8	93	60	16	37	31	4	22
Newbury	8	1	8	0	74	60	25	1	0	0	28
Newburyport	11	10	19	0	88	61	14	6	0	0	52
Oak Bluffs	20	36	37	27	77	35	4	27	21	12	48
Orleans	0	0	0	10	61	72	52	6	19	0	10
Plymouth	9	46	52	55	73	24	12	18	34	20	51
Provincetown	8	4	10	1	94	74	10	23	17	17	19
Quincy	44	45	62	33	67	6	33	30	18	11	60
Revere	71	26	79	18	92	5	24	20	0	43	30
Rockport	33	26	49	75	14	1	5	12	27	19	65
Rowley	0	0	0	0	43	43	57	0	0	0	0
Salem	60	31	83	15	22	0	9	38	19	47	50
Salisbury	13	12	13	0	100	83	3	19	0	7	51
Sandwich	1	2	3	5	98	77	21	11	22	1	57
Scituate	25	44	50	43	67	19	27	12	10	5	63
Swampscott	73	13	75	51	46	5	0	17	8	20	80
Tisbury	14	24	28	12	88	45	18	13	59	13	60
Truro	6	0	6	41	100	51	1	44	37	11	31
Wareham	16	21	36	25	62	36	31	22	54	4	51
Wellfleet	9	7	16	38	71	38	54	27	50	3	29
West Tisbury	1	4	5	16	97	43	3	15	64	2	24
Westport	4	6	9	8	89	71	11	34	16	0	27
Weymouth	31	37	48	40	93	5	20	20	58	3	41
Winthrop	69	59	86	31	80	0	8	16	2	3	94
Yarmouth	9	26	30	4	80	58	30	27	35	8	35

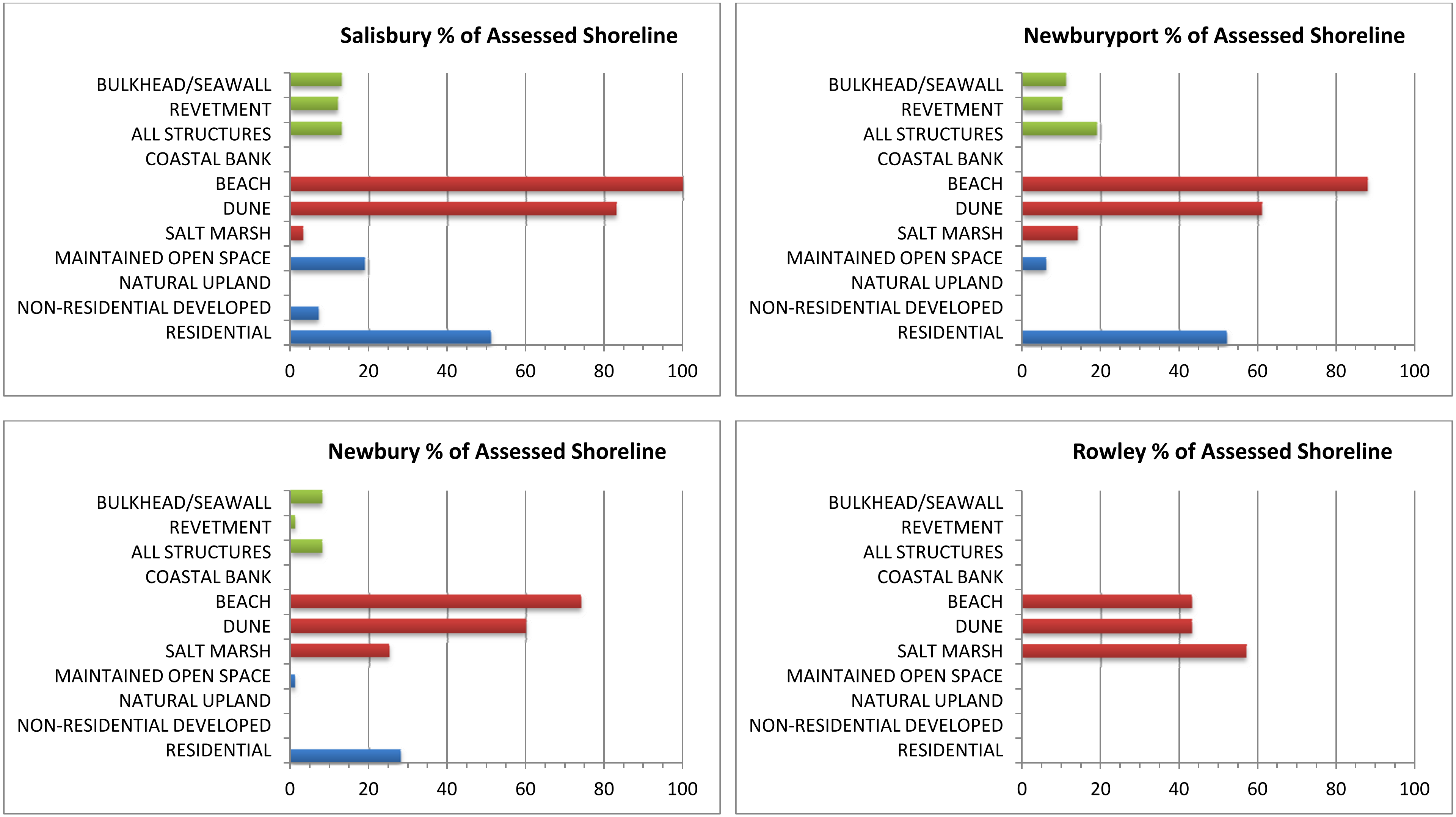


Figure 5a. Percent of assessed shoreline for each class or bin by community: Salisbury, Newburyport, Newbury, and Rowley (North Shore Region). Multiple classes could occur at each shoreline segment.

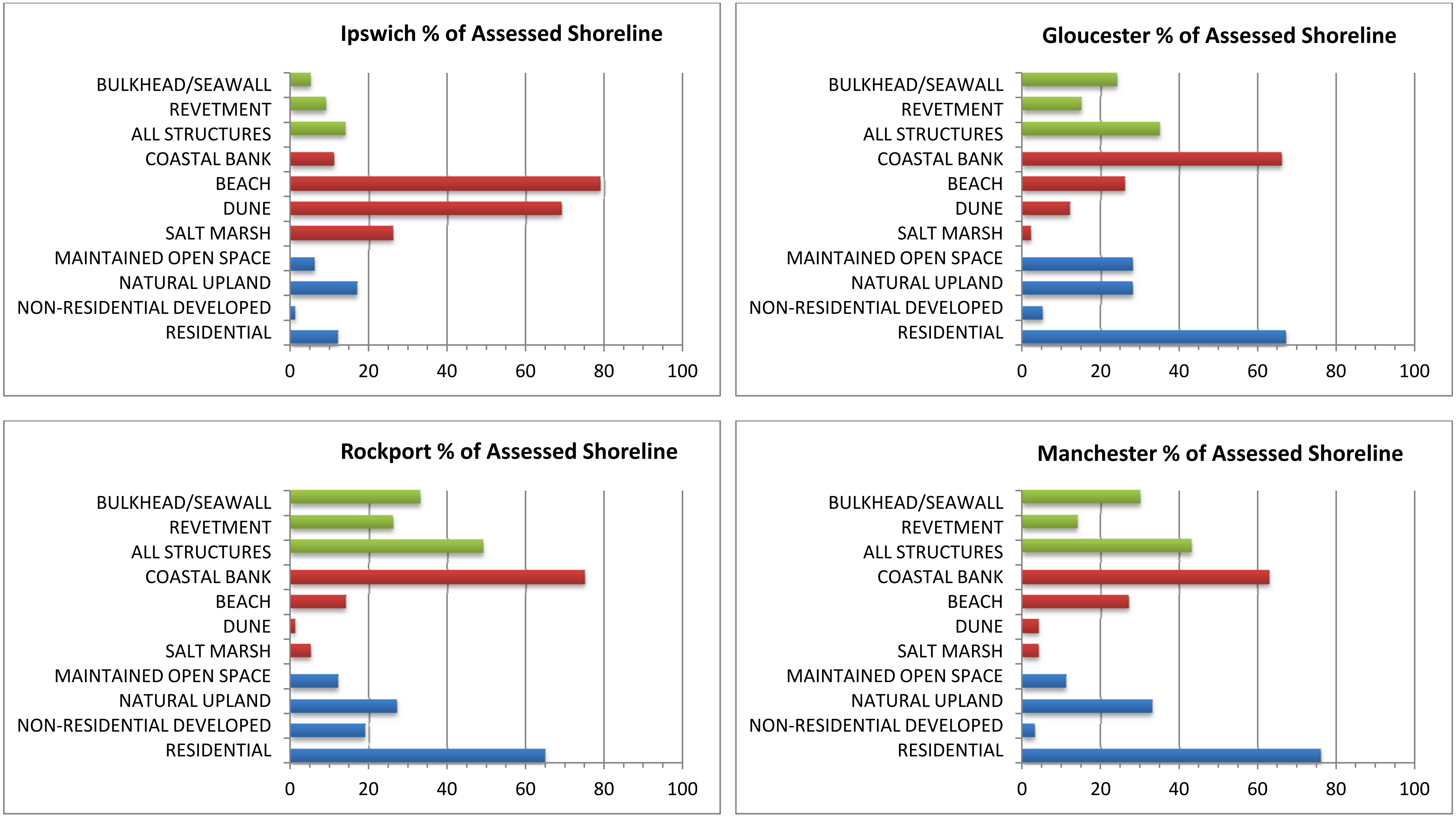


Figure 5b. Percent of assessed shoreline for each class or bin by community: Ipswich, Gloucester, Rockport, and Manchester (North Shore Region). Multiple classes could occur at each shoreline segment.

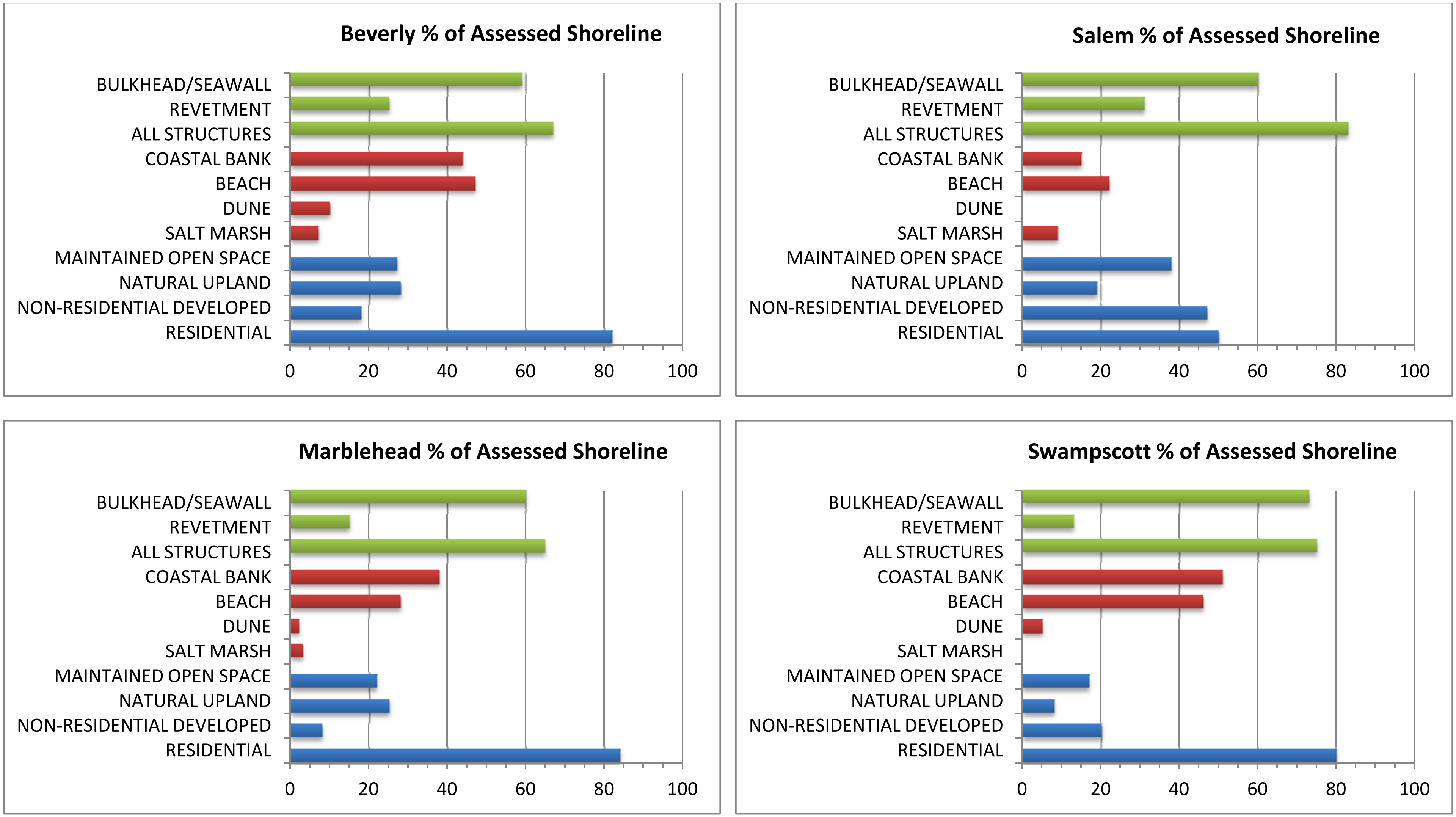
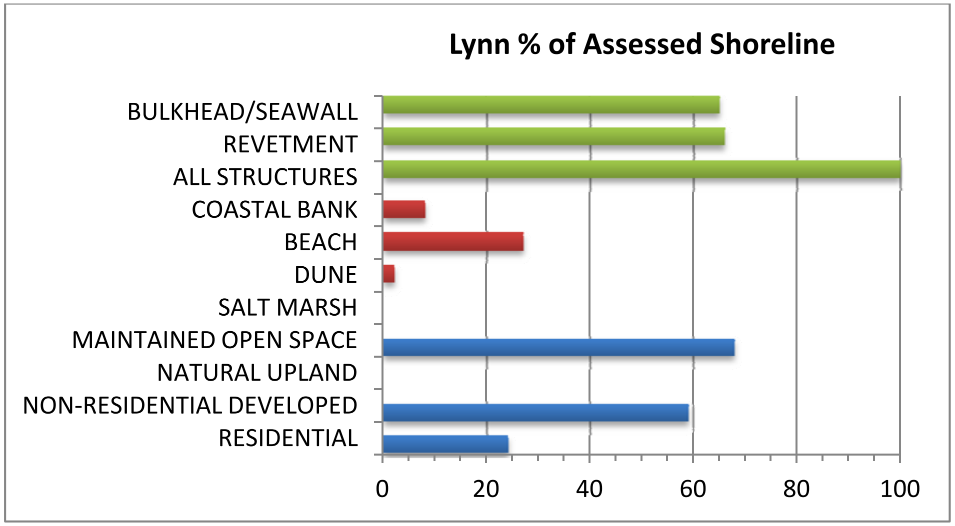
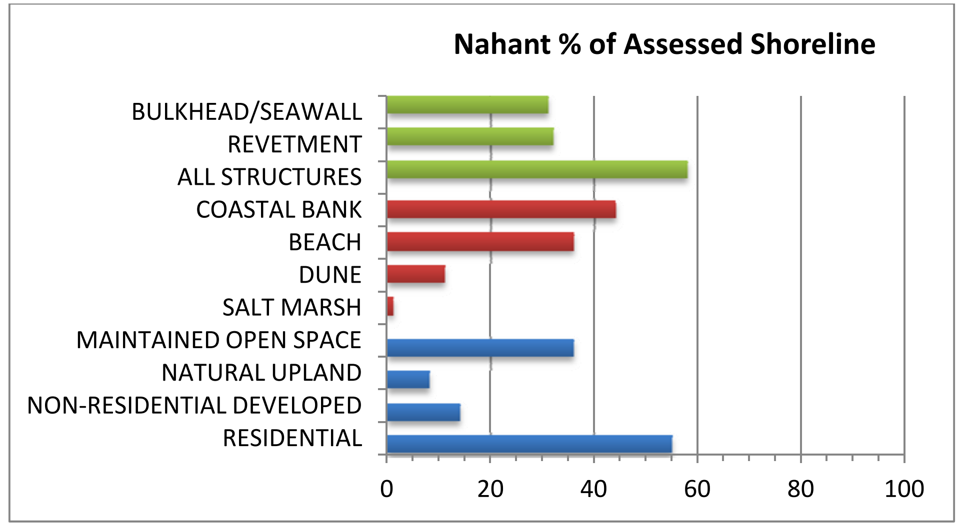


Figure 5c. Percent of assessed shoreline for each class or bin by community: Beverly, Salem, Marblehead, and Swampscott (North Shore Region). Multiple classes could occur at each shoreline segment.





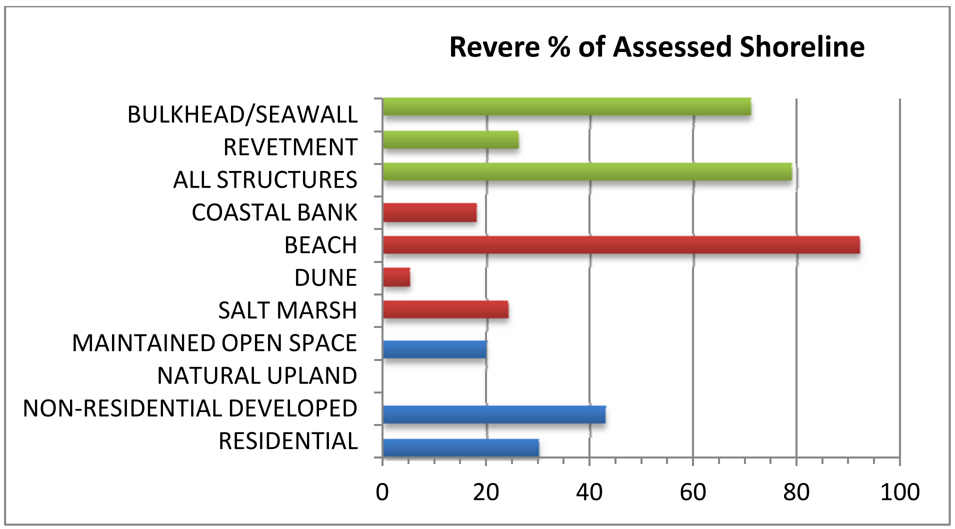


Figure 5d. Percent of assessed shoreline for each class or bin by community: Lynn, Nahant, and Revere (North Shore Region). Multiple classes could occur at each shoreline segment.

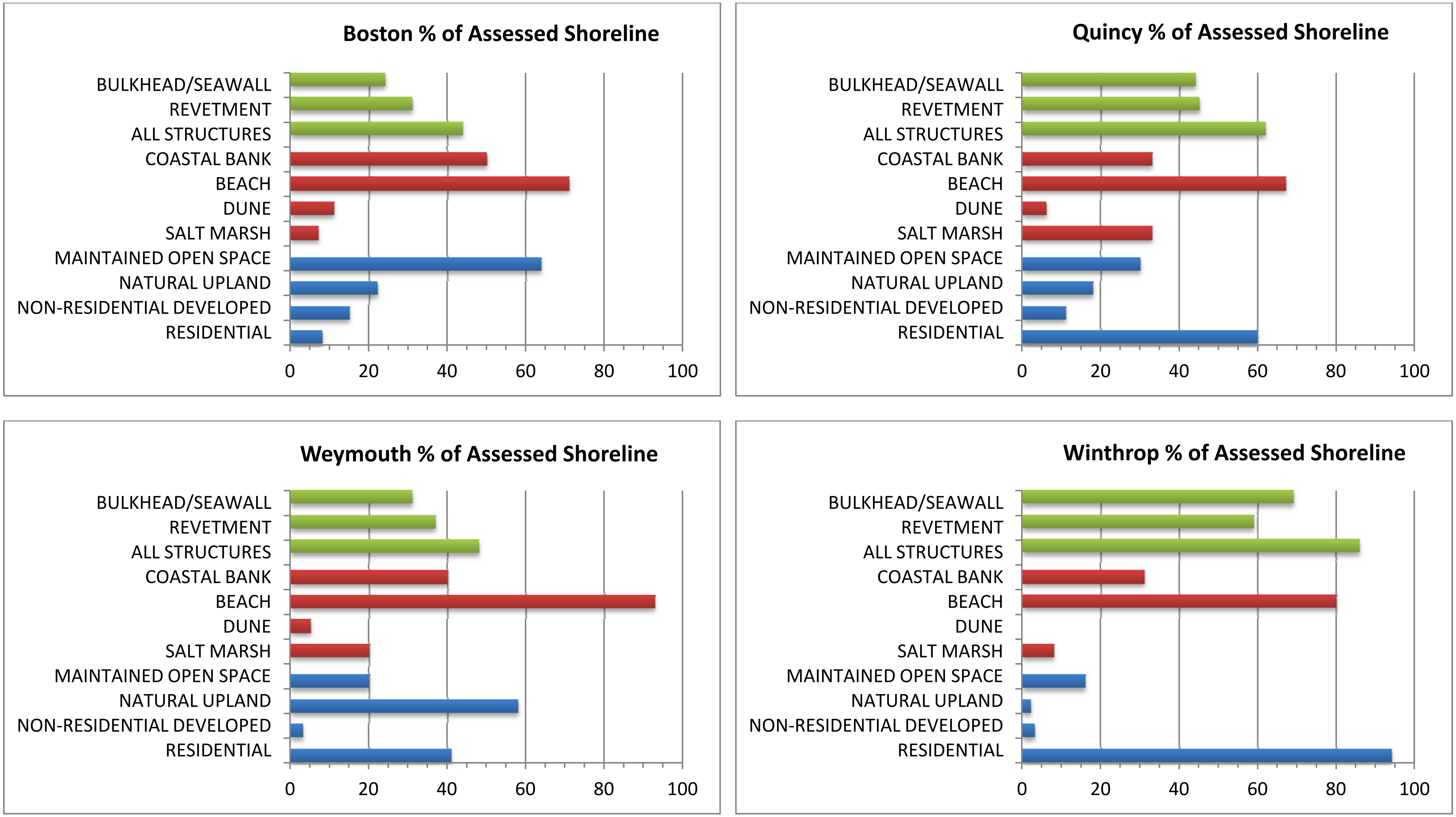


Figure 5e. Percent of assessed shoreline for each class or bin by community: Boston, Quincy, Weymouth, Winthrop (Boston Harbor Region). Multiple classes could occur at each shoreline segment.

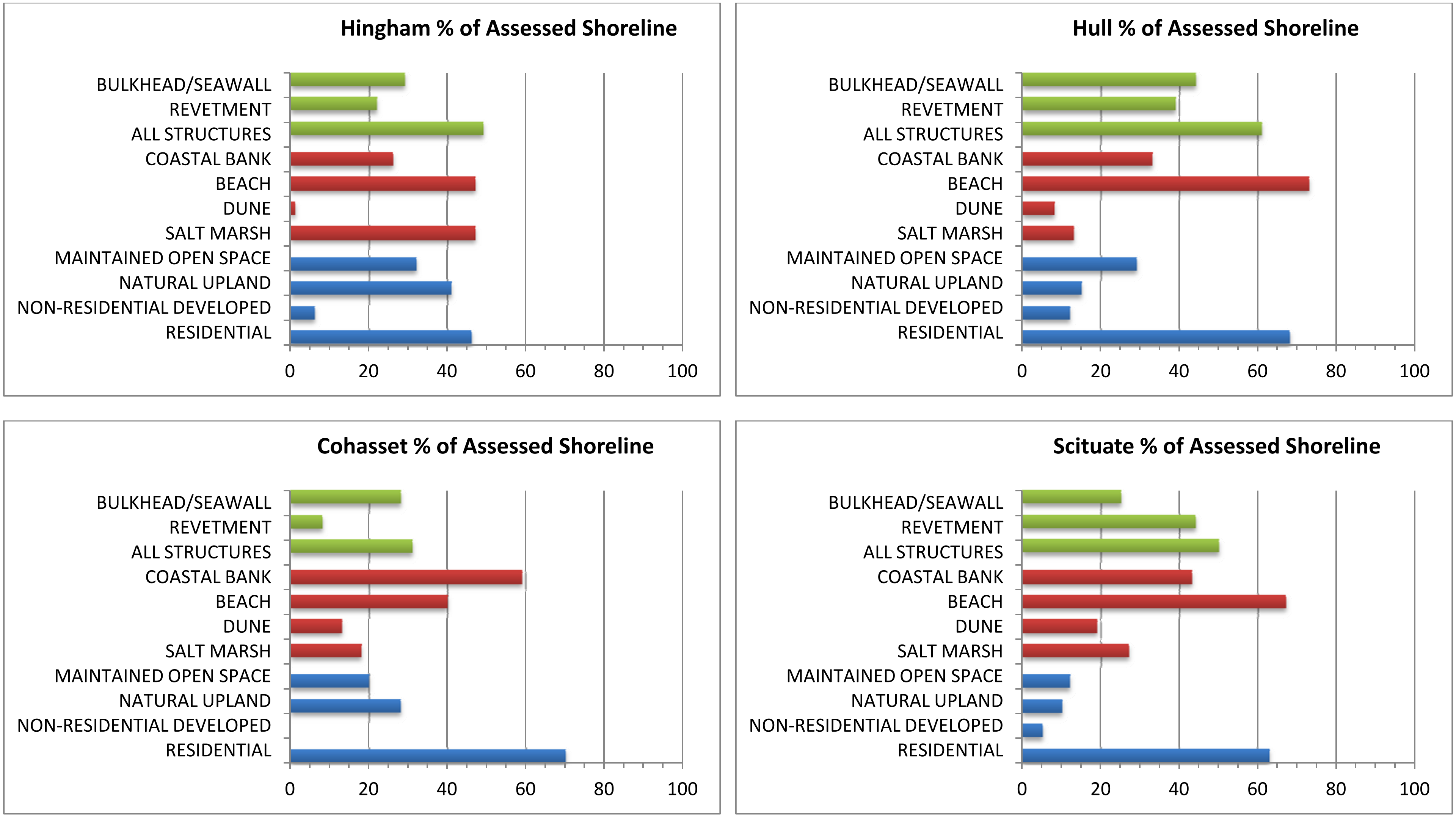


Figure 5f. Percent of assessed shoreline for each class or bin by community: Hingham, Hull, Cohasset, and Scituate (South Shore Region). Multiple classes could occur at each shoreline segment.

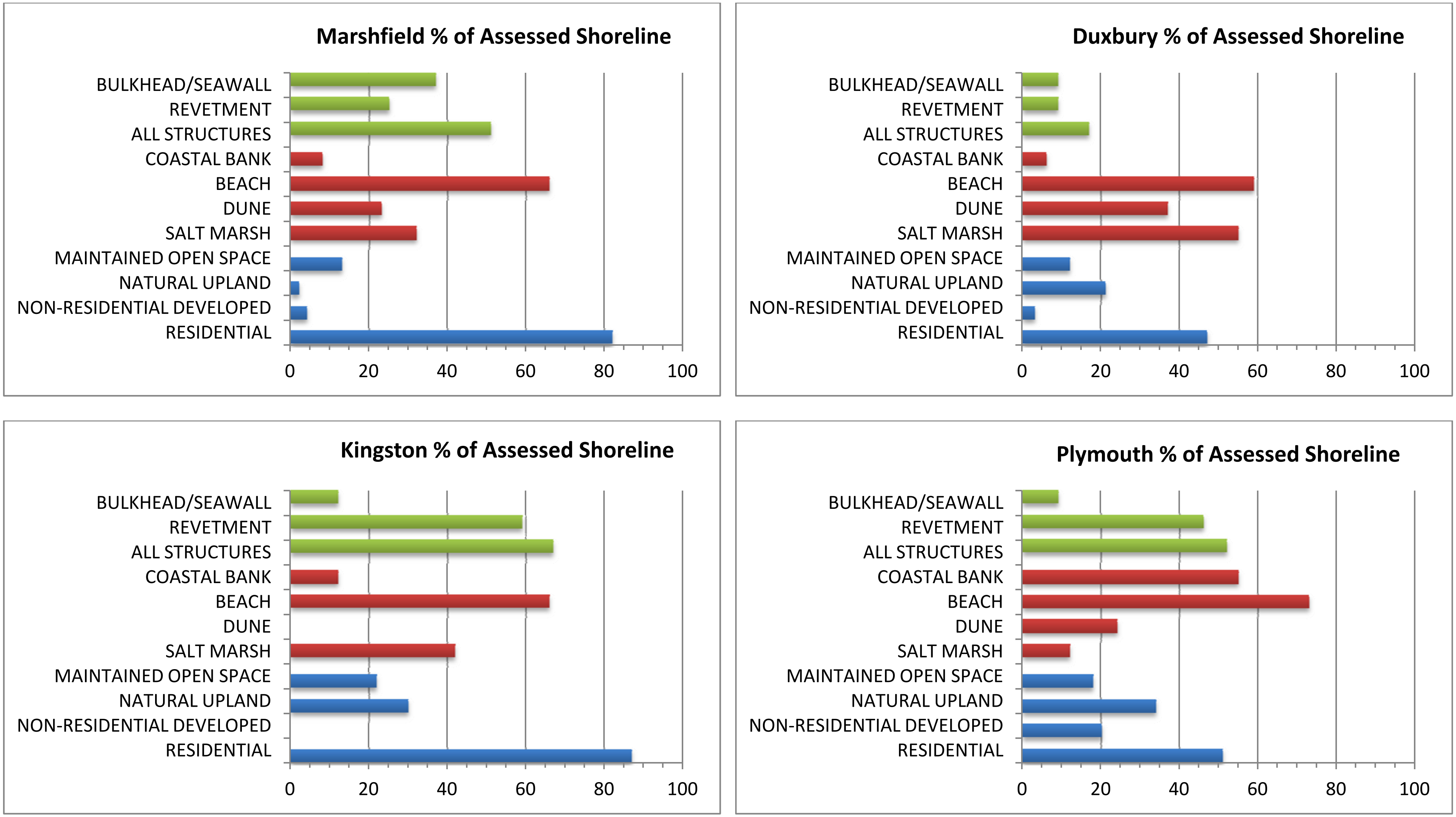


Figure 5g. Percent of assessed shoreline for each class or bin by community: Marshfield, Duxbury, Kingston, Plymouth (South Shore Region). Multiple classes could occur at each shoreline segment.

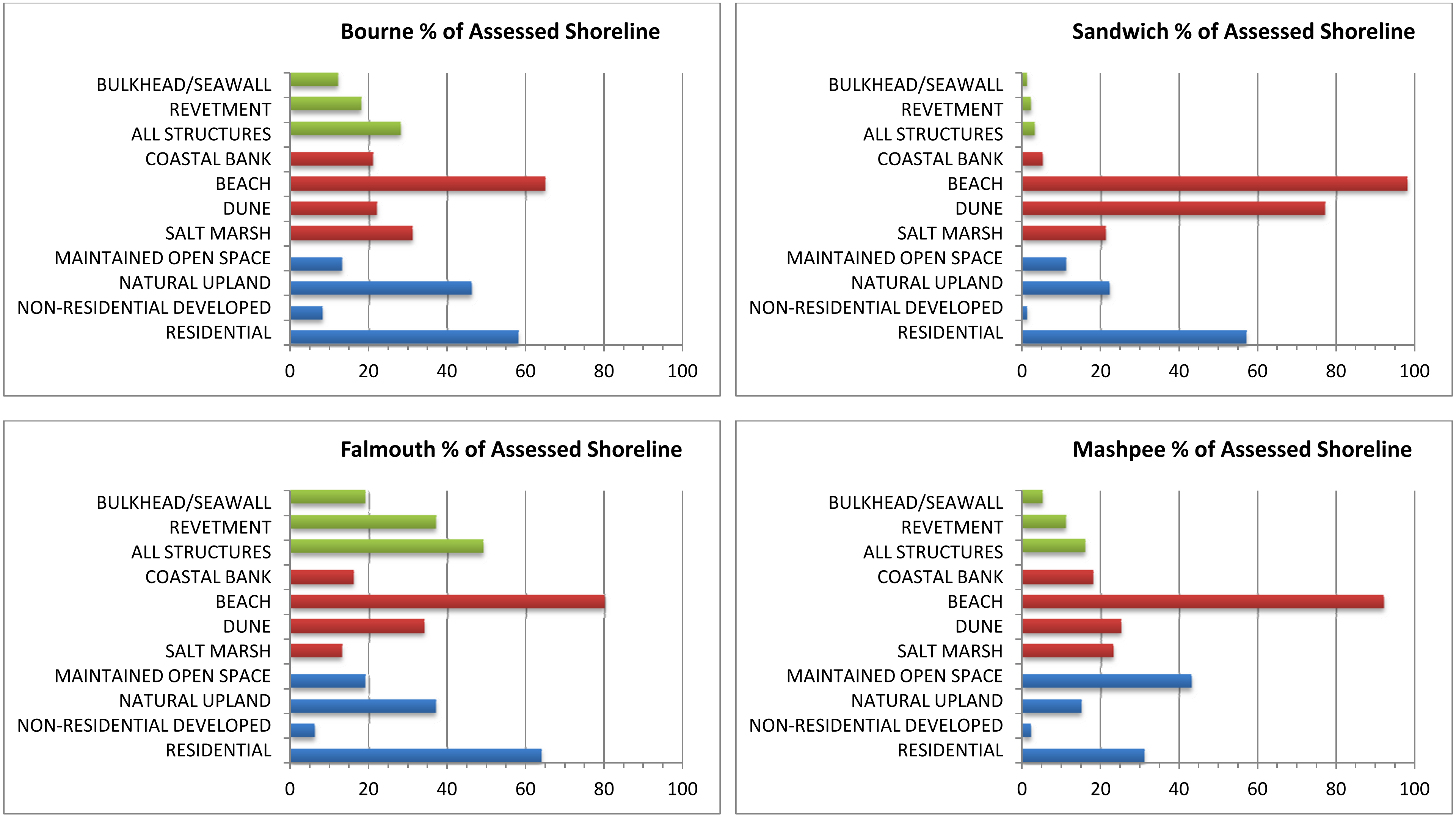


Figure 5h. Percent of assessed shoreline for each class or bin by community: Bourne, Sandwich, Falmouth, and Mashpee (Cape Cod & Islands Region). Multiple classes could occur at each shoreline segment.

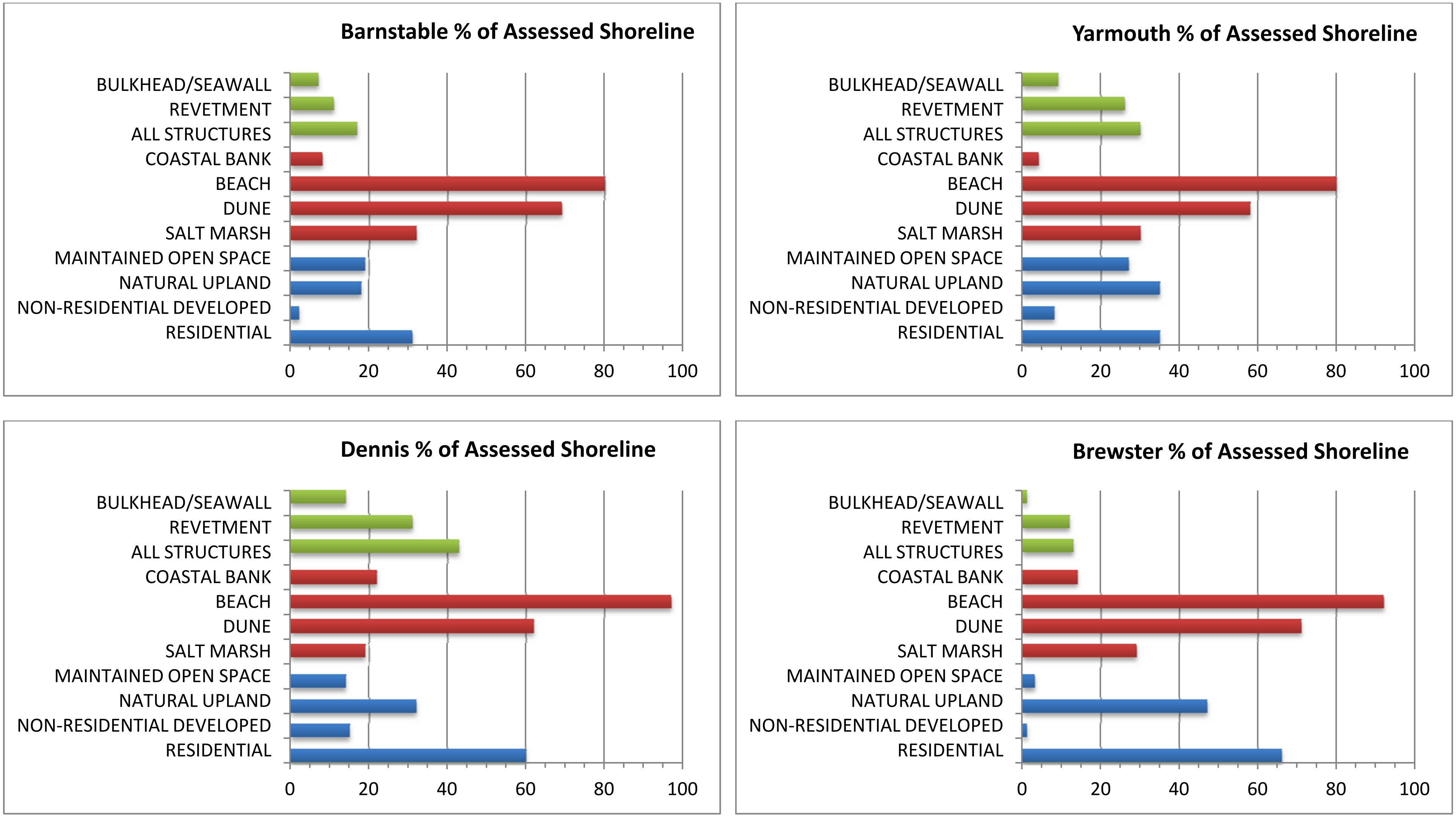


Figure 5i. Percent of assessed shoreline for each class or bin by community: Barnstable, Yarmouth, Dennis, and Brewster (Cape Cod & Islands Region). Multiple classes could occur at each shoreline segment.

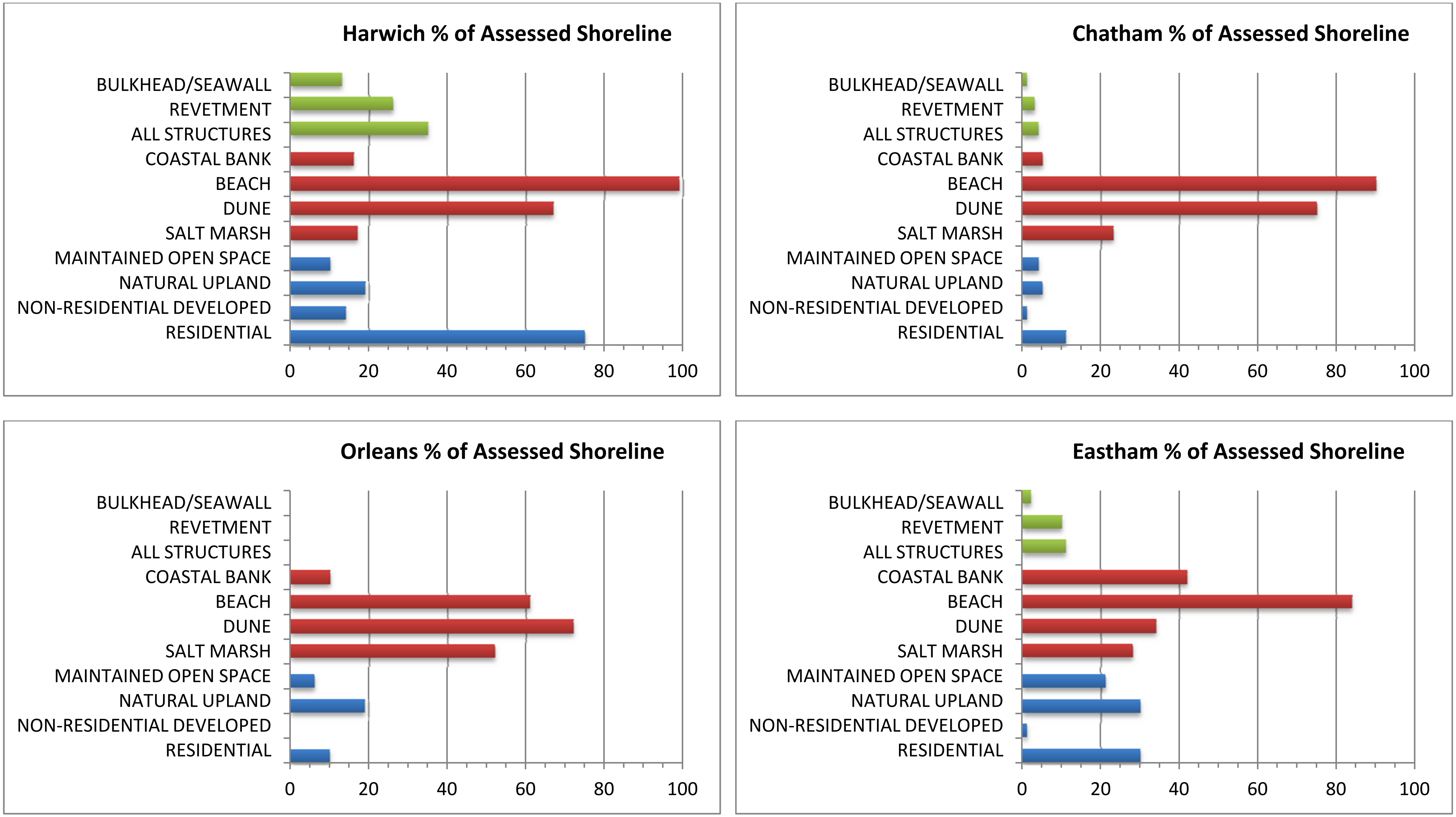


Figure 5j. Percent of assessed shoreline for each class or bin by community: Harwich, Chatham, Orleans, Eastham (Cape Cod & Islands Region). Multiple classes could occur at each shoreline segment.

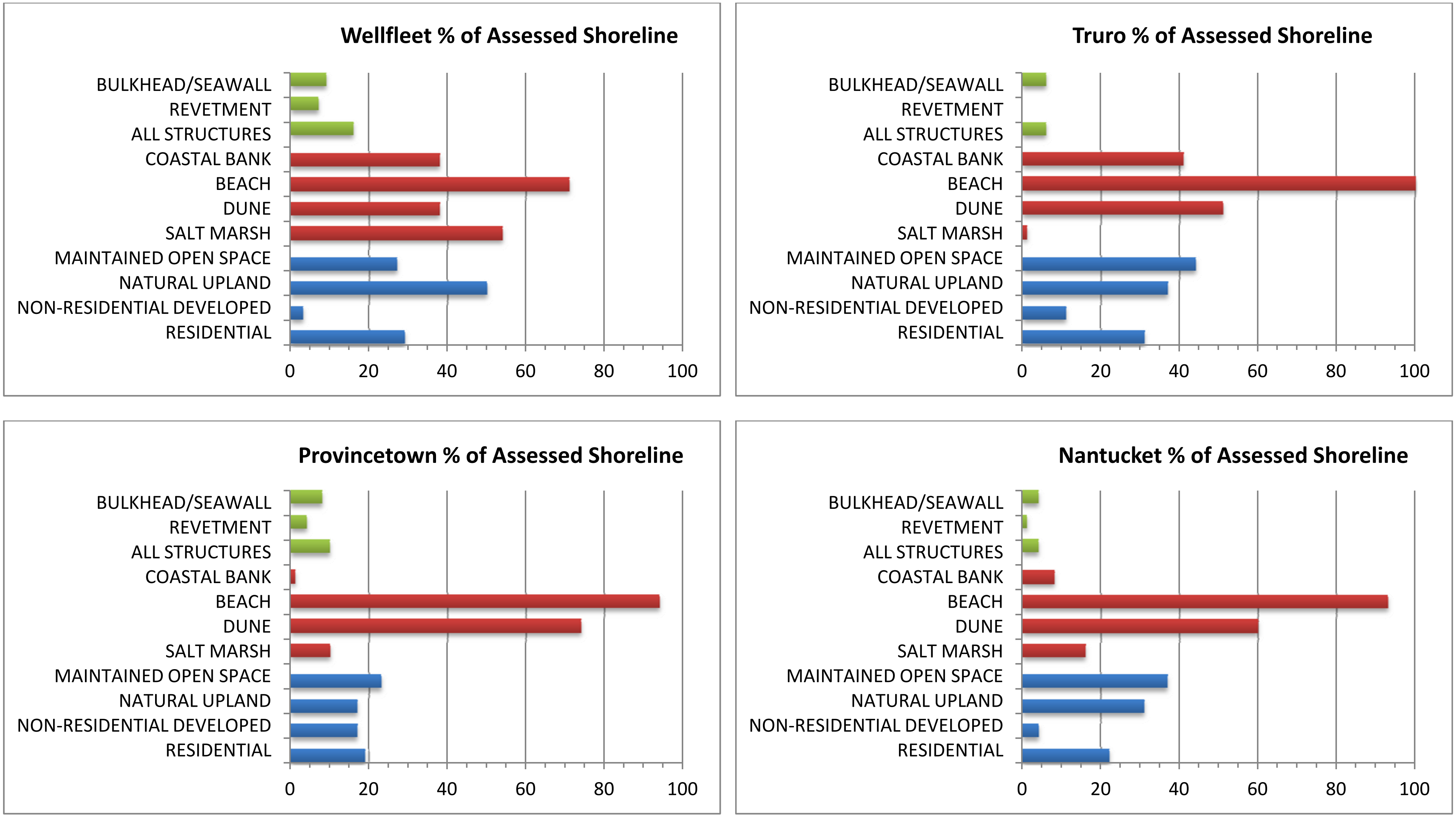


Figure 5k. Percent of assessed shoreline for each class or bin by community: Wellfleet, Truro, Provincetown, and Nantucket (Cape Cod & Islands Region). Multiple classes could occur at each shoreline segment.

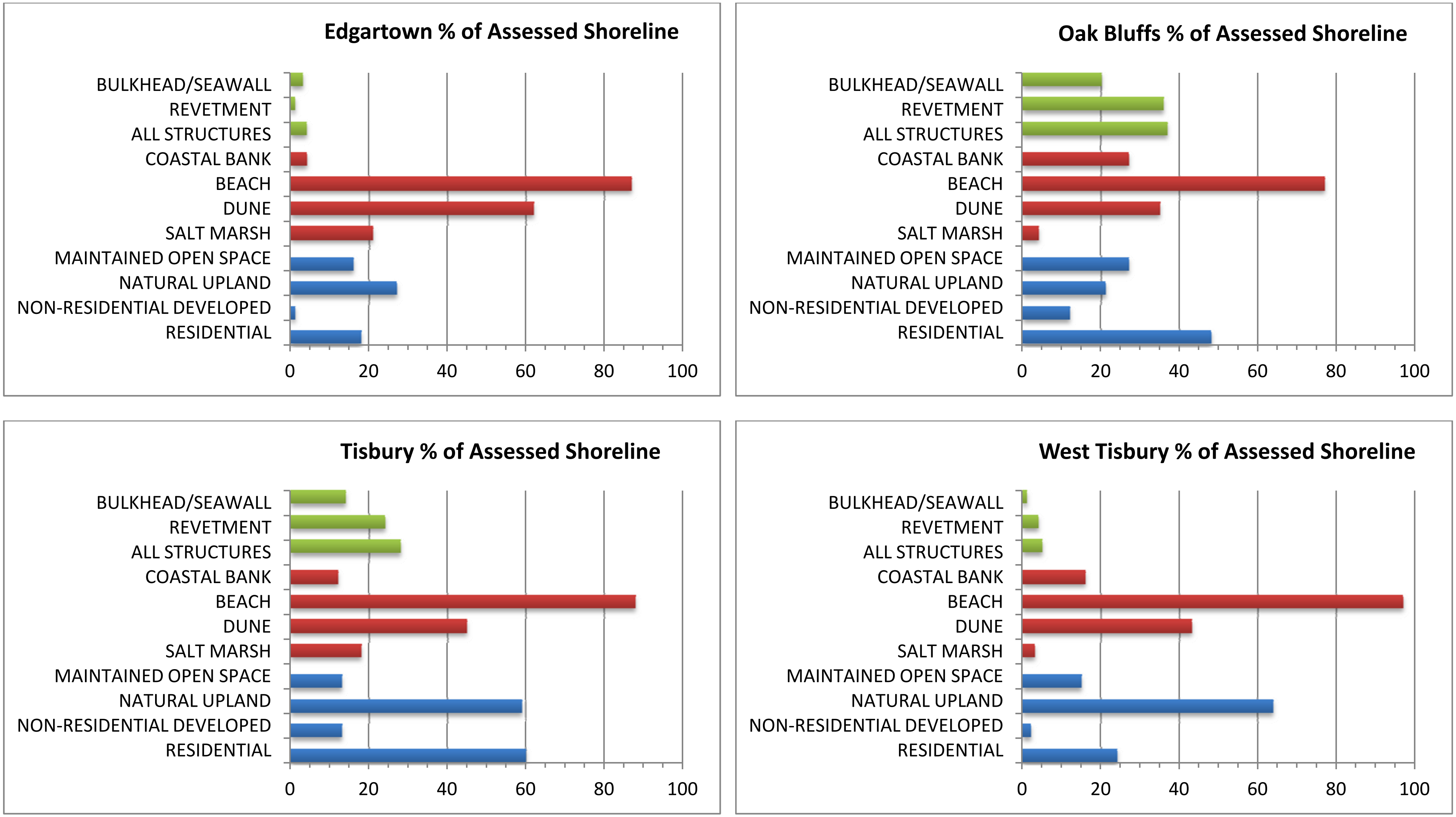
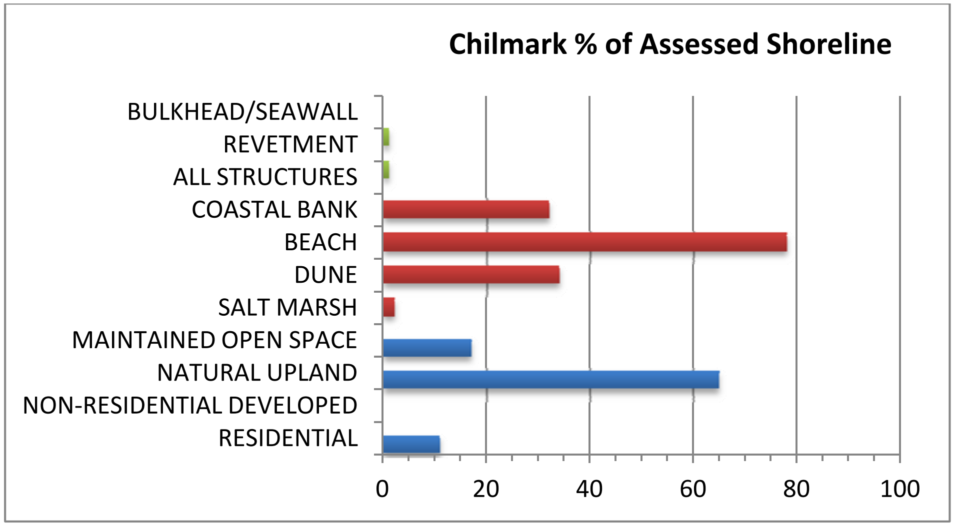
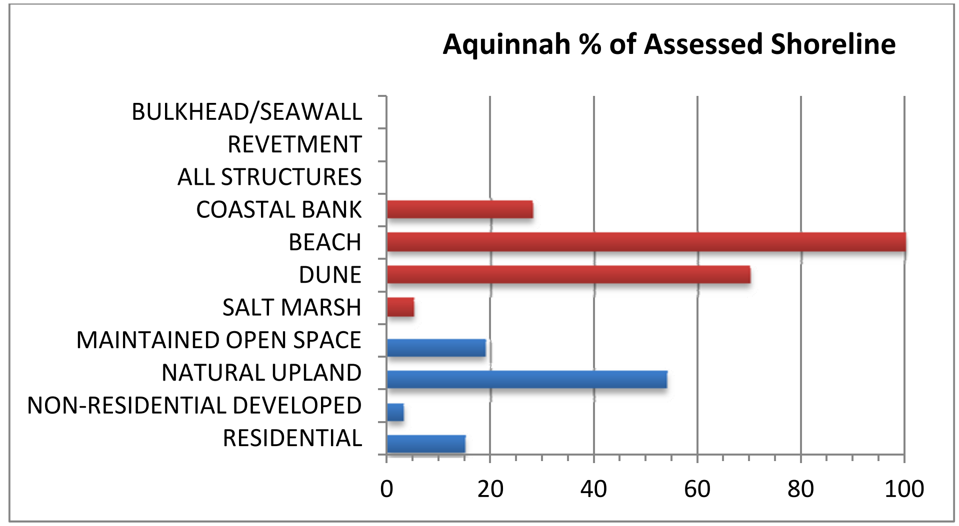


Figure 5l. Percent of assessed shoreline for each class or bin by community: Edgartown, Oak Bluffs, Tisbury, and West Tisbury (Cape Cod & Islands Region). Multiple classes could occur at each shoreline segment.





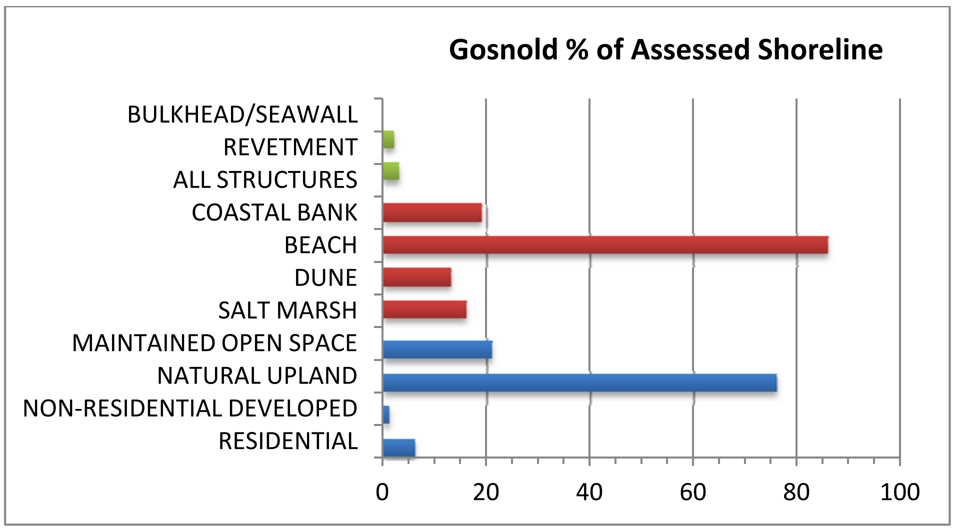


Figure 5m. Percent of assessed shoreline for each class or bin by community: Chilmark, Aquinnah, and Gosnold (Cape Cod & Islands Region). Multiple classes could occur at each shoreline segment.

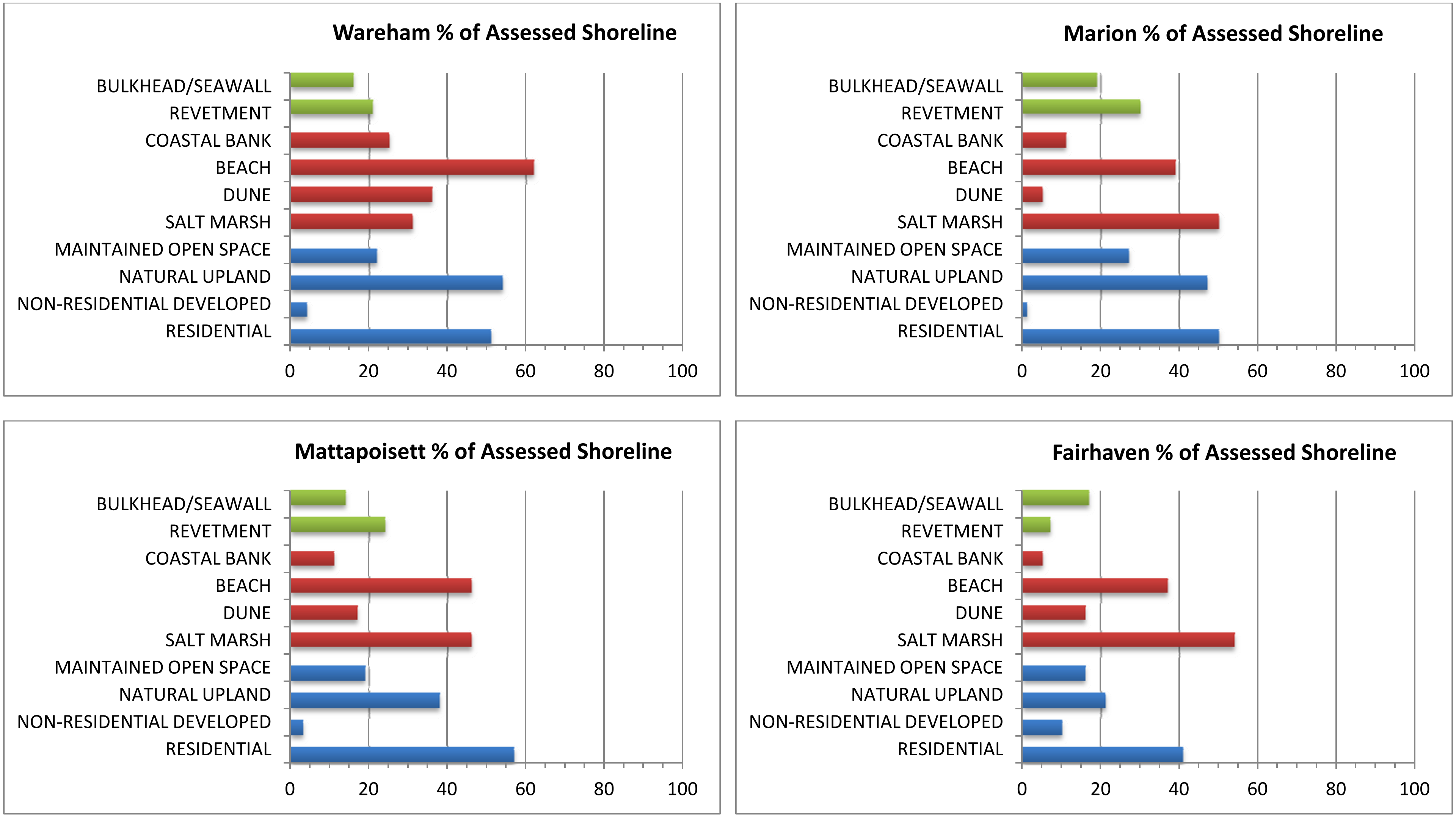
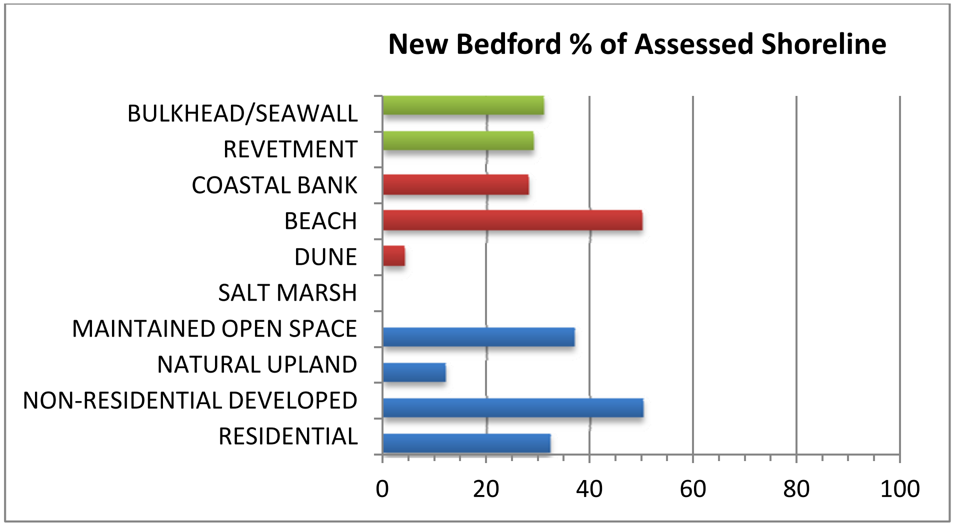
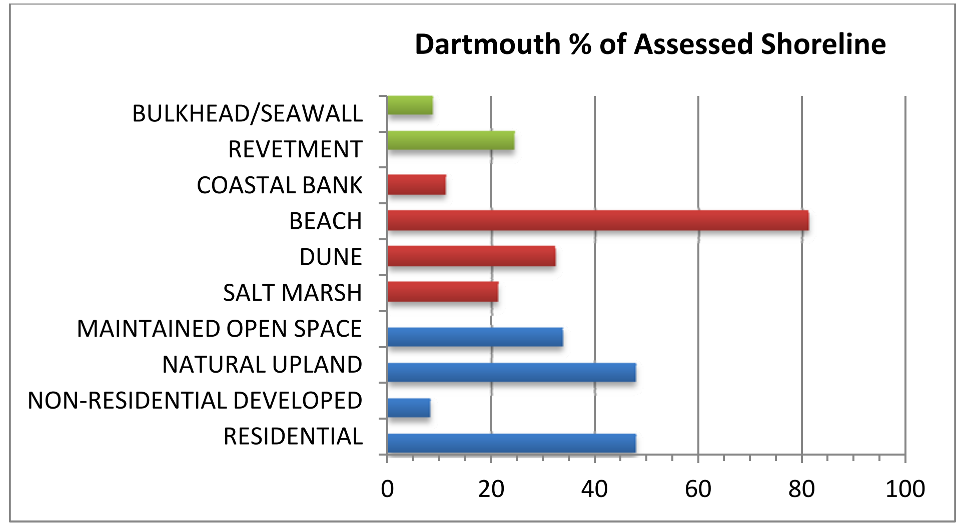


Figure 5n. Percent of assessed shoreline for each class or bin by community: Wareham, Marion, Mattapoisett, and Fairhaven (Buzzards Bay Region). Multiple classes could occur at each shoreline segment.





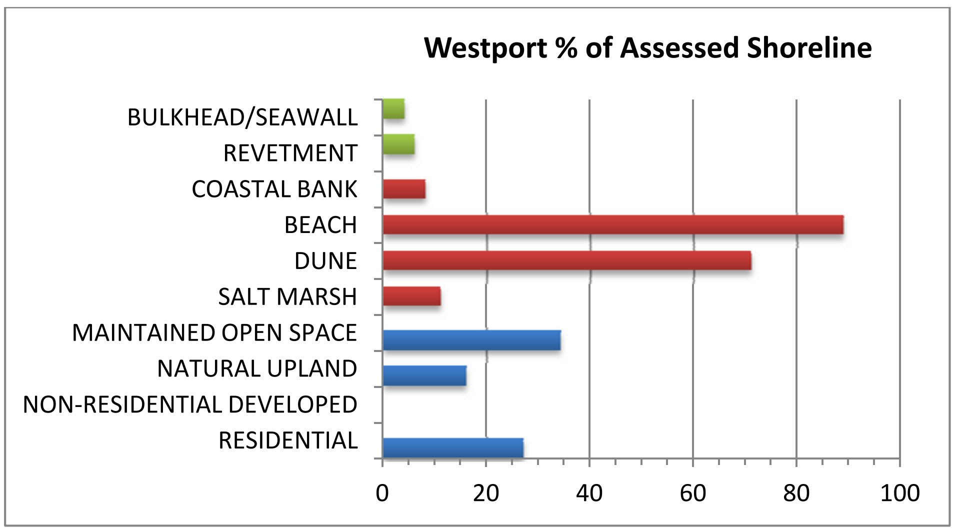


Figure 5o. Percent of assessed shoreline for each class or bin by community: New Bedford, Dartmouth, and Westport (Buzzards Bay Region). Multiple classes could occur at each shoreline segment.

Science and Technology Working Group - Appendix B

Shoreline Change

Appendix B: Figures and Tables of Shoreline Change Trends

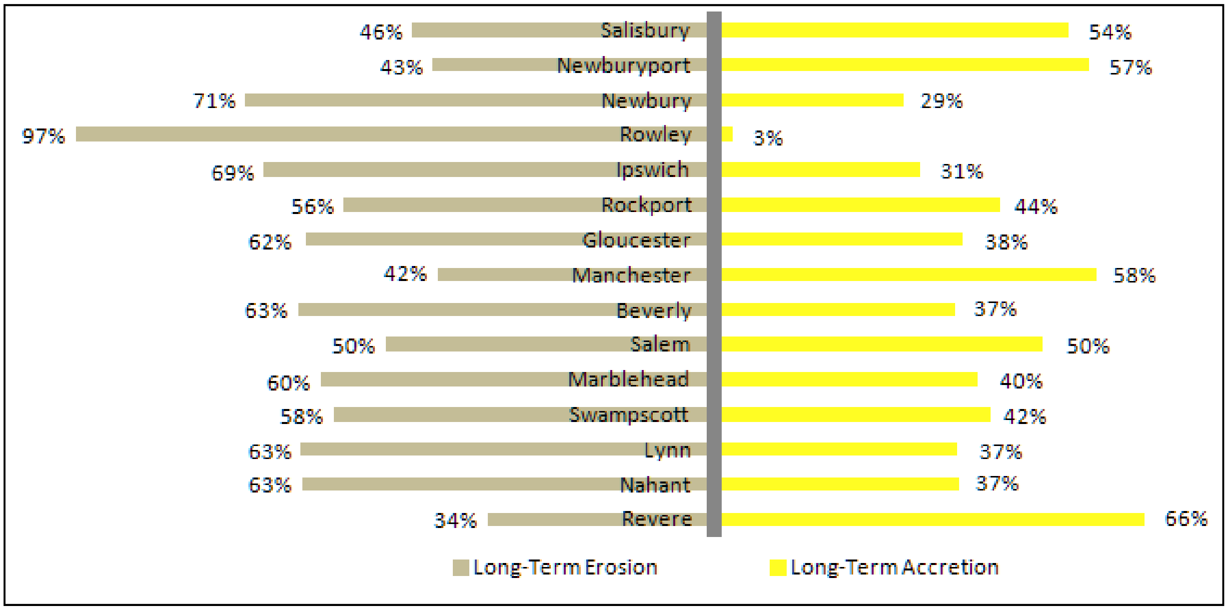


Figure 1. Normalized Long-term (1844-2009) Shoreline Change Trends on the North Shore. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting.

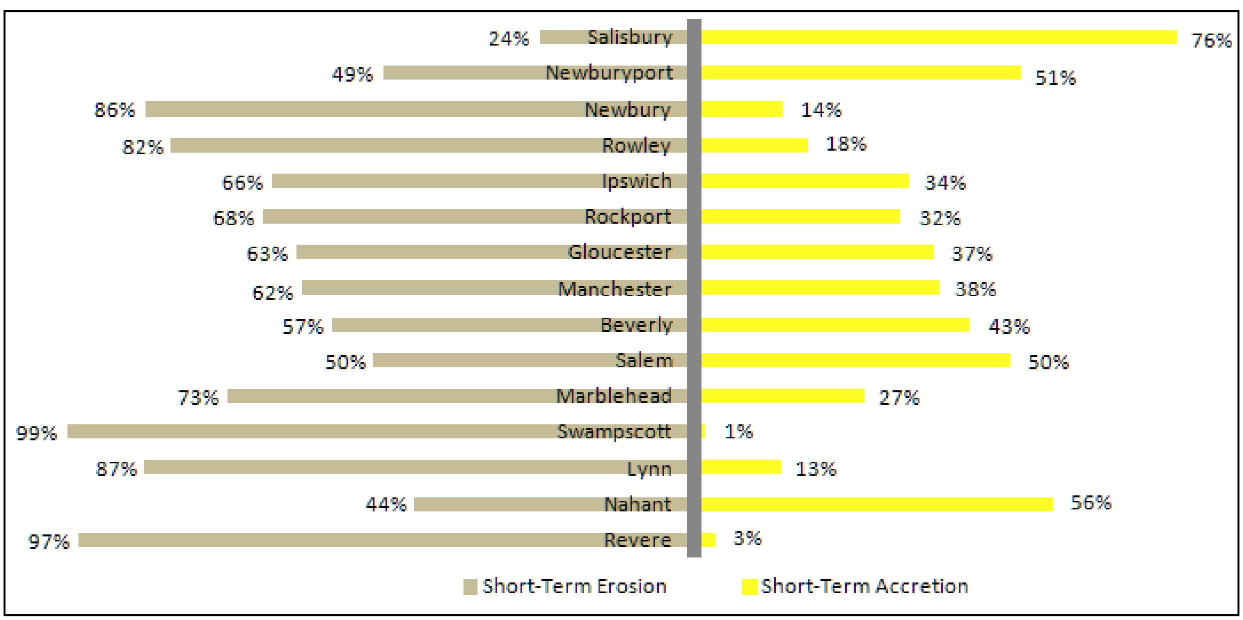


Figure 2. Normalized Short-term (1970-2009) Shoreline Change Trends on the North Shore. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting.

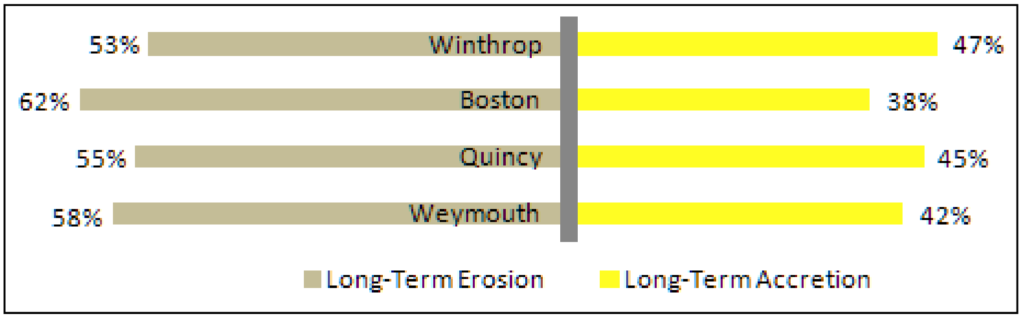


Figure 3. Normalized Long-term (1844-2009) Shoreline Change Trends in Boston Harbor. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting.

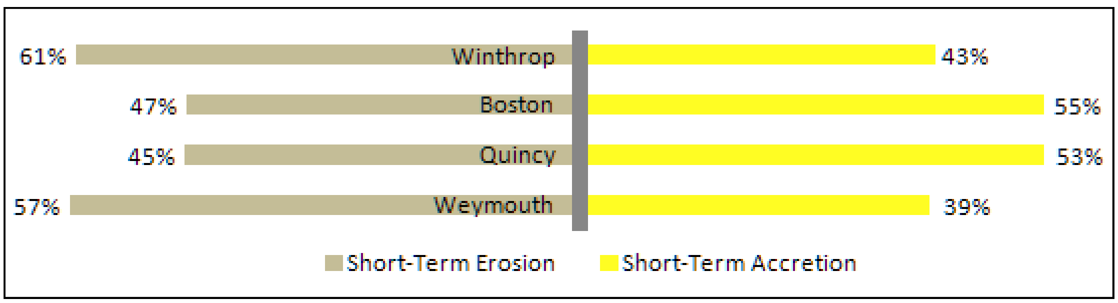


Figure 4. Normalized Short-term (1970-2009) Shoreline Change Trends in Boston Harbor. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting.

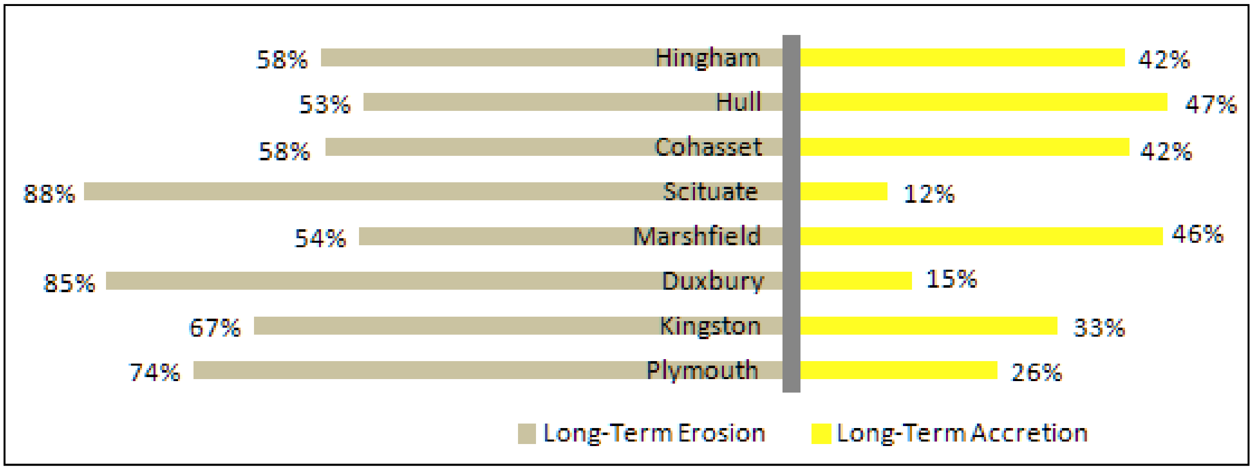


Figure 5. Normalized Long-term (1844-2009) Shoreline Change Trends on the South Shore. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting.

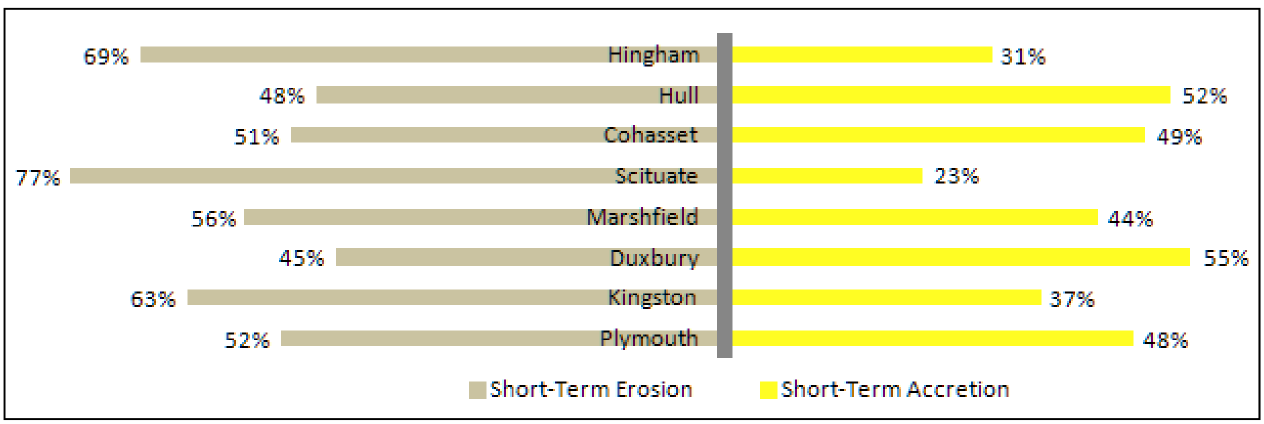


Figure 6. Normalized Short-term (1970-2009) Shoreline Change Trends on the South Shore. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting.

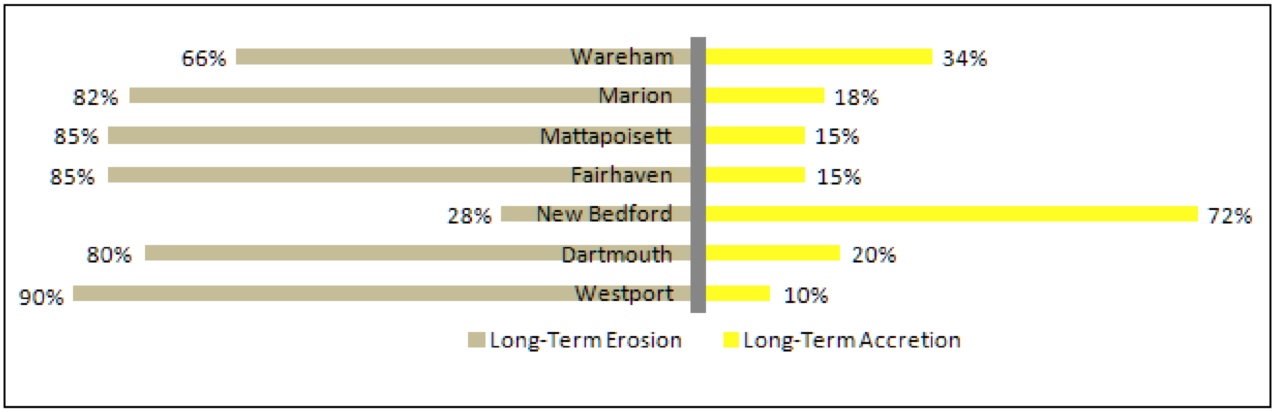


Figure 7. Normalized Long-term (1844-2009) Shoreline Change Trends on the South Coast. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting.

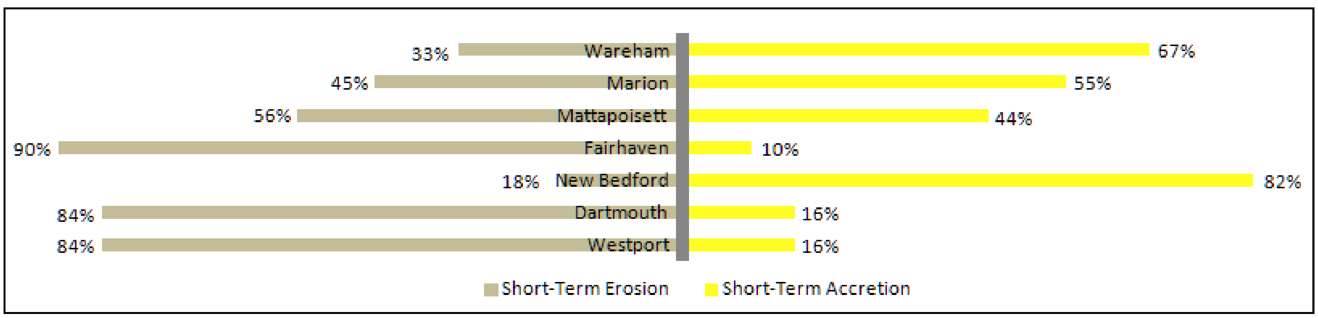


Figure 8. Normalized Short-term (1970-2009) Shoreline Change Trends on the South Coast. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting.

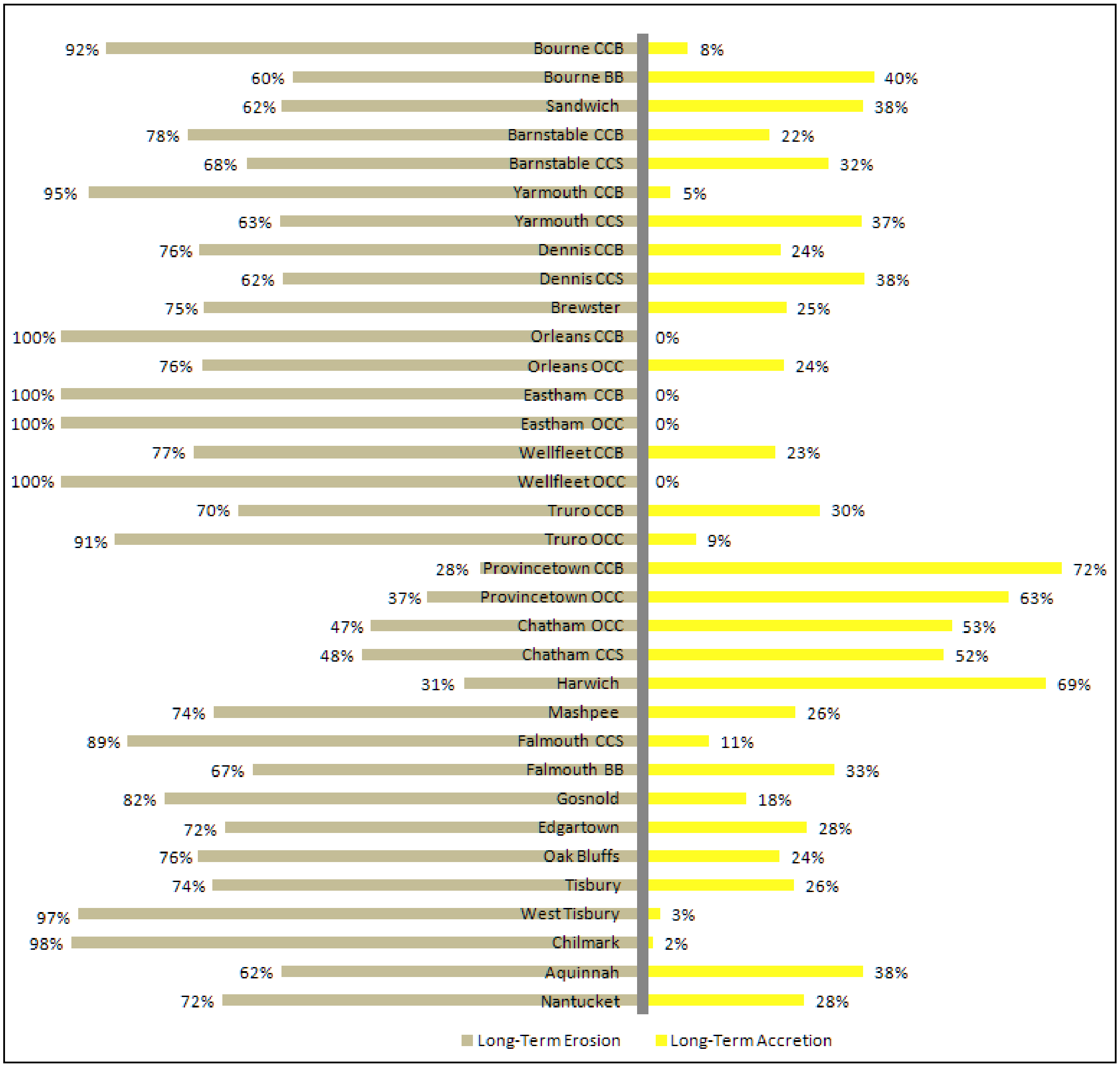


Figure 9. Normalized Long-term (1844-2009) Shoreline Change Trends on the Cape and Islands. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting. For Cape Cod communities that border more than one major body of water (Cape Cod Bay, Atlantic Ocean, Nantucket Sound, or Buzzards Bay), the communities are presented as sub-regions (CCB = Cape Cod Bay, CCS = Cape Code South (bordering Vineyard Sound), OCC = Outer Cape Cod (bordering the Atlantic Ocean), BB = Buzzards Bay).

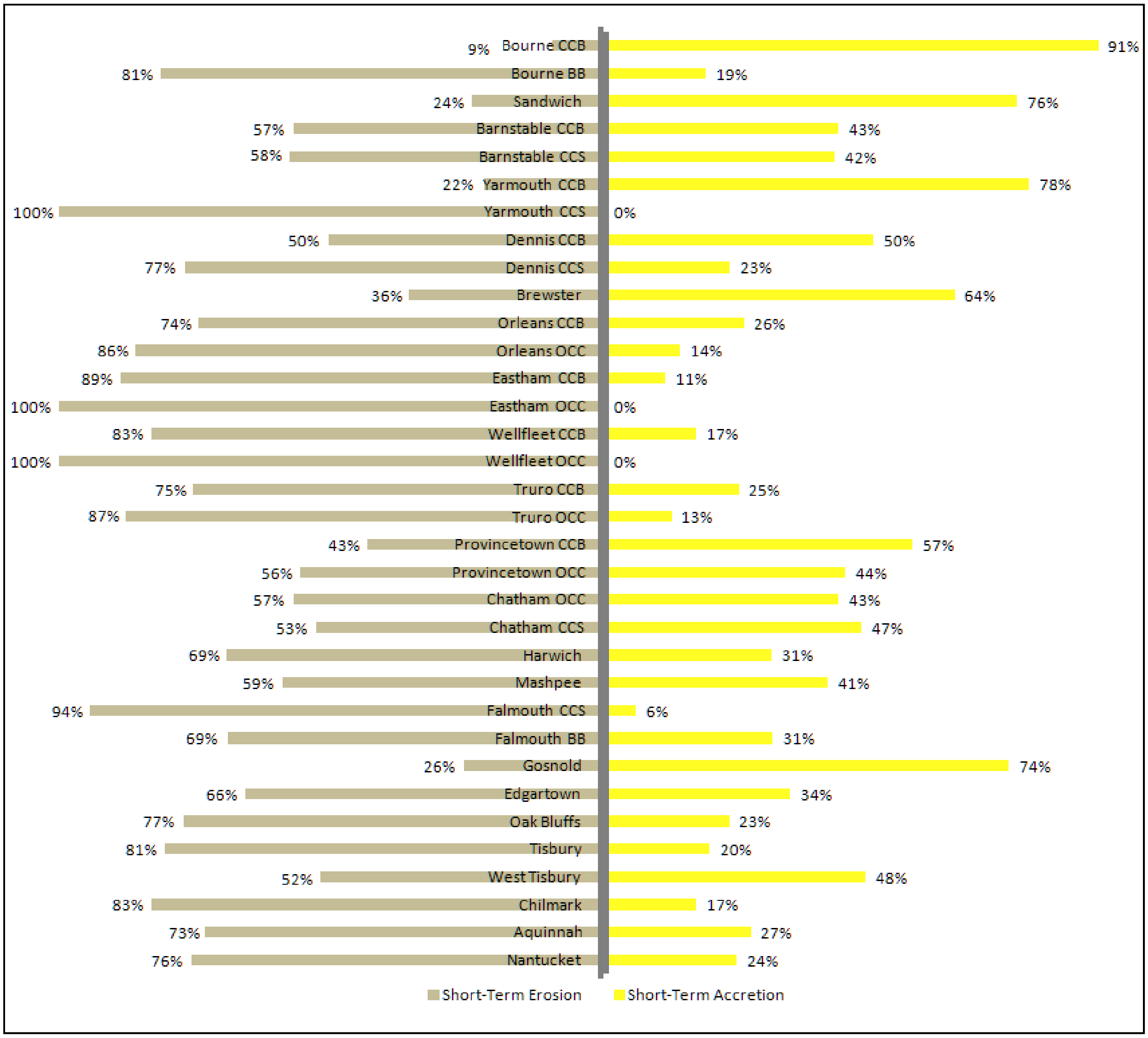


Figure 10. Normalized Short-term (1970-2009) Shoreline Change Trends on the Cape and Islands. Chart denotes dominant shoreline change (represented by percent of the community's shoreline length) where negative values equal shoreline erosion while positive values equal accretion. These normalized values represent the percent of a town's shoreline length that is either eroding or accreting. For Cape Cod communities that border more than one major body of water (Cape Cod Bay, Atlantic Ocean, Nantucket Sound, or Buzzards Bay), the communities are presented as sub-regions (CCB = Cape Cod Bay, CCS = Cape Code South (bordering Vineyard Sound), OCC = Outer Cape Cod (bordering the Atlantic Ocean), BB = Buzzards Bay).

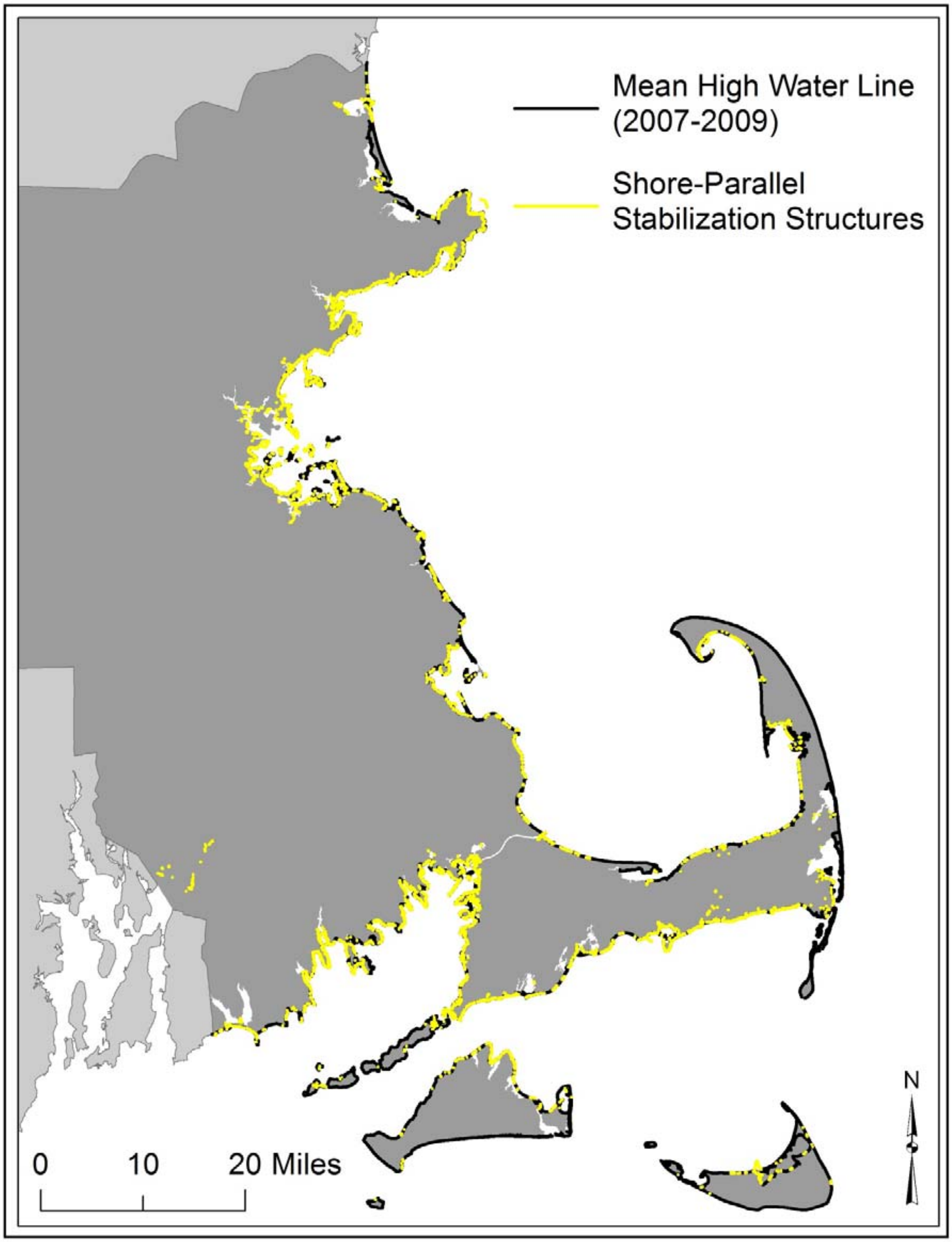


Figure 11. Distribution of Shore-parallel Stabilization Structures in the Commonwealth. 27% of the Commonwealth's shoreline is armored. This figure displays the geographic distribution of shore-parallel structures (seawalls, bulkheads, and revetments).

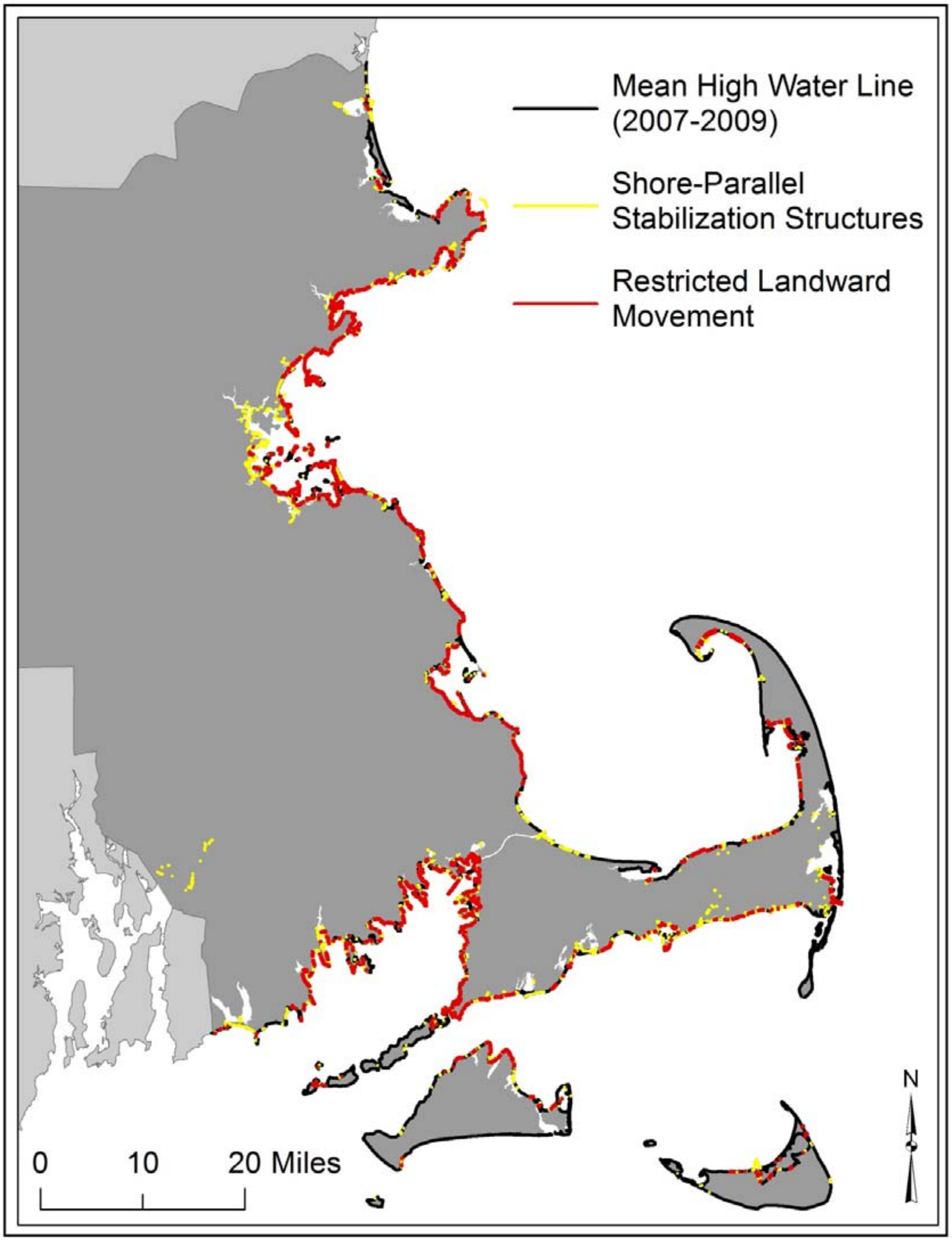


Figure 12. Distribution of Transects with Restricted Landward Shoreline Movement Due to Shore-parallel Stabilization Structures. 21% of the +26,000 transects are tagged as having a shoreline with restricted landward movement. Lowering of the beach elevation (vertical erosion) still occurs and is not captured in shoreline change analysis. These segments of shoreline occur where the current High Water Line (2007-2009) overlaps with shore-parallel structures (seawalls, bulkheads, and revetments).

Average Shoreline Change Rates by Shoreline Type

Table 1. Average Shoreline Change Rates by Shoreline Type. The results from the shoreline characterization (Task 1B) were used to further analyze shoreline change rates for each community. This was done to demonstrate the long-term and short-term erosion or accretion trends for seven shoreline types (classes) per community. For definitions of shoreline classes, see Table 4 under Task 2A. Definition queries and other techniques were used to select transects where each of these shoreline types occur.

* Indicates that a community's shoreline is also reported by coastal region, where BB = Buzzards Bay, CCB = Cape Cod Bay, CCS = Cape Cod South (bordering Vineyard or Nantucket Sound), and OCC = Outer Cape Cod (bordering the Atlantic Ocean).

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Aquinnah	Beach	-2.22	0.62	-1.18	1.22
	Beach w/ Dune	-0.23	1.74	0.08	3.26
	Beach w/ Bank	-1.01	0.71	-1.24	1.26
Barnstable	Beach	0.01	0.96	-0.51	1.51
	Beach w/ Dune	0.14	2.15	1.47	6.56
	Beach w/ Bank	-0.23	0.09	-0.71	0.30
	Beach w/ Structure	-1.06	2.72	0.22	1.23
	Bank	-0.59	0.46	-0.05	0.13
	Salt Marsh	-1.27	1.30	-1.77	3.15
	Structure	-0.63	0.41	0.12	0.22
Barnstable* (CCB)	Beach w/ Dune	0.62	2.72	3.14	8.83
	Beach w/ Structure	-0.50	0.42	-0.12	1.06
	Bank	-0.80	0.25	-0.10	0.10
	Salt Marsh	-1.14	1.14	-1.42	3.11
	Structure	-0.80	0.25	-0.10	0.10
Barnstable* (CCS)	Beach	0.01	0.96	-0.51	1.51
	Beach w/ Dune	-0.32	1.23	-0.14	2.08
	Beach w/ Bank	-0.23	0.09	-0.71	0.30
	Beach w/ Structure	-1.10	2.82	0.25	1.24
	Bank	0.03	0.00	0.10	0.00
	Salt Marsh	-1.92	1.82	-3.62	2.76
	Structure	-0.53	0.48	0.26	0.14
Beverly	Beach	0.08	0.26	-0.56	0.67
	Beach w/ Dune	0.00	0.40	-0.74	0.78
	Beach w/ Bank	0.33	0.15	-0.07	0.55
	Beach w/ Structure	-0.16	0.29	-0.58	0.85
	Bank	-0.08	0.31	-0.08	0.39
	Salt Marsh	-0.10	0.00	0.00	0.00
	Structure	-0.10	0.36	-0.08	0.41

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Boston	Beach	0.65	2.37	0.10	1.28
	Beach w/ Dune	-0.12	1.05	1.16	1.68
	Beach w/ Bank	-0.25	0.32	-0.49	1.63
	Beach w/ Structure	0.44	1.97	0.70	2.19
	Bank	-0.18	0.99	0.17	1.93
	Salt Marsh	1.01	0.31	-1.02	1.57
	Structure	0.20	1.17	0.01	1.86
Bourne	Beach	-0.09	0.38	-0.45	0.68
	Beach w/ Dune	-0.07	1.07	-0.28	1.54
	Beach w/ Bank	-0.28	0.33	0.28	1.75
	Beach w/ Structure	-0.11	0.27	-0.39	0.94
	Bank	0.02	0.56	-0.36	0.45
	Salt Marsh	0.01	0.72	-0.16	0.96
	Structure	-0.04	0.64	-0.39	0.78
Bourne* (BB)	Beach	-0.09	0.38	-0.48	0.56
	Beach w/ Dune	-0.05	1.12	-0.46	1.43
	Beach w/ Bank	-0.13	0.25	-0.63	0.52
	Beach w/ Structure	-0.10	0.26	-0.53	0.47
	Bank	0.02	0.56	-0.36	0.45
	Salt Marsh	0.01	0.72	-0.16	0.96
	Structure	-0.04	0.64	-0.39	0.78
Bourne* (CCB)	Beach	-0.20	0.00	4.43	0.00
	Beach w/ Dune	-0.25	0.28	1.39	1.59
	Beach w/ Bank	-0.65	0.20	2.49	1.70
	Beach w/ Structure	-0.37	0.38	3.42	1.94
Brewster	Beach	-0.38	0.62	1.43	1.40
	Beach w/ Dune	-0.24	0.63	0.58	1.74
	Beach w/ Bank	-0.10	0.25	2.37	1.82
	Beach w/ Structure	-0.53	0.47	0.90	1.10
	Salt Marsh	-1.85	2.13	-2.63	10.70
	Structure	-0.16	0.00	0.46	0.00
Chatham	Beach	-0.85	2.05	-46.54	72.40
	Beach w/ Dune	2.77	9.89	-6.16	30.44
	Beach w/ Bank	-1.76	3.19	-7.83	26.45
	Beach w/ Structure	-1.93	4.37	-34.20	60.14
	Bank	0.54	3.97	1.77	3.19
	Salt Marsh	2.55	9.18	2.95	9.51
	Structure	0.42	3.76	1.73	1.87

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Chatham* (CCS)	Beach w/ Dune	0.10	2.65	0.35	2.35
	Beach w/ Bank	-3.51	0.47	-1.71	0.19
	Beach w/ Structure	-4.51	6.59	-1.24	1.25
	Bank	-11.52	0.00	-7.97	0.00
	Salt Marsh	-14.11	0.00	-2.43	0.00
	Structure	-13.32	0.00	-2.00	0.00
Chatham* (OCC)	Beach	-0.85	2.05	-46.54	72.40
	Beach w/ Dune	3.03	10.29	-6.79	31.81
	Beach w/ Bank	-1.32	3.46	-9.37	29.77
	Beach w/ Structure	-1.58	3.96	-38.69	62.84
	Bank	1.47	2.01	2.52	1.58
	Salt Marsh	3.39	8.56	3.22	9.67
	Structure	1.19	1.81	1.94	1.69
Chilmark	Beach	-1.29	1.33	-1.30	1.49
	Beach w/ Dune	-3.90	1.93	-2.43	2.14
	Beach w/ Bank	-1.31	1.10	-1.93	1.71
	Beach w/ Structure	-0.74	0.41	-0.94	1.30
Cohasset	Beach	-0.44	0.44	-0.55	0.82
	Beach w/ Dune	0.73	1.34	2.72	2.10
	Beach w/ Bank	-0.24	0.15	0.20	1.04
	Beach w/ Structure	-0.22	0.27	0.13	0.91
	Bank	-0.04	0.28	-0.15	1.01
	Salt Marsh	1.17	1.33	6.36	4.01
	Structure	-0.03	0.26	0.95	2.44
Dartmouth	Beach	-0.21	0.26	-0.69	0.46
	Beach w/ Dune	-0.50	0.40	-1.02	2.78
	Beach w/ Bank	0.08	0.45	-0.24	0.93
	Beach w/ Structure	-0.09	0.29	-0.36	0.65
	Bank	-0.37	0.29	-0.25	0.50
	Salt Marsh	-0.03	0.73	2.25	7.65
	Structure	-0.30	0.39	-0.30	0.96
Dennis	Beach	-0.61	0.47	-0.25	1.27
	Beach w/ Dune	-0.68	4.04	-0.67	4.70
	Beach w/ Bank	-0.60	0.18	-0.20	1.08
	Beach w/ Structure	-0.74	1.17	-0.32	1.06
	Salt Marsh	-2.81	0.90	0.57	2.18
	Structure	-1.12	0.08	-0.74	0.45

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Dennis* (CCB)	Beach	-0.79	0.50	0.18	1.49
	Beach w/ Dune	-1.57	3.63	-1.13	5.30
	Beach w/ Bank	-0.60	0.18	-0.20	1.08
	Beach w/ Structure	-1.02	1.07	-0.36	1.28
	Salt Marsh	-2.81	0.90	0.57	2.18
	Structure	-1.12	0.08	-0.74	0.45
Dennis* (CCS)	Beach	-0.35	0.26	-0.90	0.29
	Beach w/ Dune	1.49	4.20	0.45	2.42
	Beach w/ Structure	-0.49	1.20	-0.28	0.83
Duxbury	Beach	-0.19	0.35	0.19	1.61
	Beach w/ Dune	-0.58	0.86	1.89	4.26
	Beach w/ Bank	-0.22	0.18	0.77	0.60
	Beach w/ Structure	-0.33	0.40	-0.26	1.41
	Bank	-0.75	0.39	-0.71	0.94
	Salt Marsh	-0.72	0.76	-1.46	2.99
	Structure	-0.59	0.51	-1.11	1.22
Eastham	Beach	-3.35	0.57	-3.21	0.66
	Beach w/ Dune	-1.92	1.28	-2.59	1.96
	Beach w/ Bank	-2.32	0.94	-3.20	1.20
	Beach w/ Structure	-1.20	0.93	-1.74	0.84
	Bank	-2.09	0.97	-1.50	2.77
	Salt Marsh	-3.69	2.76	-1.74	9.31
Eastham* (CCB)	Beach	-1.51	0.00	-2.89	0.00
	Beach w/ Dune	-1.64	1.17	-2.49	2.05
	Beach w/ Bank	-1.12	0.29	-2.14	0.76
	Beach w/ Structure	-1.20	0.93	-1.74	0.84
	Bank	-2.09	0.97	-1.50	2.77
	Salt Marsh	-3.59	3.18	-0.09	10.17
Eastham* (OCC)	Beach	-3.51	0.13	-3.23	0.68
	Beach w/ Dune	-3.54	0.22	-3.21	1.15
	Beach w/ Bank	-3.01	0.20	-3.80	0.96
	Salt Marsh	-4.00	0.31	-6.69	2.17

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Edgartown	Beach	-0.82	1.09	-0.93	4.07
	Beach w/ Dune	-2.65	3.97	-1.62	9.83
	Beach w/ Bank	-1.61	0.81	-0.15	0.48
	Beach w/ Structure	-0.93	0.47	-0.43	0.64
	Bank	-0.98	0.28	0.58	0.59
	Salt Marsh	-0.98	2.57	-4.57	8.86
	Structure	-0.48	0.66	0.35	0.68
Fairhaven	Beach	-0.33	0.33	-0.72	0.61
	Beach w/ Dune	-0.57	0.57	-0.75	0.87
	Beach w/ Bank	-0.32	0.22	-1.02	1.06
	Beach w/ Structure	-0.18	0.33	-0.45	0.52
	Bank	-0.33	0.28	-0.90	0.31
	Salt Marsh	-0.39	0.46	-0.96	0.98
	Structure	-0.11	0.31	-0.34	1.04
Falmouth	Beach	-0.14	0.30	-0.27	0.42
	Beach w/ Dune	-0.53	0.97	-0.93	1.27
	Beach w/ Bank	-0.14	0.32	-0.42	0.53
	Beach w/ Structure	-0.25	0.40	-0.38	0.63
	Bank	-0.22	0.43	-0.35	0.42
	Salt Marsh	-0.08	0.63	-0.87	5.63
	Structure	0.07	0.58	-0.18	0.42
Falmouth* (BB)	Beach	-0.09	0.25	-0.20	0.38
	Beach w/ Dune	-0.32	0.61	-0.61	1.03
	Beach w/ Bank	-0.11	0.30	-0.26	0.42
	Beach w/ Structure	-0.12	0.26	-0.19	0.46
	Bank	-0.09	0.20	-0.27	0.41
	Salt Marsh	-0.08	0.63	-0.87	5.63
	Structure	0.18	0.50	-0.11	0.38
Falmouth* (CCS)	Beach	-0.40	0.39	-0.65	0.41
	Beach w/ Dune	-0.91	1.32	-1.50	1.45
	Beach w/ Bank	-0.31	0.42	-1.15	0.27
	Beach w/ Structure	-0.62	0.50	-0.96	0.69
	Bank	-0.81	0.69	-0.71	0.32
	Structure	-0.72	0.55	-0.72	0.31

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Gloucester	Beach	-0.31	0.33	-0.19	1.53
	Beach w/ Dune	0.08	0.78	0.17	4.28
	Beach w/ Bank	-0.36	0.54	-0.75	1.01
	Beach w/ Structure	-0.14	0.33	-0.32	1.47
	Bank	-0.13	0.35	-0.31	1.69
	Salt Marsh	-0.01	0.13	1.53	2.04
	Structure	-0.09	0.32	0.00	1.35
Gosnold	Beach	-0.26	0.35	0.59	1.00
	Beach w/ Dune	-0.26	0.61	1.03	1.70
	Beach w/ Bank	-0.22	0.20	0.70	0.75
	Beach w/ Structure	-0.11	0.84	0.95	1.09
	Bank	-0.12	0.02	-0.36	0.14
	Salt Marsh	-0.06	0.42	-0.49	1.70
	Structure	0.12	0.33	0.45	1.42
Harwich	Beach	-0.24	0.90	-1.21	0.84
	Beach w/ Dune	1.31	1.92	0.56	2.32
	Beach w/ Bank	0.92	0.00	-0.39	0.00
	Beach w/ Structure	-0.02	0.72	-0.39	0.79
Hingham	Beach	-0.05	0.80	-0.26	1.50
	Beach w/ Dune	-1.94	1.03	-4.10	0.14
	Beach w/ Bank	-0.37	0.08	-0.68	1.14
	Beach w/ Structure	-0.12	0.26	-0.30	1.58
	Bank	-0.06	0.40	-1.07	1.55
	Salt Marsh	-0.11	0.40	-1.70	1.92
	Structure	-0.05	0.38	-1.99	2.09
Hull	Beach	-0.12	0.39	-0.67	2.21
	Beach w/ Dune	0.08	0.38	1.13	1.15
	Beach w/ Bank	0.03	0.30	-2.62	2.67
	Beach w/ Structure	-0.05	0.33	0.08	1.32
	Bank	0.39	0.87	-0.04	1.43
	Salt Marsh	0.07	0.36	-0.35	1.68
	Structure	0.38	0.86	0.02	1.10

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Ipswich	Beach	-0.13	0.33	-2.10	1.03
	Beach w/ Dune	-0.39	2.33	-3.98	13.25
	Beach w/ Bank	0.04	0.27	0.54	1.79
	Beach w/ Structure	0.00	0.72	-1.70	4.62
	Bank	0.18	0.36	0.61	0.48
	Salt Marsh	-1.04	1.63	-4.27	6.80
	Structure	-0.11	0.43	0.15	1.09
Kingston	Beach	-0.14	0.23	-0.28	0.87
	Beach w/ Structure	-0.12	0.30	-0.26	1.30
	Bank	0.03	0.11	-0.80	0.23
	Salt Marsh	-0.40	0.54	-0.14	1.30
	Structure	-0.44	0.55	-0.37	0.43
Lynn	Beach w/ Structure	-0.16	0.15	-1.31	1.50
	Bank	0.58	0.60	-0.19	0.15
	Structure	0.69	1.09	-0.49	0.57
Manchester	Beach	-0.40	0.36	-0.59	0.12
	Beach w/ Dune	0.16	0.13	-0.37	1.18
	Beach w/ Bank	0.14	0.26	-0.23	0.97
	Beach w/ Structure	0.13	0.36	-0.32	0.95
	Bank	0.04	0.29	-0.22	0.68
	Salt Marsh	-0.14	0.18	-0.21	0.74
	Structure	-0.03	0.27	-0.15	0.49
Marblehead	Beach	0.11	0.43	-0.85	0.90
	Beach w/ Dune	-0.50	0.27	-0.64	0.98
	Beach w/ Bank	-0.46	0.69	-0.58	1.51
	Beach w/ Structure	-0.31	0.46	-0.62	0.68
	Bank	-0.14	0.35	-0.15	0.45
	Salt Marsh	0.06	0.09	0.05	0.38
	Structure	-0.05	0.33	-0.09	0.50
Marion	Beach	-0.10	0.29	0.06	0.86
	Beach w/ Dune	-0.34	0.25	0.30	0.83
	Beach w/ Bank	-0.52	0.00	-0.07	0.00
	Beach w/ Structure	-0.22	0.26	0.14	0.62
	Bank	-0.10	0.29	0.00	0.54
	Salt Marsh	-0.38	0.41	0.10	1.42
	Structure	-0.22	0.38	0.05	0.65

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Marshfield	Beach	-1.01	0.75	-1.19	2.85
	Beach w/ Dune	0.68	2.63	0.99	3.11
	Beach w/ Bank	-0.44	0.13	-3.48	0.46
	Beach w/ Structure	0.08	0.45	-0.41	1.31
	Bank	0.12	0.28	-0.88	0.99
	Salt Marsh	0.04	0.81	1.33	4.03
	Structure	-0.01	0.31	0.34	2.29
Mashpee	Beach	-1.49	1.34	-0.50	1.20
	Beach w/ Dune	-0.74	0.98	0.51	1.96
	Beach w/ Bank	-1.67	1.04	-1.19	2.32
	Beach w/ Structure	-1.01	0.51	-0.52	0.56
	Bank	-0.89	0.08	-1.01	0.25
	Salt Marsh	-2.91	3.20	-3.34	3.04
	Structure	-0.89	0.08	-1.01	0.25
Mattapoisett	Beach	-0.34	0.26	-0.47	0.75
	Beach w/ Dune	-0.26	0.28	-0.40	0.69
	Beach w/ Bank	-0.26	0.19	-0.24	0.94
	Beach w/ Structure	-0.15	0.27	-0.01	0.91
	Bank	-0.18	0.32	0.10	0.60
	Salt Marsh	-0.58	0.43	-0.09	1.37
	Structure	-0.21	0.33	0.24	0.74
Nahant	Beach	-0.84	0.75	-1.14	1.84
	Beach w/ Dune	0.08	0.16	-1.35	2.95
	Beach w/ Bank	-0.52	0.54	0.44	1.36
	Beach w/ Structure	-0.11	0.43	-0.63	2.33
	Bank	0.06	0.65	-0.24	1.36
	Salt Marsh	0.24	0.03	-0.73	0.51
	Structure	0.00	0.65	0.31	0.96
Nantucket	Beach	-4.15	3.96	-4.80	6.85
	Beach w/ Dune	-1.29	4.89	-2.21	6.91
	Beach w/ Bank	-4.04	4.40	-5.30	7.80
	Beach w/ Structure	-0.84	2.14	-1.18	2.07
	Bank	-0.68	0.03	-1.90	0.10
	Salt Marsh	-0.25	0.49	-1.63	3.44
	Structure	-0.08	0.69	-0.50	1.12

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
New Bedford	Beach	0.38	0.51	1.79	2.48
	Beach w/ Dune	1.13	0.85	0.49	1.07
	Beach w/ Bank	0.28	0.52	2.38	1.67
	Beach w/ Structure	0.06	0.43	0.66	1.03
	Bank	1.63	1.11	2.64	1.88
	Structure	1.69	1.51	0.58	0.91
Newbury	Beach w/ Dune	-0.06	1.68	-2.30	2.05
	Beach w/ Structure	-0.35	0.06	-0.74	0.11
	Salt Marsh	-0.53	1.21	-2.42	5.31
	Structure	1.46	2.16	1.79	2.43
Newburyport	Beach w/ Dune	4.02	5.42	-1.93	6.03
	Beach w/ Structure	-0.25	0.15	-0.22	0.23
	Salt Marsh	1.63	0.57	2.31	2.00
	Structure	2.00	0.34	3.75	0.19
Oak Bluffs	Beach	-0.44	0.24	-0.67	0.62
	Beach w/ Dune	0.09	1.39	0.21	1.89
	Beach w/ Bank	-0.75	0.29	-1.93	0.25
	Beach w/ Structure	-0.57	0.87	-1.22	1.04
	Bank	-0.29	0.53	-0.63	0.36
	Salt Marsh	-1.59	0.96	-0.14	0.96
	Structure	-0.57	0.89	-0.60	0.35
Orleans	Beach	0.00	0.00	-3.90	0.00
	Beach w/ Dune	-3.89	2.53	-4.03	5.09
	Beach w/ Bank	-0.22	0.33	-0.45	1.28
	Bank	-0.27	0.36	-0.48	1.05
	Salt Marsh	-0.54	1.84	-4.28	5.67
Orleans* (CCB)	Beach w/ Dune	-3.13	1.65	-0.95	1.14
	Salt Marsh	-2.63	1.22	-1.45	3.41
Orleans* (OCC)	Beach	0.00	0.00	-3.90	0.00
	Beach w/ Dune	-3.91	2.55	-4.10	5.12
	Beach w/ Bank	-0.22	0.33	-0.45	1.28
	Bank	-0.27	0.36	-0.48	1.05
	Salt Marsh	0.27	1.34	-5.38	6.00

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Plymouth	Beach	-0.67	0.80	-0.26	1.83
	Beach w/ Dune	0.09	1.06	1.46	5.70
	Beach w/ Bank	-0.48	0.57	-0.17	1.94
	Beach w/ Structure	-0.59	0.59	0.12	1.98
	Bank	-0.15	0.82	0.14	1.41
	Salt Marsh	-0.75	0.55	0.14	2.64
	Structure	0.12	1.14	-0.03	1.24
Provincetown	Beach	0.86	2.53	-0.78	3.30
	Beach w/ Dune	1.15	2.17	0.16	4.19
	Beach w/ Bank	1.33	0.16	-1.48	0.13
	Beach w/ Structure	0.77	1.31	0.13	2.28
	Bank	0.47	0.09	0.70	0.56
	Salt Marsh	-0.50	1.47	-0.20	0.19
	Structure	0.47	0.09	0.70	0.56
Provincetown* (CCB)	Beach	0.88	2.57	-0.78	3.35
	Beach w/ Dune	1.68	1.77	-2.64	3.61
	Beach w/ Bank	1.33	0.16	-1.48	0.13
	Beach w/ Structure	0.77	1.31	0.13	2.28
	Bank	0.47	0.09	0.70	0.56
	Salt Marsh	-0.50	1.47	-0.20	0.19
	Structure	0.47	0.09	0.70	0.56
Provincetown* (OCC)	Beach	0.10	0.00	-0.66	0.00
	Beach w/ Dune	1.08	2.21	0.49	4.13
Quincy	Beach	-0.52	0.74	0.10	1.60
	Beach w/ Dune	-0.77	0.59	-3.12	4.98
	Beach w/ Bank	0.00	0.61	-0.62	2.10
	Beach w/ Structure	0.02	0.87	0.87	2.52
	Bank	0.83	1.83	-1.52	2.05
	Salt Marsh	-0.12	0.87	-3.42	4.69
	Structure	0.30	1.70	-0.85	1.51
Revere	Beach	0.23	0.23	0.19	0.20
	Beach w/ Dune	0.88	0.91	0.27	0.29
	Beach w/ Bank	-0.67	0.44	-0.38	0.11
	Beach w/ Structure	0.40	0.96	0.78	1.18
	Bank	-0.49	0.93	-0.18	1.13
	Salt Marsh	-0.35	0.56	1.01	1.09
	Structure	0.26	1.84	-0.80	0.71

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Rockport	Beach	-0.16	0.05	-0.48	1.26
	Beach w/ Dune	-1.17	0.02	0.20	1.11
	Beach w/ Bank	-0.05	0.31	-1.14	1.38
	Beach w/ Structure	-0.50	0.52	-0.92	1.42
	Bank	0.01	0.51	-0.03	1.34
	Structure	0.08	0.54	0.07	1.37
Rowley	Beach w/ Dune	-0.88	0.19	-2.76	1.04
	Salt Marsh	-1.57	1.05	-3.83	4.40
Salem	Beach	0.20	0.79	-0.98	1.36
	Beach w/ Bank	0.01	0.15	-0.54	0.93
	Beach w/ Structure	0.00	0.62	-0.43	0.74
	Bank	0.58	1.53	-0.29	0.41
	Salt Marsh	-0.06	0.58	-0.31	0.72
	Structure	0.41	1.20	-0.20	0.42
Salisbury	Beach w/ Dune	0.15	0.70	-4.13	0.97
	Beach w/ Structure	-0.94	1.29	-1.59	2.49
Sandwich	Beach	-0.33	0.67	1.20	0.65
	Beach w/ Dune	0.40	2.41	2.18	4.28
	Beach w/ Bank	-0.43	0.05	1.98	0.88
	Beach w/ Structure	-0.57	0.72	3.30	3.71
	Bank	0.18	0.11	1.46	1.51
Scituate	Beach	-0.65	1.39	-0.06	1.78
	Beach w/ Dune	-2.06	2.24	-2.71	2.40
	Beach w/ Bank	-0.08	0.28	-0.69	1.18
	Beach w/ Structure	-0.62	0.50	-1.71	1.57
	Bank	-0.32	0.53	-0.43	1.15
	Salt Marsh	-4.20	2.52	-0.04	2.68
	Structure	-0.46	0.62	-0.56	1.20
Swampscott	Beach	-0.31	0.40	-1.84	1.48
	Beach w/ Dune	-0.26	0.21	-2.73	0.50
	Beach w/ Bank	0.13	0.00	-0.75	0.00
	Beach w/ Structure	-0.09	0.30	-1.08	0.92
	Bank	0.02	0.30	-0.59	1.04
	Structure	-0.03	0.28	-0.56	1.05

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Tisbury	Beach	-0.55	0.48	-1.41	1.27
	Beach w/ Dune	-0.27	1.15	-0.68	1.05
	Beach w/ Bank	-0.23	0.37	-1.81	0.13
	Beach w/ Structure	-0.41	0.46	-1.27	0.66
	Bank	-0.20	0.09	-0.54	0.42
	Salt Marsh	0.03	0.29	0.13	0.25
	Structure	-0.08	0.29	-0.01	0.43
Truro	Beach	2.50	5.52	-7.00	6.83
	Beach w/ Dune	-0.32	1.39	-2.57	3.07
	Beach w/ Bank	-1.73	0.75	-2.62	2.09
	Beach w/ Structure	-0.02	0.49	0.19	1.04
Truro* (CCB)	Beach	7.27	0.40	-12.91	0.44
	Beach w/ Dune	0.18	1.47	-2.13	2.22
	Beach w/ Bank	-0.44	0.35	-1.37	1.40
	Beach w/ Structure	-0.02	0.49	0.19	1.04
Truro* (OCC)	Beach	-2.28	0.07	-1.10	0.16
	Beach w/ Dune	-0.86	1.07	-3.04	3.72
	Beach w/ Bank	-2.08	0.33	-2.97	2.11
Wareham	Beach	-0.20	0.52	0.38	1.19
	Beach w/ Dune	0.00	1.04	0.74	2.20
	Beach w/ Bank	0.44	0.60	2.01	2.35
	Beach w/ Structure	-0.01	0.60	0.75	1.19
	Bank	-1.29	1.25	0.65	1.25
	Salt Marsh	-0.35	0.38	0.24	1.11
	Structure	-0.31	0.48	0.19	0.60
Wellfleet	Beach	-0.59	0.60	-1.14	1.04
	Beach w/ Dune	-0.38	1.45	-2.67	3.75
	Beach w/ Bank	-2.40	0.97	-2.55	1.65
	Beach w/ Structure	-1.28	1.24	-1.12	2.44
	Bank	-2.51	2.55	-1.94	2.60
	Salt Marsh	-2.09	2.08	-2.63	5.23
	Structure	-0.33	0.82	-0.73	1.22

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Wellfleet* (CCB)	Beach	-0.59	0.60	-1.14	1.04
	Beach w/ Dune	-0.34	1.44	-2.56	3.70
	Beach w/ Bank	-1.63	1.32	-1.60	1.38
	Beach w/ Structure	-1.28	1.24	-1.12	2.44
	Bank	-2.51	2.55	-1.94	2.60
	Salt Marsh	-2.09	2.08	-2.63	5.23
	Structure	-0.33	0.82	-0.73	1.22
Wellfleet* (OCC)	Beach w/ Dune	-2.57	0.03	-8.31	0.20
	Beach w/ Bank	-2.79	0.32	-3.02	1.57
West Tisbury	Beach	-0.76	0.96	0.11	1.14
	Beach w/ Dune	-3.83	2.89	-1.90	2.52
	Beach w/ Bank	-0.56	0.28	0.39	0.64
	Beach w/ Structure	-0.61	0.24	-0.24	0.84
Westport	Beach	-0.51	0.39	-1.09	0.59
	Beach w/ Dune	-0.64	0.68	-1.15	1.26
	Beach w/ Bank	-0.28	0.30	-0.33	0.16
	Beach w/ Structure	-0.50	0.33	-0.75	0.57
	Bank	-0.20	0.21	-0.45	0.40
	Salt Marsh	-0.47	0.45	0.64	2.17
	Structure	-0.23	0.38	1.26	2.22
Weymouth	Beach	0.03	0.34	-0.74	2.46
	Beach w/ Dune	0.34	0.40	-0.13	3.75
	Beach w/ Bank	-0.09	0.24	-1.18	1.23
	Beach w/ Structure	0.03	0.42	0.28	1.38
	Bank	0.03	0.13	-7.79	2.93
	Salt Marsh	0.38	0.62	-7.26	4.01
Winthrop	Beach	2.39	2.44	0.78	1.47
	Beach w/ Structure	0.11	0.53	0.01	1.17
	Bank	-0.15	0.21	-0.10	0.25
	Salt Marsh	2.63	1.80	5.41	3.64
	Structure	0.05	0.54	0.18	1.32
Yarmouth	Beach	-0.09	0.63	-0.47	1.72
	Beach w/ Dune	0.11	0.86	0.23	1.78
	Beach w/ Structure	-0.12	0.68	0.16	1.12
	Bank	-0.31	0.17	1.42	0.74
	Salt Marsh	-2.48	1.96	-7.52	6.77
	Structure	-0.24	0.21	1.21	0.77

Town	Shoreline Type	Long-Term Rate		Short-Term Rate	
		Mean (ft/yr)	Std Dev (ft/yr)	Mean (ft/yr)	Std Dev (ft/yr)
Yarmouth* (CCB)	Salt Marsh	-2.83	1.88	-8.68	6.58
Yarmouth* (CCS)	Beach	-0.09	0.63	-0.47	1.72
	Beach w/ Dune	0.11	0.86	0.23	1.78
	Beach w/ Structure	-0.12	0.68	0.16	1.12
	Bank	-0.31	0.17	1.42	0.74
	Salt Marsh	-0.40	0.79	-0.58	2.28
	Structure	-0.24	0.21	1.21	0.77

Science and Technology Working Group - Appendix C

Kalman Filter Technical Paper

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L13603, doi:10.1029/2012GL052180, 2012

Extended Kalman Filter framework for forecasting shoreline evolution

Joseph W. Long[1] and Nathaniel G. Plant[1]

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[1] A shoreline change model incorporating both long- and short-term evolution is integrated into a data assimilation framework that uses sparse observations to generate an updated forecast of shoreline position and to estimate unobserved geophysical variables and model parameters. Application of the assimilation algorithm provides quantitative statistical estimates of combined model-data forecast uncertainty which is crucial for developing hazard vulnerability assessments, evaluation of prediction skill, and identifying future data collection needs. Significant attention is given to the estimation of four non-observable parameter values and separating two scales of shoreline evolution using only one observable morphological quantity (i.e. shoreline position). **Citation:** Long, J. W., and N. G. Plant (2012), Extended Kalman Filter framework for forecasting shoreline evolution, *Geophys. Res. Lett.*, *39*, L13603, doi:10.1029/2012GL052180.

1. Introduction

[2] Coastal managers have an increasing need for predictions of shoreline evolution in order to evaluate vulnerability and protect coastal infrastructure, human safety, and habitats. Computationally efficient models are required that are capable of predicting the shoreline response to seasonal, storm, and longer-term forcing that either prograde or erode the beach on a variety of temporal and spatial scales. However, over time, prediction errors resulting from errors in (1) model parameterizations, (2) initial and (3) boundary conditions may grow, rendering a model prediction meaningless for management applications and vulnerability assessments. This necessitates that forecasts of shoreline evolution be based on the combination of a computationally efficient model (requiring a trade-off between the amount of process parameterization and an acceptable level of model detail) and on-going observations of shoreline position to guide, calibrate, and re-initialize the model forecast. Hence, a framework for the combination of these two pieces of information is needed. The framework must be capable of minimizing forecast error by using information contained in the model and the data, dynamically estimating unobservable, poorly constrained model parameters, separating important time scales of shoreline evolution pertinent for different management needs, and statistically quantifying forecast error.

[3] It is clear from existing literature that progress in the development of empirical [e.g., *Frazer et al.*, 2009] and process-based models [e.g., *Yates et al.*, 2009; *Roelvink et al.*, 2009] and observational techniques [e.g., *Stockdon et al.*, 2002; *Plant et al.*, 2007] has and continues to occur. Rather than a complete review of shoreline models or observational techniques, here we develop a framework that efficiently combines model- and data-derived shoreline positions to generate more reliable forecasts as well as quantitative estimates of the forecast uncertainty. The three generic components to an assimilation framework of this type include (1) measured data that are updated occasionally, (2) a numerical model capable of predicting morphologic evolution, and (3) a formal assimilation scheme that can optimally blend (1) and (2). Assimilation methods vary in complexity but can help to estimate model parameters [e.g., *Feddersen et al.*, 2004], boundary conditions [e.g., *Wilson et al.*, 2010] and evolution rates (including changes in parameters/rates) as well as quantify the uncertainty in the forecasted state (e.g. shoreline position). Determining the uncertainty in the forecast will provide guidance for planning purposes, identify requirements for data collection (e.g. when uncertainty exceeds certain limits), and highlight shortcomings in the model formulation. As shown here, a data assimilation framework can provide more than an estimate of the shoreline position driven by a combination of processes that occur on different temporal scales (as would be seen by data alone). This method can separate the shoreline motions and essentially cast what is considered noise at one time scale (e.g. scatter in a linear regression model) into model skill when placed in the context of another forcing mechanism that occurs on a different timescale.

2. Methods

2.1. Shoreline Change Model

[4] Empirical, equilibrium shoreline change models that relate wave conditions to shoreline change without explicitly modeling the complex physical process interactions make skillful predictions of observed shoreline change over time spans of several years at a temporal resolution of O(hours to days) [*Miller and Dean*, 2004; *Yates et al.*, 2009; *Davidson et al.*, 2010]. The models have 3 [*Miller and Dean*, 2004] or 4 [*Yates et al.*, 2009] free parameters which all rely on observations for site-specific calibration and, when calibrated, can reproduce observations over O(years). These equilibrium models address the seasonal changes that occur in shoreline position, and to some degree the storm response. Long-term trends in position due to processes like sea-level rise or alongshore gradients in sediment transport are not

[1]U.S. Geological Survey Coastal and Marine Geology Program, St. Petersburg Coastal and Marine Science Center, St. Petersburg, Florida, USA.

Corresponding author: J. W. Long, U.S. Geological Survey Coastal and Marine Geology Program, St. Petersburg Coastal and Marine Science Center, St. Petersburg, FL 33701-4846, USA. (jwlong@usgs.gov)

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explicitly considered but can be incorporated by the addition of a linear trend to the equilibrium change rate. The slope of the trend relies on a regression of historical data with no updates for future conditions [e.g., *Davidson et al.*, 2010]. Long-term rates and parameter values that fit previous observations may, however, require continual updating due to possible changes in storminess, the rate of sea-level rise, or human intervention (e.g. coastal structures, nourishment).

[5] We selected the equilibrium shoreline evolution model of *Yates et al.* [2009] to include in our assimilation framework, however we expand their approach by adding a long-term component (X_{lt}) formulated as a linear trend which represents shoreline change related to processes which are not considered by equilibrium change models, unless, for example there exists a long-term increase/decrease in wave energy [e.g., *Ruggiero et al.*, 2010]. We define the shorter-term shoreline response (X_{st}) as the position and change in position driven on the timescale of changing wave energy (O(hours to days)) which is modeled with the equilibrium formulation. Hence, in the most basic form, the total shoreline position and change in position is expressed as

$$X(t) = X_{lt}(t) + X_{st}(t) \tag{1a}$$

$$\frac{dX}{dt} = v_{lt} + CE^{1/2}\Delta E \tag{1b}$$

where, v_{lt} represents the long-term rate of change of shoreline position (assumed constant or slowly varying) and the second term in equation (1b) is the wave-driven rate of change of shoreline position given by *Yates et al.* [2009].

[6] Equilibrium theory (and the model applied here for short-term shoreline evolution) assumes that for a given wave energy (defined in *Yates et al.* [2009] as $E = H^2$, where H is the significant wave height), there exists a shoreline position such that the beach would remain in equilibrium (i.e. remain fixed with stationary wave forcing). In this particular model, $\Delta E = E - E_{eq}$, and represents the dis-equilibrium of the existing short-term (wave-driven) shoreline position from the equilibrium position (E_{eq}) expected for the instantaneous wave energy. *Yates et al.* [2009] define the equilibrium shoreline position from historical observations as $E_{eq} = aX_{st} + b$ where the free parameters a and b are the slope and y-intercept of the linear best-fit line that fits the relationship between surveyed shoreline positions as a function of average wave energy observed between surveys. Following the more recent work of *Yates et al.* [2011], who found only a 10% increase in root-mean-square error when reducing their model to three free parameters, we use a change rate coefficient (C) that does not vary with accretive and erosive conditions. This short-term evolution model has been applied to four different sites [*Yates et al.*, 2009, 2011] with root-mean-square errors in hindcasted shoreline position of approximately 5 m and correlations between observed and modeled shoreline positions between R^2 = 0.61 to 0.94 indicating skill in predicting shoreline evolution.

2.2. Assimilation Algorithm

[7] Kalman Filtering is a simple, computationally efficient, and widely used data assimilation method with extensions applicable for nonlinear applications [*Kalman*, 1960; *Wan and Van Der Merwe*, 2001]. Here, we use the joint extended Kalman Filter (hereinafter still referred to as eKF) which uses the general Kalman Filter algorithm but performs a first-order linearization of the forecast equations at each time step [e.g., *Kopp and Orford*, 1963; *Haykin*, 2001]. Most recent contributions of Kalman filtering techniques applied to coastal geophysical applications use ensemble approaches which are necessitated by the complexity of the numerical models [e.g., *Chen et al.*, 2009; *Wilson et al.*, 2010]. Few, if any, studies have applied assimilative techniques to the range of simple predictive models needed to forecast at large spatial and temporal scales that exploit empirical relationships between forcing and response (e.g. sand bars, dune erosion, wave runup).

[8] Based on equation (1), there are three states (X_{lt},v_{lt},X_{st}) and three parameters (C, a, b) we aim to estimate by assimilating the model and the observations of instantaneous shoreline position. Concatenating these variables into one state vector, ψ, gives

$$\psi = \begin{bmatrix} X_{lt} \\ v_{lt} \\ X_{st} \\ C \\ a \\ b \end{bmatrix}. \tag{2}$$

To propagate each variable of the state vector through time we define a set of discrete state-space equations, f:

$$\begin{aligned} \dot{X}_{lt} &= v_{lt} \\ \dot{v}_{lt} &= 0 \\ \dot{X}_{st} &= CE_k^{1/2}(E_k - (aX_{st,k} + b)) \\ \dot{C} &= 0 \\ \dot{a} &= 0 \\ \dot{b} &= 0 \end{aligned} \tag{3}$$

where the $^{\bullet}$ represents the time derivative and k is the discrete time step index. The state estimate is determined from $\psi_k^- = \psi_{k-1} + f(\psi_{k-1})\Delta t$, where superscript $-$ denotes the *a priori* quantity (not yet corrected by the eKF) and Δt is the discrete time step (such that $t = t_0 + k\Delta t$). The *a priori* error covariance is given by

$$P_k^- = J_k P_{k-1} J_k^T + Q_{k-1} \tag{4}$$

where Q is the matrix of noise inherent in the model ("process noise") which is assumed constant here, and J is the Jacobian matrix of partial derivatives of the state-space model with respect to ψ and implements the linearization required by the eKF:

$$J_{i,j} = \frac{\partial f_i}{\partial \psi_j}. \tag{5}$$

In equation (5), i and j, represent the vector and matrix indices. The measurement update equation for the state vector is

$$\psi_k = \psi_k^- + K_k\left(d_k - H\psi_k^-\right) \tag{6}$$

where ψ is the posterior (corrected) physical state. Equation (6) is actually the linear Kalman Filter measurement update equation which can be applied here because our measurement equation (e.g. equation (1a)) is linear. The quantity in parentheses represents the difference between the observation, d,

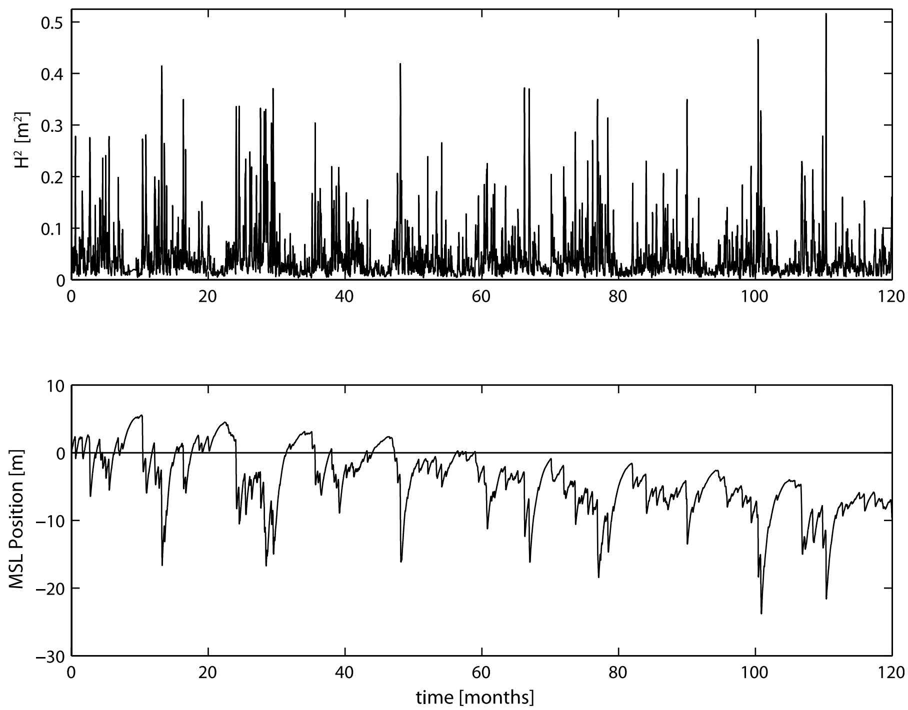

Figure 1. (top) Time series of squared wave height (H^2) and (bottom) simulated shoreline position using equation (1) with $C =$ 1.25 m hr ^{1}/m^3, $a =$ 0.008 m^2/m, $b = 0.075$ m^2.

and the corresponding modeled state, $H\psi$, and is commonly referred to as the innovation. Note that the filter does not require that the observed state (total shoreline position, X) and the forecasted state be the same, only that they are linearly related by H. For this set of state-space equations, $H = [1, 0, 1, 0, 0, 0]$ indicating that the observed shoreline should be compared to the summation of the forecasted short- and long-term positions. The innovation is weighted by the Kalman gain which is computed using the following equation:

$$K_k = P_k H_k^T \; H_k P_k H_k^T + R_k \quad ^{1}. \tag{7}$$

Therefore, the innovation is weighted according to the error covariance of the predicted state vector, P , and the observed state, R_k. For small values of R_k (very accurate measurements) the value of K tends towards unity and the posterior state becomes equal to the observation. Alternately, when the observations are noisy or inaccurate and R_k is large, the forecast will be dominated by the model prediction. After the forecast has been updated with available data, the error covariance of the posterior state (the state including information from both the model and the data) is updated by

$$P_k = (I \quad K_k H) P_k \tag{8}$$

where I is the identity matrix. At each time step when data are available, the eKF has minimized the mean-square error of the forecast (based on knowledge of model and data errors) and this posterior covariance quantifies the combined uncertainty that remains in the forecast.

3. Results

[9] The field tested and calibrated model of *Yates et al.* [2009] and a dense observational time series of wave height were used to generate a synthetic time series of X_{st}. A 10-year wave height time series is taken from a buoy that contains seasonal variations in wave energy along with characteristic noise (Figure 1). Given this time series, the synthetic shoreline position is determined using equation (1b) with a time step of 1 hour, $v_{lt} = 1.4e$ 4 m/hr , $C = 1.25$ m hr ^{1}/m^3, $a =$ 0.008 m^2/m, and $b = 0.075$ m^2. These are typical values from the multiple sites considered by *Yates et al.* [2009, 2011] and values represent a potential time series of shoreline position given the input wave energy. The baseline, highly resolved, modeled shoreline is then subsampled to provide monthly shoreline positions and normally distributed noise with a standard deviation of 0.5 meters (typical horizontal error using GPS measurements) is added to each subsampled synthetic observation.

[10] The eKF is initialized with the following values for the initial state vector, the *a priori* error covariances, and the covariance of process noise (note that the initial vector represents a first-guess and is not equal to the initial conditions used to generate the synthetic time series):

$$\psi_{t=0} = \begin{bmatrix} 0 \\ 1.7e\;\;4 \\ 0 \\ 1 \\ 0.002 \\ 0 \end{bmatrix} P_{t=0} = diag \begin{bmatrix} 0.5 \\ 3e\;\;4 \\ 0.5 \\ 0.8 \\ 0.004 \\ 1 \end{bmatrix}^2 Q = diag \begin{bmatrix} 1e\;\;3 \\ 1e\;\;8 \\ 1e\;\;1 \\ 1e\;\;8 \\ 1e\;\;8 \\ 1e\;\;8 \end{bmatrix}^2. \tag{9}$$

[11] The optimal choices of Q and P depend on knowledge of the true process noise and error covariance, which are unknown. Our choice of the initial error covariance is based on published field results where the model has been

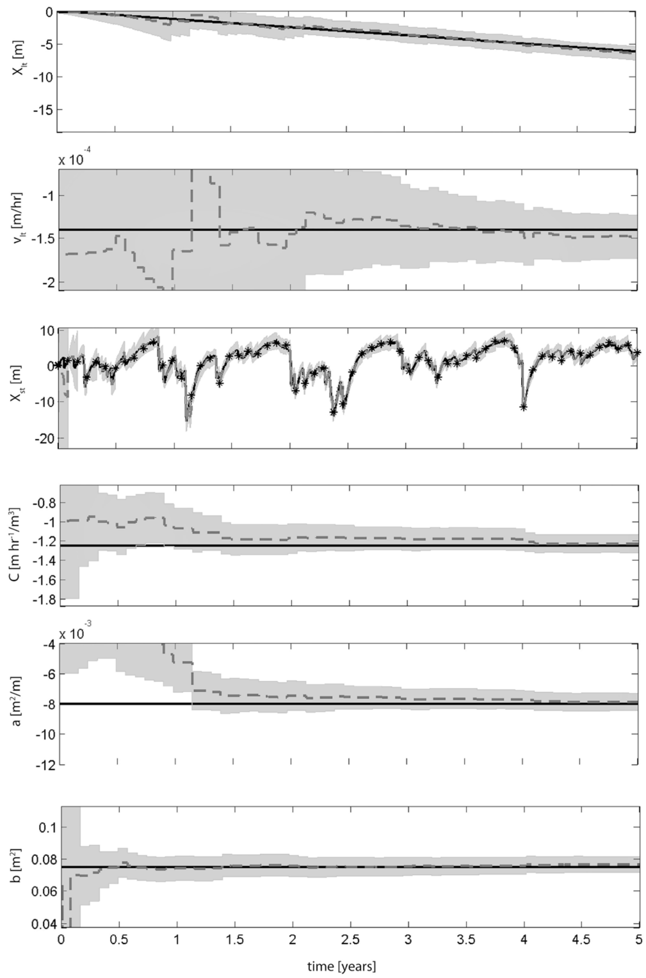

Figure 2. Results from the model-data assimilation algorithm. (top to bottom) Long-term shoreline position (X_{lt}), long-term shoreline rate (v_{lt}), short-term shoreline position (X_{st}), C, a, b with "true" (solid) and modeled (dashed) results and data (asterisks) used in the assimilation process. The shaded area represents the forecast uncertainty (i.e. bounds of the root-mean-square forecast error).

implemented and represents how certain we are about the initial conditions in the state vector. We assume that an observation of shoreline position is available at $t = 0$ and the initial error of the long and short term shoreline positions were set equal to the measurement noise. For initial errors in the three parameters governing the short-term shoreline change we use twice the average standard deviation of the calibrated parameter values reported by *Yates et al.* [2009] except for the value of b, which is entirely site dependent and unknown and is assigned an error covariance of unity (e.g. high uncertainty). Finally, while we could have set the long-term rate to zero and assigned a high value of uncertainty, it is likely that at least a few past observations will be available to guide an initial estimate long-term rate [e.g., *Hapke et al.*, 2006]. We assumed an error in the long-term rate of approximately twice the initial rate provided to the model also indicating a fairly high uncertainty. Because the long-term rate and the three free parameters in the short-term evolution model are typically assumed constant, we assign a small but finite amount of process noise (Q values in equation (9)). This mainly ensures filter stability. The impact of all these choices will be discussed further in section 4.

[12] The time history of the scale-separated shoreline position and model parameters are given in Figure 2. We only show the first half of the time series to highlight the convergence characteristics. The model alone, initialized with the incorrect physical conditions given in equation (9) (ψ), would have given an erroneous forecast of the shoreline position. However, when assimilated with the monthly samples using the eKF, the estimates of model parameters and the individual short- and long-term components of shoreline position converge to near the correct values within two years. The filtering routine was also able to extract the long-term shoreline position and rate, despite initializing the model with an inaccurate value. Given the set of filter parameters that were used here, the long-term shoreline change rate required the longest convergence time. Both the short-term shoreline position and the relationship between the wave height and equilibrium shoreline position converged faster than the long-term trend. Once the parameter values converged on the true values, the levels of uncertainty also converged to the minimum levels of uncertainty which correspond to the estimates of process noise provided to the eKF.

[13] We ran the numerical model (including the baseline model and sampling of observations with random uniform noise) and assimilation routine ten times and averaged the convergence time from all ten runs. The average convergence times (standard deviation) of v_{lt}, C, a, and b were 27.6(7.9), 4(2.6), 13.7(0.7), and 1.0(0) months, respectively. Here, convergence is defined as the point in the time series where all future values have a relative error of less than 20% of the true value.

4. Discussion

[14] Applications of the eKF using a variety of choices for the values of process noise, Q, and error covariance, P, show that for almost all initial values, convergence occurs but at different rates. Convergence is also affected by the quality of the data as can be seen in equation (7), where increasing the data error term (R), decreases the Kalman weight and slows convergence. The eKF weights the forecast more toward the model estimate when poor quality data are available and therefore the Kalman gain is small. Increasing the value of the process noise, Q, causes the forecast uncertainty to have an increased lower limit (after convergence) and to result in a forecast with increased variance. Also, there are correlations between parameters that allow some sub-optimal combinations of parameter estimates to perform well when the noise terms are larger or the sample rate is sparser. This can be seen between b (the short-term equilibrium shoreline position which essentially offsets the time series up and down) and v_{lt} (the long-term rate). We find that realistic values of the initial uncertainty of the model parameters are required rather than initializing with all parameters equal to zero and applying large values of initial error covariance and expecting the algorithm to converge. Too much error on too many parameters results in an unstable filter (convergence to an incorrect combination of parameters) for all sample rates shorter than hourly observations of the shoreline and wave height inputs.

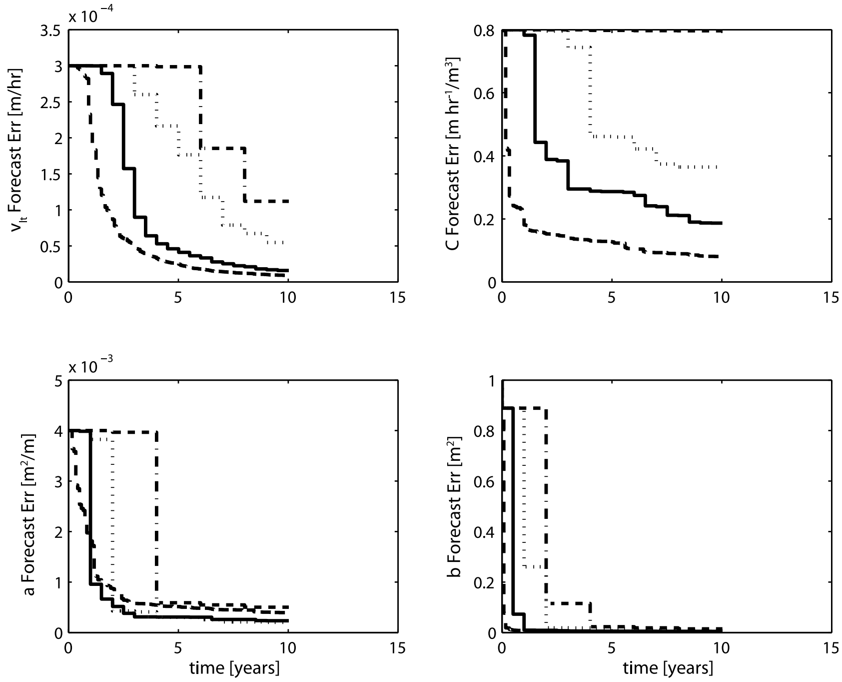

Figure 3. Forecasted error estimates from the Kalman filter for the parameters v_{lt}, C, a, b. Line style indicates the data sampling rate: 1 month (dashed), 6 months (solid), 1 year (dotted), 2 years (dashed-dot).

[15] The sensitivity to different sampling rates was examined by sampling the synthetic time series at intervals ranging from hourly to once every four years with 18 different sampling rates in total. The error estimates of the parameters and shoreline positions are reduced over time due to the assimilation of shoreline observations, regardless of the sampling rate. Four of the different sampling rates (monthly, biannually, annually, and biennially) are shown in Figure 3 illustrating the convergence characteristics. Each step decrease in the error indicates the reduction of forecast error due to information extracted from the data. The assimilation and relative density of the data is apparent in the error estimates by the degree to which errors are reduced gradually (dense data) or are reduced in pronounced step features (sparse data). Note that even when sampling biennially, the parameters associated with the equilibrium shoreline position (a and b) converge the fastest (less than 5 years, only two data points). The erosion coefficient (C) cannot converge with such sparse observations and, hence, error remains large. We note that at some sites, *Yates et al.* [2011] could not find best-fit values for this parameter within an order of magnitude during accretionary times due to the insensitivity of the model to changes in the parameter. For almost all sampling rates and using the current set of values for process noise and initial error covariance, the long-term rate has a slower convergence rate and a biennial sampling strategy would require more than 10 years of data (more than 5 points) because the algorithm focuses on reducing error in the short-term model, given our choices of P and Q.

[16] Kalman filters remain optimal estimators provided that noise is normally distributed. While this assumption is often used, the impact is not well-understood for the majority of applications. Because noise in a natural shoreline data set may not be normally distributed, we repeated the analysis presented here by including both uniformly and rayleigh-distributed noise and found no impact on the convergence characteristics.

5. Conclusions

[17] The joint eKF algorithm was applied to the process of shoreline change using a model consisting of long- and short-term shoreline dynamics. The eKF minimizes the mean square error in the predicted state using available observations. Because it is a recursive filter, it is not necessary to store all of the prior information about the physical state. The data included in the filter can be non-uniform in space and time and inferred from different types of instruments with different noise variances (e.g. shorelines derived from historical photographs or ground surveys, remote sensing, etc.). Combining a process-based model and noisy observations of instantaneous shoreline position using the eKF, four parameters and two scales of shoreline evolution can be estimated using a single observable. Convergence of all six states/parameters occurs within two years given monthly observations (Figure 2) and within several years using biennial observations. Unlike previous methodologies, the approach shown here can explicitly account for temporal variations in parameters, indicates when the parameters have converged, and has added the estimate of a long-term trend which is often neglected in equilibrium model studies. While most studies treat either long- or short-term evolution in isolation and caution against using calibrated models for long-term forecasts [e.g., *Yates et al.*, 2011] our proposed Kalman filter method provides two advantages: 1) model parameters/states can be updated continuously and perpetually in time and do not require constant values and 2) uncertainty estimates identify confidence of the forecasts and parameter estimates and can guide data

collection intervals and/or convey forecast credibility for use in coastal management. The method is computationally very fast and can be applied over a long stretch of coast where parameters/processes are expected to vary and can be run operationally such that forecast updates are produced as soon as new observations are available.

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