Mapping and Analysis of Privately-Owned Coastal Structures along the Massachusetts Shoreline

Client: Massachusetts Office of Coastal Zone Management

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Date Submitted: 31 March 2013

Project Number: 2012-266

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1 Executive Summary

The Massachusetts Executive Office of Energy and Environmental Affairs Office of Coastal Zone Management (MACZM) contracted Applied Science Associates, Inc., (dba RPS ASA) to map and analyze privately-owned coastal structures along the Commonwealth's shoreline. The work is a continuation of the Massachusetts Coastal Infrastructure Inventory and Assessment Project. Previous phases of the project, conducted between 2002 and 2009, provided an inventory and assessment of all publically-owned coastal structures covering approximately 140 miles (225 km) of the Massachusetts shoreline. The addition of privately-owned structures requested under the current scope of work expands the existing database of structures by approximately 230 miles (361 km).

RPS ASA's inventory of privately-owned coastal structures was carried out over a study area that corresponds with the previous phases and includes the ocean-facing shoreline (approximately 1,115 miles [1,794 km]) of all five MACZM coastal regions. The ocean-facing shoreline contains a variety of engineering structures designed for shore protection and stabilization. Many of these structures were built prior to modern coastal policies and regulations and until recently, no centralized database of coastal structures existed.

While previous phases included detailed analyses of structure condition, RPS ASA's assessment of the privately-owned structures is limited to delineating the structures and extracting basic information on type, material, length, elevation, and height from remotely sensed data and available Chapter 91 license documents. The location, length, type, material, and elevation of each structure were determined using a combination of orthophotography, oblique aerial imagery, and LiDAR data. Coastal structures considered for this inventory included shore-parallel features designed to prevent shoreline migration (i.e., seawalls, bulkheads, revetments, and structural sand bags) as well as shore-perpendicular structures that restrict the alongshore movement of sediment or provide channel stabilization (i.e., groins and jetties). The complete database provides fundamental information for coastal management, including baseline statistics describing the number and type of structures and their frequency on the Massachusetts coastline.

In total, 6,611 privately-owned coastal structures were mapped. The final inventory includes 2,967 bulkheads/seawalls, 1,660 revetments, 1,969 groins/jetties, and 15 sandbag structures. Approximately 196 miles (316 km) of shore-parallel structures and 34 miles (55 km) of shore-perpendicular structures were digitized. When combined with publically-owned structures, statewide, nearly 27% of the coastline is armored by some form of public or private coastal protection. The Boston Harbor region has the highest percentage of protected coastline (58%).

The Cape Cod and Islands region has the lowest percentage of protected coastline (13%). The mean (weighted by length) elevation of shore-parallel structures is approximately 12 feet (3.6 meters) NAVD88; shore-perpendicular structures (groins/jetties) average approximately 6 feet (1.7 meters) NAVD88.

2 Introduction

The Massachusetts Executive Office of Energy and Environmental Affairs Office of Coastal Zone Management (MACZM) contracted Applied Science Associates, Inc., (dba RPS ASA) to map and analyze privately-owned coastal structures along the Commonwealth's shoreline. The work is a continuation of the Massachusetts Coastal Infrastructure Inventory and Assessment Project. Previous phases of the project were conducted between 2002 and 2009. The initial phase (Phase 0), consisted of a GPS field survey to collect coordinates and attribute information for all coastal structures determined to be within "high hazard areas" of the Massachusetts coastline. High hazard areas included parcels immediately adjacent to coastal embayments or the Atlantic Ocean, parcels located within coastal flood zones, and parcels immediately adjacent to intertidal areas. The work was completed between 2002 and 2006. Phases 1 and 2, completed in 2009, provided an inventory and assessment of all publically-owned coastal structures, which cover approximately 140 miles (225 km) of the Massachusetts shoreline. The addition of privately-owned structures requested under the current scope of work expands the existing database of structures by approximately 230 miles (370 km).

While Phases 1 and 2 included detailed analyses of structure condition, RPS ASA's assessment of the privately-owned structures is limited to delineating the structures and extracting basic information on type, material, length, elevation, and height from remotely sensed data and available Chapter 91 license documents. Chapter 91 (the Massachusetts Public Waterfront Act) is a licensing program that allows Massachusetts to protect the public's interest in waterways of the Commonwealth. It ensures that the public rights to fish, fowl, and navigate are not unreasonably restricted. Chapter 91 licenses are required for any structure or structure alteration in flowed or filled tidelands. The license documents require detailed plans which often include structure type, material, elevation, and height information.

RPS ASA's inventory of privately-owned coastal structures was carried out over a study area that corresponds with the previous phases and includes the ocean-facing shoreline of all five MACZM coastal regions. The location, length, type, and material of each structure were determined using a combination of orthophotography and oblique aerial imagery. Elevations were assigned using LiDAR data. Upon completion of the inventory, all data was imported into a GIS database of privately-owned structures that is modeled on and compatible with the databases generated for the previous phases.

The sections below provide an overview of the structure inventory process and a summary of the project results. The purpose of the study is provided in Section 3. Section 4 provides an overview of methodology, including a summary of input data sources, approaches for digitizing and attributing structures, and assumptions and limitations of the study. Section 5 discusses the final database structure in detail and Section 6 provides results, summarized both statewide and by MACZM region. Section 7 provides a brief summary of structure elevations relative to predicted sea level rise. Finally, a summary of the project with conclusions is provided in Section 8.

Note: All geospatial data are provided in the Massachusetts State Plane Coordinate System, Mainland Zone, NAD83, meters and adhere to FGDC metadata standards. All elevation data are referenced to NAVD88, meters.

3 Purpose

Massachusetts' ocean-facing coastline extends over 1,100 miles (1,770 km) and includes a variety of coastal structures for shore protection and stabilization. Many of these structures were built prior to modern coastal policies and regulations and until recently, no centralized database of coastal structures existed. In 2009, the MACZM and Department of Conservation and Recreation completed a comprehensive inventory of publically-owned coastal infrastructure to assess the condition of existing structures and assist in prioritization of maintenance and repairs. The purpose of the current work is to expand this inventory by mapping and characterizing the remaining coastal structures within the Commonwealth, which are presumed to be privately owned. The complete database will provide fundamental information for coastal management, including baseline statistics describing the number and type of structures and their frequency on the Massachusetts coastline. The dataset also provides a means of comparing permitted structures with those present on the shoreline. Additionally, because structures were attributed using high accuracy elevations, the dataset can be used to assess the potential impacts of coastal flood events or future sea level changes. The database and GIS files are designed for easy update. The inventory of private structures considered the following: seawalls, bulkheads, revetments, sandbags, and groins/jetties.

4 Methodology

4.1 Data Sources

A variety of data sources were used to define the scope of work, locate coastal protection structures, and to determine or generate structure attribution. The list below summarizes the primary sources of data used for this project.

Previous Structures Inventory

The Massachusetts Office of Coastal Zone Management (MACZM) and Department of Conservation and Recreation have conducted previous statewide mapping of coastal protection structures through the Massachusetts Coastal Infrastructure Inventory and Assessment Project (MACZM, 2009). The initial phase of this work (Phase 0) was completed between 2002 and 2006 and consisted of a comprehensive field survey to collect GPS coordinates and attribute information for all coastal structures determined to be within "high hazard areas" of the Massachusetts coastline. Phases 1 and 2, completed by teams of consultants between 2006 and 2009, provided an inventory and assessment of publically-owned coastal structures covering approximately 140 miles (225 km) of the Massachusetts shoreline. The results of this previous work, including GIS shapefiles, databases, photographs, and summary reports, were used to mask the project area and identify and classify coastal structures and assign ownership. All coastal structures not included in previous phases (and thus mapped for this project) were presumed to be privately-owned. As a result, the inventory may include public structures that were not included in Phase 1 and 2, or were constructed since the completion of earlier Phases of the project.

Project Shoreline

Massachusetts' ocean-facing shoreline was used as the extent of the project area. The 'ocean-facing shoreline' was defined using historical shoreline data, digitized by MACZM and the U.S. Geological Survey (USGS) as part of the Massachusetts Shoreline Change Mapping and Analysis Project, 2013 Update (MACZM, 2013). MACZM provided a shoreline change GIS layer that included vector shorelines (representing the high water line) for the Commonwealth for the years between 1844 and 2009. The most recent shoreline for each coastal reach was used to define the overall project scope.

2008/2009 USGS Color Ortho Imagery

Aerial photography for the Commonwealth of Massachusetts is available for download from the Massachusetts Office of Geographic Information (MassGIS). The most recent data (acquired in 2008 and 2009 by the USGS), were used as a reference layer for digitizing coastal structures, as well as a source for identifying structures and their attributes. The imagery is orthorectified and has a pixel resolution of either 15 or 30 cm (MassGIS, 2012b). All tiles covering the Massachusetts coastal area were downloaded in MrSID format and stored as an ArcGIS mosaic dataset. The mosaic dataset automatically combines the tiles and preferentially uses the highest resolution. Figure 1 shows the extent of imagery used for this project, as well as the resolution and year of acquisition.

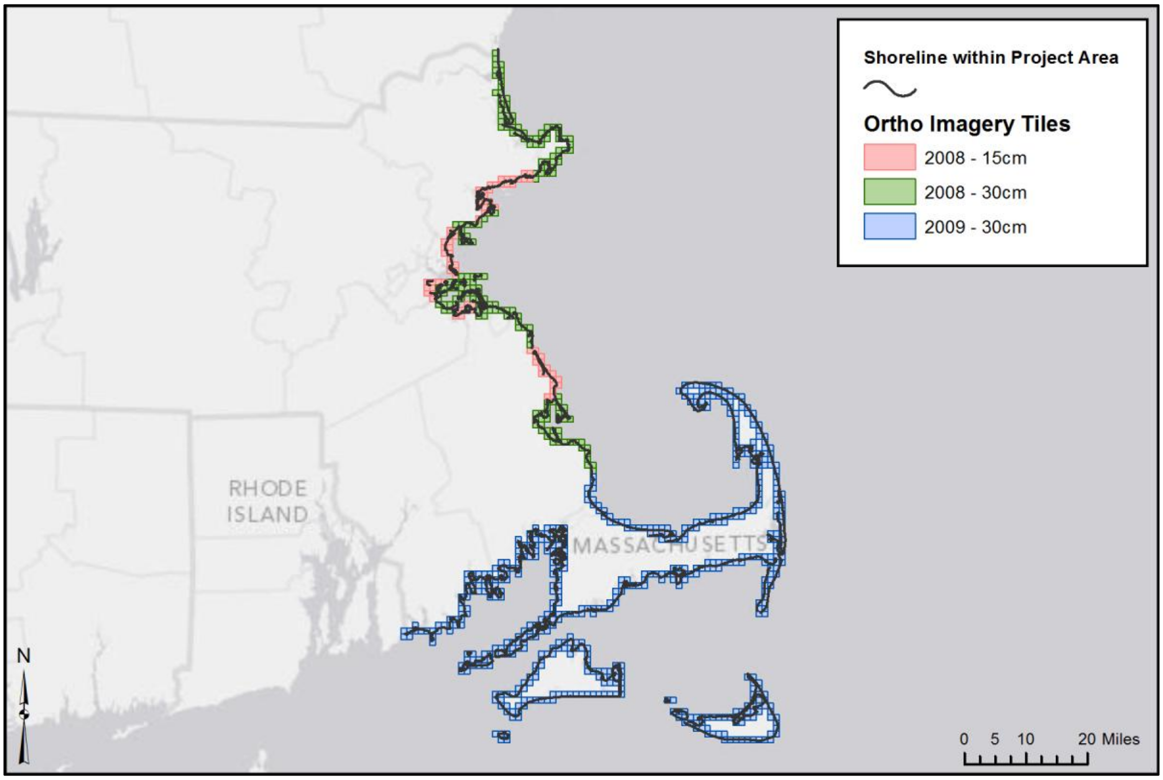


Figure 1. Ortho imagery tiles used for mapping and attribution of privately-owned coastal structures. Colors indicate date of acquisition and resolution.

LiDAR

Light Detection and Ranging (LiDAR) terrain data were used to assign elevations to mapped coastal structures. LiDAR Digital Elevation Models (DEMs) were obtained from the MassGIS website, which hosts seventeen LiDAR datasets collected between 2002 and 2011 (MassGIS, 2012a). Eight of the datasets available are within the project area and were used for structure attribution. Figure 2 shows these LiDAR sources and their coverage. The elevation datasets were combined into an ArcGIS mosaic dataset, which automatically converted all LiDAR tiles to the same projection and units and preferentially uses the most recent tiles. The LiDAR dataset was used to assign elevations to structures that were mapped as part of the inventory. A full description of the individual elevation datasets, mosaicking process, and the methods used to evaluate coastal structure elevations is included in Appendix A.

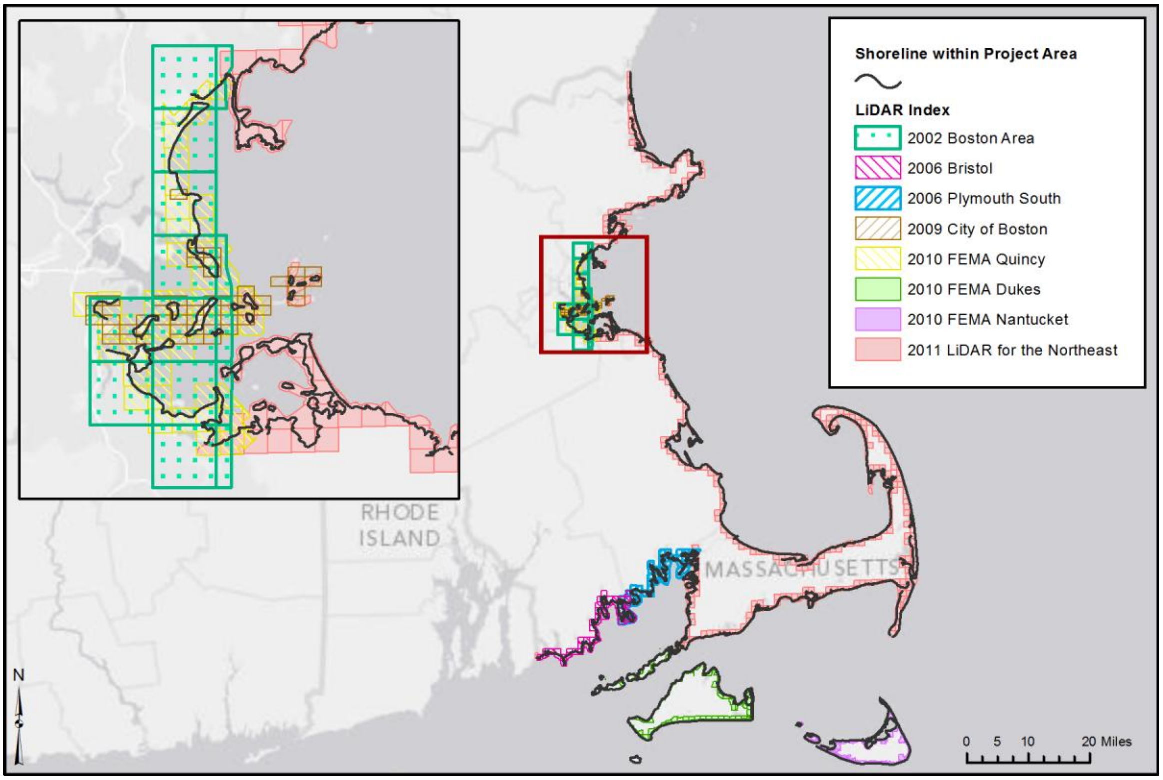


Figure 2. LiDAR tiles used for attribution of privately-owned coastal structures. Colors indicate source and date of acquisition.

MACZM Regions

The Massachusetts coastal zone is divided into 5 regions by MACZM for planning and administrative purposes: North Shore, Boston Harbor, South Shore, Cape Cod & Islands, and South Coastal. A GIS layer representing the boundaries of the MACZM regions was acquired from MassGIS and used to summarize the project results at both the statewide and regional level (MassGIS, 2008). Figure 3 shows the five MACZM regions and the municipal boundaries within each region.

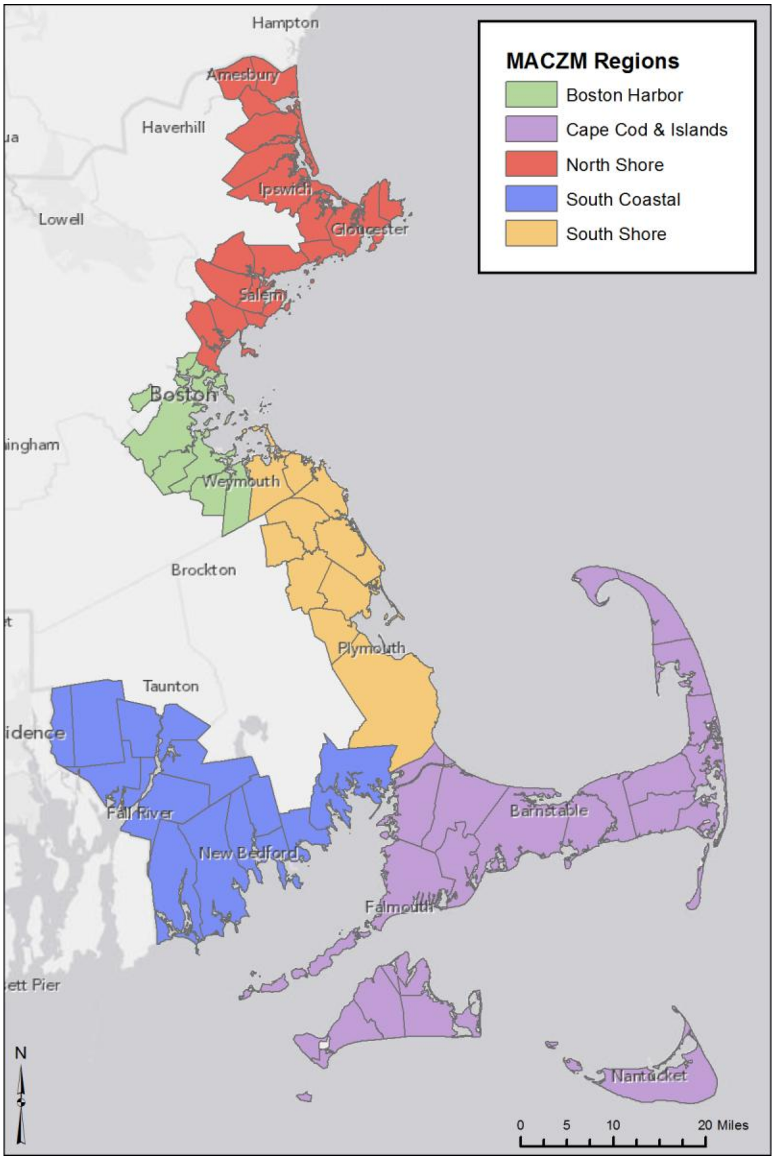


Figure 3. MACZM regions used to summarize the project results.

Massachusetts Oblique Imagery (Pictometry)

The Massachusetts Department of Transportation (MassDOT) hosts a library of low-altitude, 8-inch pixel resolution, oblique digital images for the state (MassDOT, n.d.). The images, (taken at an angle of approximately 45°), were collected by Pictometry International in 2008. The imagery is available for public viewing through a web-based imagery viewer on the MassDOT website: https://www.massdot.state.ma.us/planning/Main/MapsDataandReports/Maps/InteractiveMaps/Pictometry.aspx. Figure 4 shows an example of the MassDOT oblique imagery in the town of

Nahant, Massachusetts. Because Pictometry images allow coastal features to be viewed at both oblique angles (approximately 45 degrees) and orthogonally (overhead), and from multiple perspectives (alongshore and cross-shore), this imagery was a primary reference for identifying coastal structures and for determining their type and construction material.

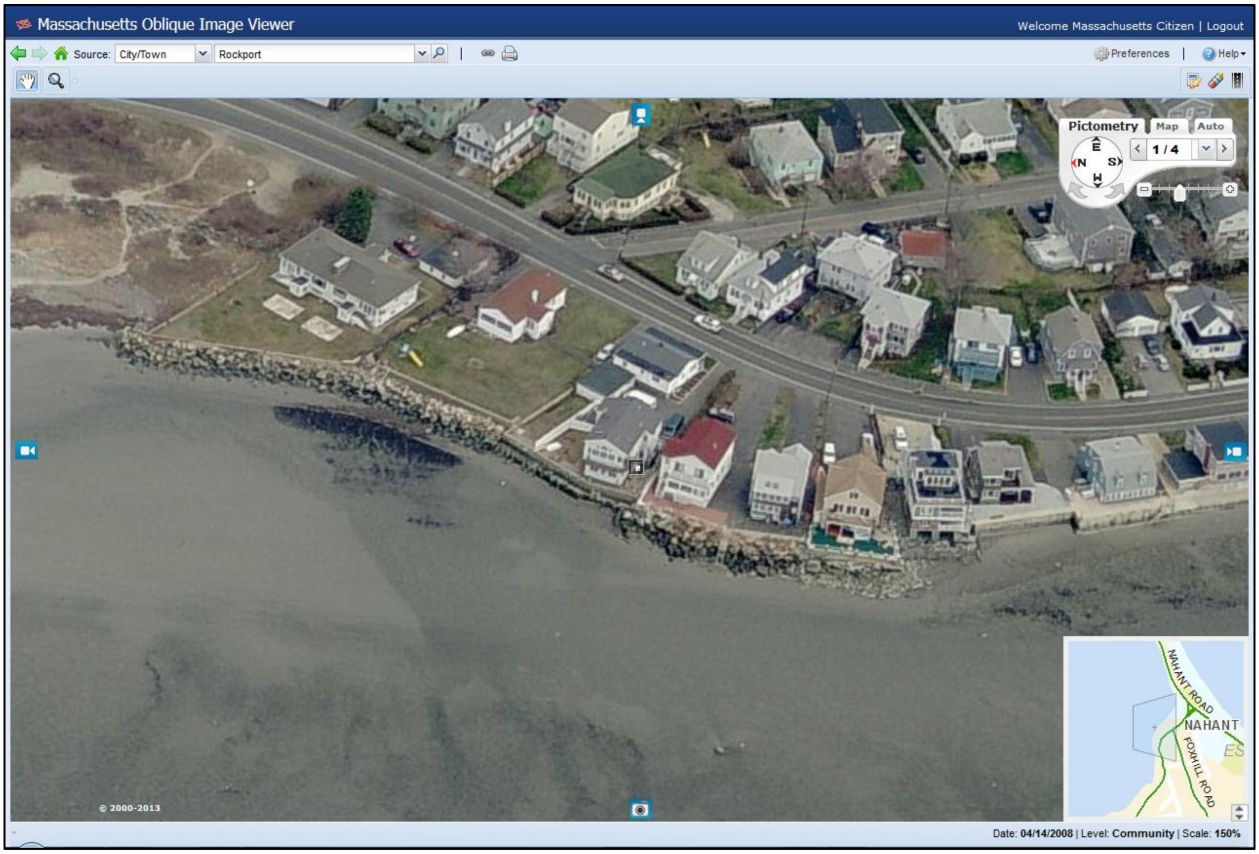


Figure 4. Example of MassDOT oblique imagery in the town of Nahant, MA.

BING

Microsoft Bing Maps (http://www.bing.com/maps/) also hosts a comprehensive library of publically-available, oblique aerial imagery (Microsoft, 2013). Bing's 'Bird's Eye' imagery can be viewed at different scales and perspectives depending on the coverage and resolution at the point of interest. This imagery was used as a secondary source for identifying coastal structures and determining their type and construction material. An example of the Bing oblique imagery for the Plymouth coastline is shown in Figure 5.

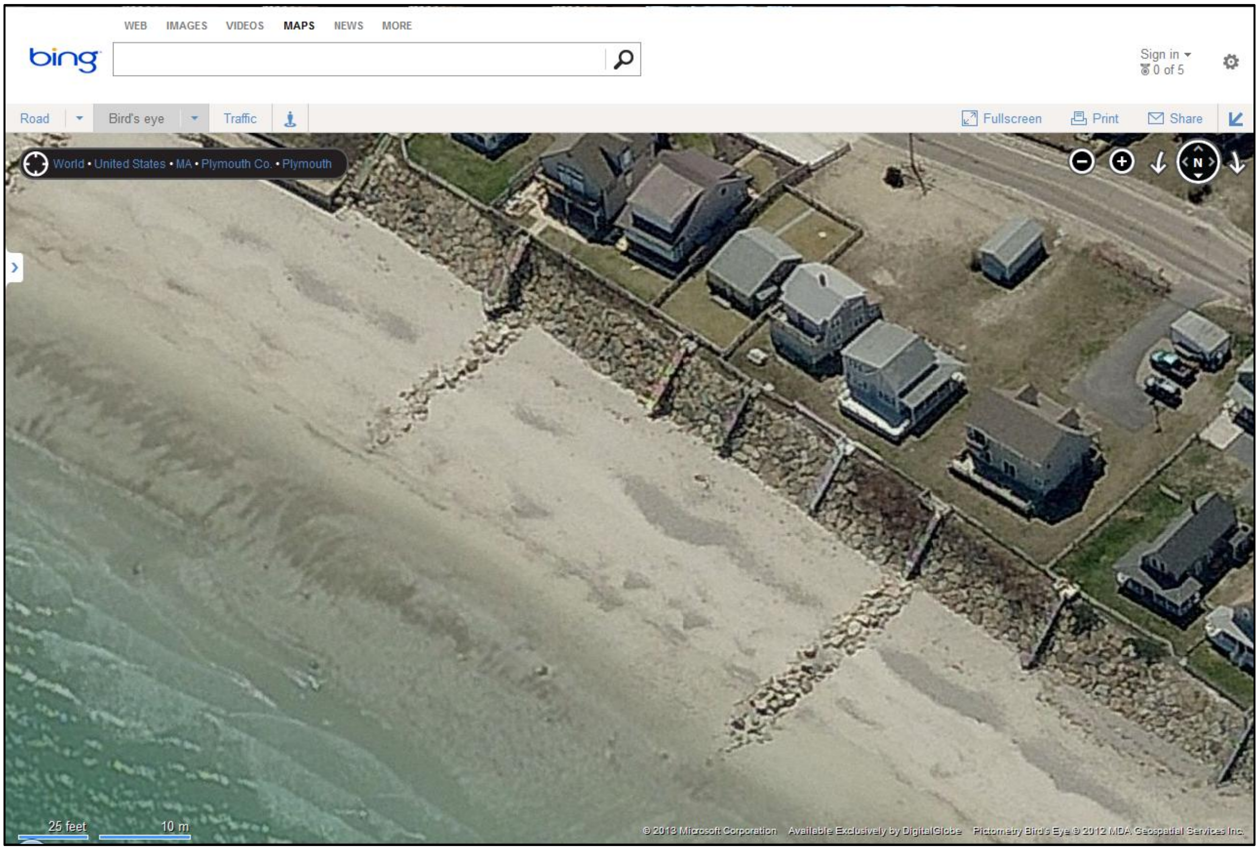


Figure 5. Example of Bing Bird's Eye imagery in the town of Plymouth, MA.

Tax Assessor's Parcels

Consistent with previous phases of the inventory, tax parcel data for Massachusetts' coastal towns was used to generate unique identification numbers for each coastal structure. Parcel data were downloaded from MassGIS for each town (with the exception of the town of Newbury, see Appendix B) (MassGIS, 2010; MassGIS, 2013). All parcels, represented as polygon features, were merged and a unique ID was generated for each structure based on the parcel nearest to the midpoint of each linear structure. Appendix B contains specific details about the parcel data and the processing steps to create and assign structure IDs.

Chapter 91 licenses and points

Massachusetts General Law Chapter 91, the Massachusetts Public Waterfront Act, requires authorization in order to build or alter structures constructed seaward of the mean high water line. Chapter 91 authorization is required for a range of engineering structures that are proposed for Massachusetts tidelands, including piers, wharves, revetments, dams, and bridges. In order to obtain authorization, detailed plans must be submitted for all structure(s); authorization is granted in the form of a license. The Massachusetts Department of Environmental Protection (MassDEP) manages Chapter 91 and maintains paper copies of all licenses at their office. MassDEP also maintains a shapefile of licensed structures, which includes coordinates of the approximate structure location, as well as information describing the structure type, applicant, and license date. The shapefile was provided to RPS ASA and was filtered to identify Chapter 91 licenses potentially relevant to the coastal structures inventory. Each potentially relevant paper license document was scanned and saved in .PDF format. The Chapter 91 license documents were primarily used to determine above-ground structure height. As described in Section 4.4, each license was linked to its corresponding structure manually. A .PDF file for each license linked to a structure is included in the final structures database as reference documentation for the corresponding structure.

Baseline

As part of the process of assigning structure elevations, an offshore reference layer was needed to determine the orientation of each structure with respect to the coastline. MACZM provided a shore-parallel polyline - a *baseline* - which was initially developed to calculate shoreline-change rates as part of the MACZM Shoreline Change Project (MACZM, 2013). The line does not correspond to any real-world feature; it was created as a reference line for transects cast by the USGS Digital Shoreline Analysis System software. The baseline is situated offshore and roughly approximates the shape of the natural coastline, thus it is ideal for the purposes of determining the orientation of each structure relative to the shoreline. The baseline layer was modified slightly to ensure that no digitized structures intersected the line.

4.2 Digitization of Structures

Man-made features designed to stabilize the shoreline or reduce coastal storm impacts were considered for this inventory. Privately-owned coastal structures digitized for this project include the following (USACE, 2002):

- Bulkhead - A shore-parallel vertical structure or partition to retain or prevent sliding of the land with a secondary purpose to protect the upland environment against damage from wave action.
- Seawall - A shore-parallel vertical structure (often concrete or stone) separating land and water areas, primarily designed to prevent erosion and other damage by wave action (typically more massive and capable of resisting greater wave forces than a bulkhead)

- Revetment - A facing of stone, concrete, or other material used to protect an embankment or another coastal structure against erosion by wave action or currents.
- Groin - A relatively narrow, shore-perpendicular structure built to reduce longshore currents and trap sediment.
- Jetty – A shore-perpendicular structure built to stabilize a channel and prevent buildup of sediment
- Sand Bags – Bags filled with sediment designed to stabilize the shoreline.

Examples of privately-owned structures identified for this inventory are presented in Table 1.

Coastal structures were digitized as polyline features from imagery using a "heads-up" approach. All geographic features were identified and manually traced in ArcGIS using the 2008/2009 USGS Color Ortho Imagery as a reference dataset. Digitizing was done at a minimum scale of 1:2,500, but typically at larger scale. A description of the general work flow follows. All coastal structures were digitized in the Massachusetts State Plane Coordinate System, Mainland Zone, NAD83, meters.

Typically, structures were identified using a combination of the oblique imagery sources (MassDOT and Bing). Given their high resolution and oblique perspective, these sources were also often used to determine structure type and material. The feature was then digitized using the ortho imagery for reference. For bulkheads and seawalls, the polyline was typically digitized along the top of the structure. For revetments, the line was digitized at the landward edge of the structure (presumed to be the highest point). For groins and jetties, a line along the center of each structure was digitized. Multiple imagery datasets were used to ensure that structures were digitized at their maximum elevation, however the final location of the structure was always digitized using the 2008/2009 USGS imagery.

As structures were located and digitized, the primary structure type and its materials were identified and recorded. For features that consist of multiple structure types and materials (for example, a bulkhead or seawall with a revetment in front), a secondary structure type and material was also recorded. For these structures, the landward feature was assigned as the primary structure and the seaward (typically lower) feature was assigned as the secondary structure.

Structures were digitized into an ArcGIS File Geodatabase (FGDB) polyline feature class. To ensure data integrity, the database and feature class were created using a subtype and domain architecture. Subtypes are used to categorize data using an attribute field. For the coastal structures feature class, a subtype was created for the *PrimaryType* field. This subtype allowed only the following values to be assigned as primary type:

1. Bulkhead/Seawall
2. Revetment
3. SandBags
4. Groin/Jetty

For each of the four subtypes defined for the *PrimaryType* field, default values or domains were created for the *PrimaryMaterial* field. For the 'Bulkhead/Seawall', 'Revetment', and 'Groin/Jetty' subtypes, domains with allowable materials for each of those features were created (see Section 4.3.2). The 'SandBag' subtype has a default material of 'Sandbags'.

The *SeconaryType* field also contains domains for each *PrimaryType* subtype; these domains constrained the type of secondary structure that could be associated with each primary structure (see Section 4.3.1). The *SecondaryMaterial* field contained a single domain listing all allowable materials.

Use of the field domain and subtype approach served two purposes. First, it ensured that only valid entries were assigned to each field, for example:

- only pre-defined structure types could be entered in the *StructureType* field;
- the structure materials were limited based on structure type;
- the secondary structure type was limited based on the primary structure type.

In addition, this approach greatly simplified the digitizing process. An editing template was created, which allowed the GIS analyst to quickly select the primary type/material combination from a list of features. Based on the selection, the primary type and material attributes were set automatically as the feature was digitized. Secondary types and materials were selected from the same predefined lists when encountered. Figure 6 shows an example of the editing template (lower left corner of the screen shot) with the primary type and material combination options available for digitizing each feature.

To comply with the database schema of the previous phases, the subtype and domain architecture was removed from the final FGDB delivered to MACZM.

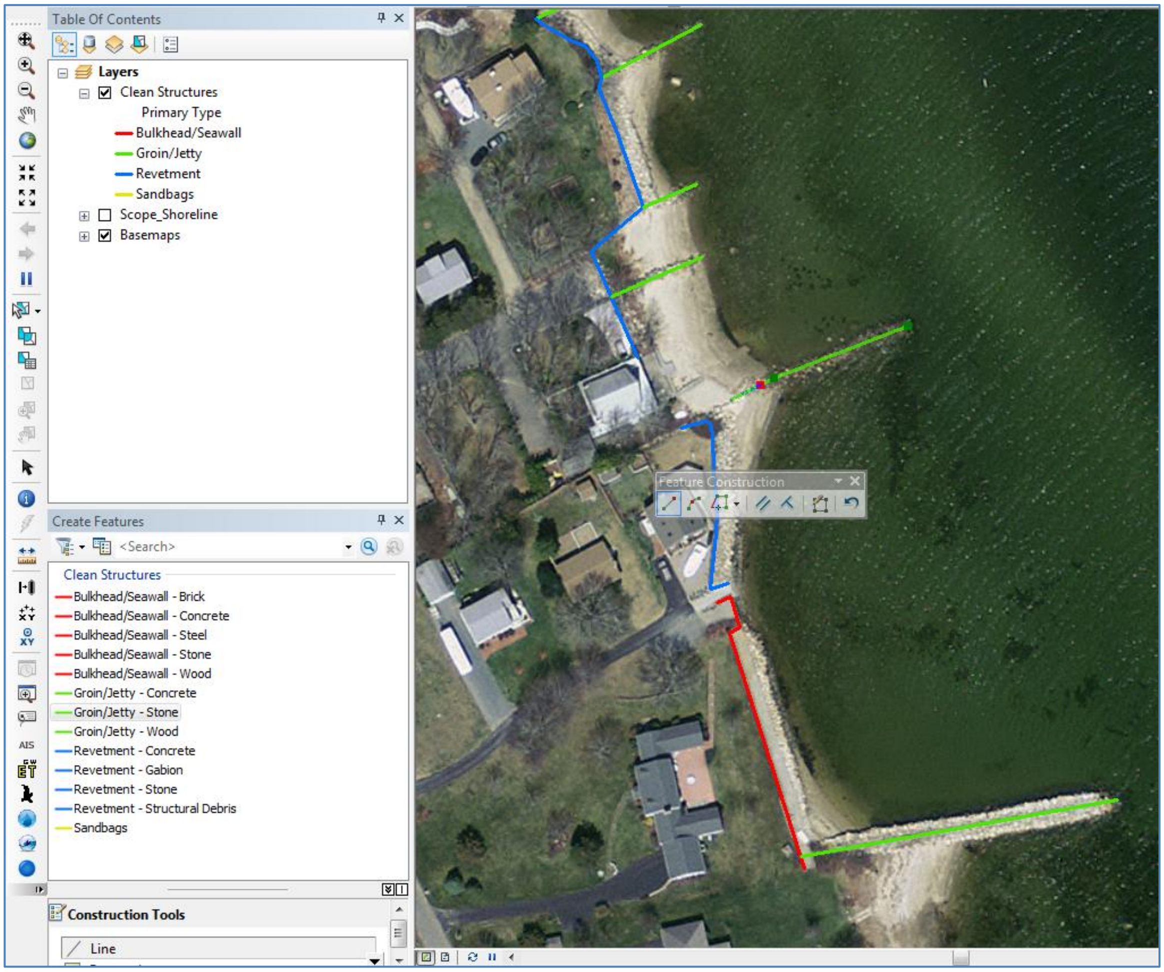


Figure 6. Editing template for "heads-up" digitizing of coastal structures.

The project shoreline provided by MACZM was used to define the extent of the project area. Structures were only digitized as far into bays, harbors, and coastal ponds as the shoreline file extended.

Phase 1 and 2 structures were used during the digitization process to determine ownership (public or private). Mapped structures that were not already included in Phase 1 or 2 were considered private, regardless of true ownership (which was not determined).

Previous mapping of Phase 0 structures was used in the following way: in the rare cases when an existing structure aligned well with the 2008/2009 ortho imagery, the feature was simply copied into the new database and the attributes were set manually. More often, Phase 0 structures were substantially offset from the imagery and required complete re-digitization. The type and material of all previously mapped structures were set based on existing Phase 0 attributes. However, in several instances, recent imagery indicated that the structure characteristics have changed since the completion of Phase 0. Figure 7 shows a concrete seawall and failed stone revetment identified in Phase 0, which has since been rebuilt as a stone revetment. In these cases, structure type or material were updated as necessary.

To ensure consistency throughout the project, all digitizing was completed by a single GIS analyst. After the initial digitization, the entire dataset was reviewed by a separate data analyst, ensuring consistency throughout the QAQC process. Any feature still in question after QAQC was flagged and a shapefile of flagged features was provided to MACZM prior to completion of the structure database. Each question was resolved by MACZM staff and all validated features were incorporated into the final structures layer.

(a)

(b)

Figure 7. Example of a structure that has been rebuilt since the completion of Phase 0. The previous structure, a combination of a failed revetment and a seawall is shown in (a). The rebuilt revetment is shown in (b)

4.3 Attribution of Structures

4.3.1 Structure Type

Table 1 lists the coastal structure types that were considered for this project and provides an example photograph of each type. Primary (landward) and secondary (seaward) types were mainly identified using the oblique aerial imagery. The primary structure type was stored in the *PrimaryType* field and the secondary structure type in the *SecondaryType* field.

Approximately 6% of all structures digitized included a secondary structure type. Of these, the most typical combination (95% of occurrences) is a bulkhead/seawall fronted by a revetment. Table 2 lists the secondary structure types available as options for each primary structure type.

Structure types for previously mapped (Phase 0) features were typically taken from the Phase 0 database. In some cases, recent imagery indicated that the structure characteristics have changed since the completion of Phase 0 (see Figure 7). In these cases, the structure type was updated to match the recent imagery. Photos taken during previous field surveys were also used to verify structure types when aerial imagery was not clear.

Table 1. Coastal structure types with an example photograph of each type.

Structure Type	Examples
Bulkhead/Seawall: A generally shore-parallel vertical structure separating land and water areas, primarily designed to prevent erosion and other damage from wave action	
Revetment: A facing of sloping stone or other material built to protect an embankment or another coastal structure against erosion by waves.	

Table 1, cont. Coastal structure types with an example photograph of each type.

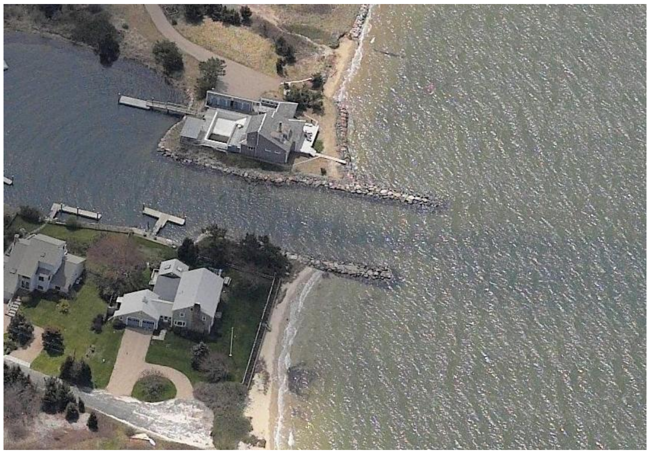
Structure Type	Examples
Groin: A relatively narrow, shore-perpendicular structure built to reduce longshore currents and trap sediment.	
Jetty: A shore-perpendicular structure built to stabilize a channel and prevent buildup of sediment	

Table 1, cont. Coastal structure types with an example photograph of each type.

Structure Type	Examples
Sand Bags: Bags filled with sediment to stabilize the shoreline.	

Table 2. Secondary structure type options for each primary structure type.

Primary Type (landward)	Secondary Type (seaward) Options
Bulkhead/Seawall	Groin/Jetty Revetment Sandbags
Revetment	Bulkhead/Seawall Groin/Jetty Sandbags
Sandbags	Bulkhead/Seawall Groin/Jetty Revetment

4.3.2 Structure Material

The structure material was also primarily determined using the oblique aerial imagery. The construction material was recorded for the primary structure type and if present the secondary structure type. The primary structure material was stored in the field named *PrimaryMaterial* and the secondary structure material in the *SecondaryMaterial* field. The pre-defined list of materials used to classify each type of structure is listed in Table 3.

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Table 3. Structure material options for each structure type.

Structure Type	Materials
Bulkhead/Seawall	Brick Steel Stone Wood Concrete
Groin/Jetty	Concrete Stone Wood
Revetment	Concrete Gabion Stone Structural Debris
Sandbags	Sandbags

As with structure type, the construction material for Phase 0 structures was typically determined using the previous database and only modified if more recent imagery indicated that the structure characteristics have changed since the competition of Phase 0. Photos from previous field surveys were used to verify structure materials when the aerial imagery was inconclusive.

Determining the material from remotely sensed data was frequently a difficult task. In locations where the oblique imagery was poorly resolved or coverage was insufficient, it was often difficult to visually distinguish between the following materials (for structure types listed in parentheses):

- concrete and stone (bulkhead/seawalls);
- wood and steel (bulkhead/seawalls);
- gabion or structural debris and stone (revetments).

Though gabions are an option for revetment construction material, this combination of structure and material was not encountered.

4.3.3 Structure Length

In FGDBs, ArcGIS automatically stores the length of each polyline feature (in the horizontal units of the layer's coordinate system) in a field called *Shape_Length*. Given the requirement to use the Massachusetts State Plane Coordinate System, the units of the *Shape_Length* field are in meters.

Using the values in the *Shape_Length* field, each structure's length in meters was converted to feet and rounded the nearest foot. This value was stored in the *Structure_Length* field.

4.3.4 Structure ID

Every coastal protection structure received a unique identifier (ID) based on tax parcel data. The first 12 digits of the ID string correspond to a combination of the town, map, block, and lot number for the nearest parcel. An additional sequential number was appended to ensure the ID was unique for cases where multiple structures occur on the same tax parcel. The ID format matches those from previous phases of the inventory. Each part of the structure ID is separated by a hyphen ("-"). Additional details on how the structure ID was generated are described in Appendix B.

As in previous phases, the components of the structure ID are stored in multiple fields (*CommunityNo, MapNo, BlockNo, ParcelNo, StructureNo*) and the full structure ID is stored in two fields, *STR_ID* and *StructureID*. The "ID" field simply lists a sequential number for all structures in the database.

Figure 8 provides examples of the structure IDs and their parts for 12 structures.

ID	StructureID	CommunityNo	MapNo	BlockNo	ParcelNo	StructureNo
1	020-052-002-000-001	020	052	002	000	001
2	020-051-008-000-001	020	051	008	000	001
3	020-051-007-001-001	020	051	007	001	001
4	020-051-007-001-002	020	051	007	001	002
5	020-051-007-001-003	020	051	007	001	003
6	020-051-007-001-004	020	051	007	001	004
7	020-051-007-002-001	020	051	007	002	001
8	020-051-007-002-002	020	051	007	002	002
9	020-051-007-002-003	020	051	007	002	003
10	020-051-007-002-004	020	051	007	002	004
11	020-051-016-000-001	020	051	016	000	001
12	020-051-016-000-002	020	051	016	000	002

Figure 8. Example structure IDs and their individual components.

4.3.5 Structure Elevation

Structure elevations were derived from the LiDAR dataset compiled for the project area (see more details on the LiDAR DEMs provided in Appendix A). All elevations are in meters relative to the NAVD88 vertical datum. Elevations are stored in the *PositionZ* field.

Attribution of structures with a single (maximum) elevation value requires careful consideration of each data source, its accuracy, and precision. For example:

1. Because structures are digitized using ortho imagery as a base layer, the alignment of these features with LiDAR is limited by the precision between the imagery and elevation datasets.
2. Most coastal structures do not maintain a consistent elevation for their full length, thus simply extracting an elevation at a point along the linear feature would not necessarily be the most representative elevation for the top of the structure.

Prior to developing the methodology to assign elevations, these issues were discussed between MACZM staff and RPS ASA. As a result, two automated processes were designed to extract the elevations for each structure. One process was developed to assign elevations to shore-parallel structures, and another was used for shore-perpendicular structures (groin and jetties). Each process is described below; Appendix A provides more detailed explanations of each.

All structures were not assigned an elevation. In some areas, the LiDAR data extended only a short distance from the coast and did not intersect with structures situated at or seaward of the shoreline. Figure 9 shows an example from Oak Bluffs on Martha's Vineyard where structures fall outside of the LiDAR coverage. Areas in grey fall within the DEM tiles, but have no elevation data. The surrounding area (in white) is outside of the LiDAR tiles entirely.

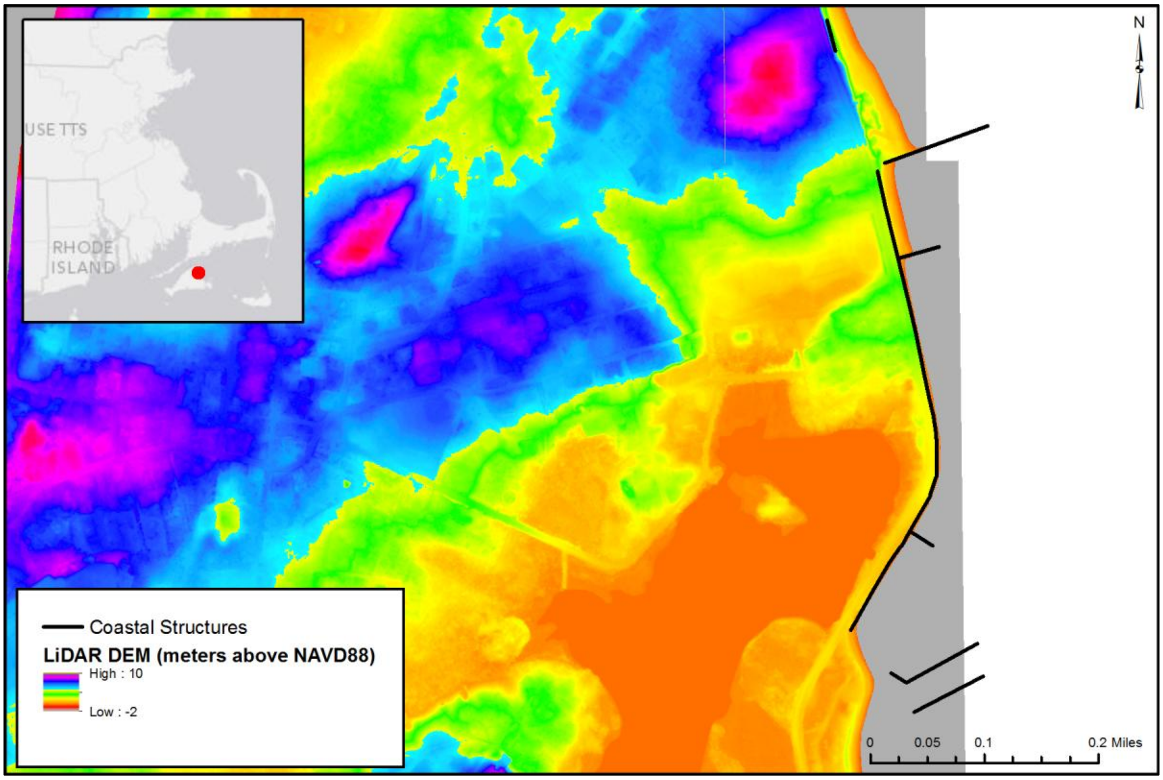

Figure 9. Example of structures outside of the extent of the LiDAR data coverage.

4.3.5.1 Shore-Parallel Structures

For shore-parallel structures, the majority of elevations were generated by creating profile lines and extracting elevations. A series of profile lines was cast perpendicular to each structure. Elevations from the corresponding LiDAR dataset were extracted along each of the profile lines. The maximum elevation of each profile was chosen to represent the structure elevation at that transect. The profile maximums were then averaged to give the structure elevation. Using this approach ensured that 1) a representative elevation was chosen for each structure regardless of any potential misalignment with the DEM, and 2) that the structure elevation value accounted for variability in elevations along each structure.

For each structure, profile lines were created with variable spacing. The spacing interval was designed to not exceed 5 meters. Each profile line was automatically extended from 50 meters in the seaward direction to 2 meters in the landward direction, perpendicular to the structure. Elevations were extracted along these lines at 1 meter intervals (the minimum resolution of the LiDAR data), for a total of 53 elevation points per profile line. In cases where some or all of the elevation points were not covered by the LiDAR DEMs, these points were excluded from analysis.

Two limits were put in place to exclude potentially invalid data from the analysis:

1. If the maximum elevation along a given profile was not within 3 meters of the location of the structure, the profile was excluded. As shown in Figure 10, this was done to remove anomalous elevations that may be introduced from substantial features in the coastal profile such as docks or piers;
2. Each structure was required to have at least 3 valid profiles for averaging.

Using this approach, 4,248 of the 4,700 shore-parallel structures were successfully assigned an elevation. The rules above were modified for the remaining 452 structures that had too few or no valid profile lines. The steps below were performed in order to assign elevations to as many structures as possible.

1. For each profile, the maximum elevation within 3 meters of the structure was calculated. This excluded the influence of any natural coastal features and/or infrastructure outside of the immediate vicinity of the structure.
2. The minimum requirement for number of profiles was removed. Any structure with at least one profile was assigned an elevation.

Collectively, these two changes produced valid elevations for an additional 382 structures. For the remaining 70 structures, cross-shore profiles were manually digitized (3 per structure).

Elevations were extracted at 1 meter intervals and the maximum elevation of each profile was averaged to represent the structure. Each profile was manually reviewed to ensure that the maximum elevation was representative of the coastal structure. An additional 69 structures were assigned an elevation using this approach.

In total, 4,699 of the 4,700 shore-parallel structures were attributed with an elevation value. The one remaining structure was entirely outside of the LiDAR extent, and thus was not assigned any elevation.

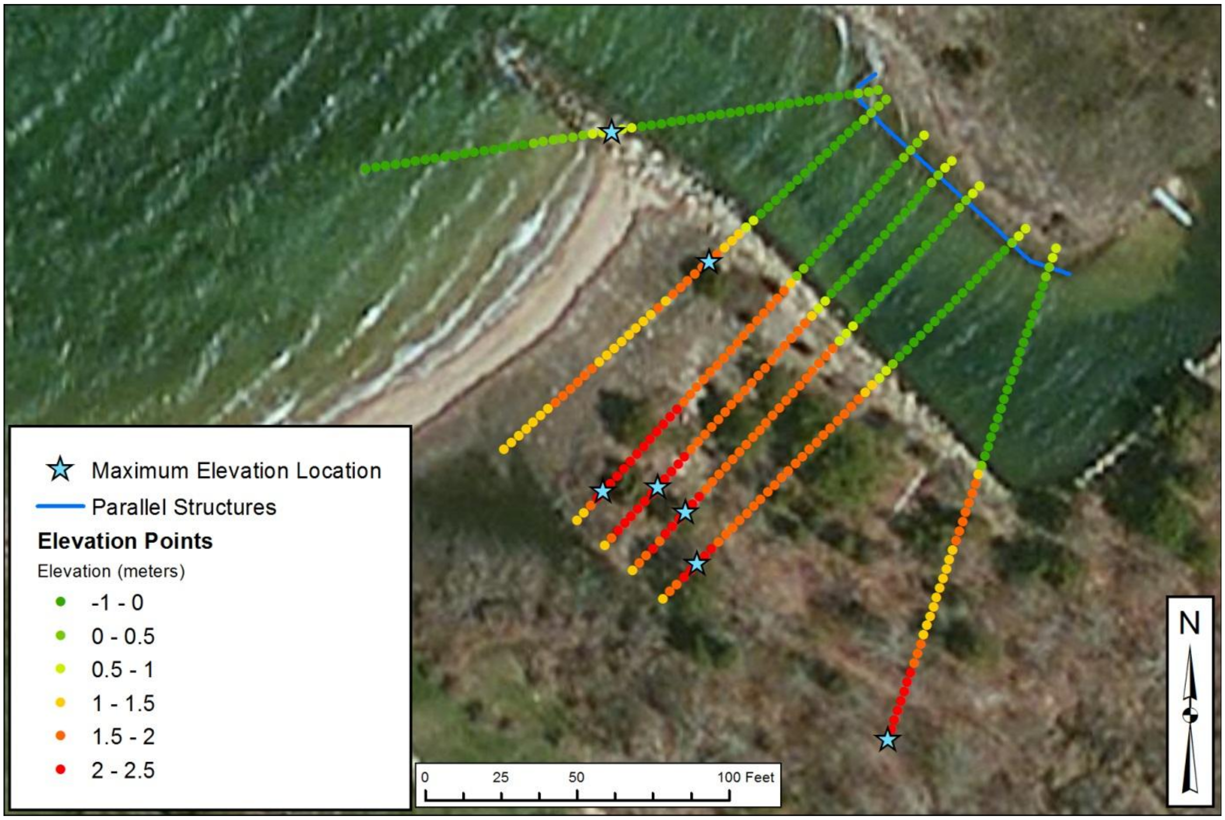

Figure 10. Invalid profiles due to maximum elevation locations (blue stars) encountered at a distance greater than 3 meters from the structure location.

4.3.5.2 Shore-Perpendicular Structures

For all shore-perpendicular structures (groins and jetties), elevations were extracted directly from the digitized line at 1 meter intervals between the seaward and landward edge of each structure. The maximum value was chosen to represent the structure elevation. In a majority of cases, this was the most landward point along the structure.

Of the 1,991 cross-shore structures, 34 were not assigned an elevation. These structures were located completely outside of the LiDAR data coverage. Another 223 structures were only partially overlapped by the LiDAR dataset (Figure 9 shows examples of each of these situations). In the case of partial coverage, an elevation was still generated based on the maximum elevation encountered.

Groins and jetties that are physically tied into a shore-parallel structure (seawall or revetment) at their landward edge were snapped to the shore-parallel structure during the digitization process to connect the two features. This may result in some anomalously high elevations for groins and jetties in the final database, particularly for locations where there are substantial height differences between the groin/jetty and the seawall or revetment to which it is connected. Figure 11 shows an example where the maximum elevation point occurs at the top of the seawall or revetment. This is particularly noticeable in the ~2.5 meter spike in the elevation profile that occurs at the intersection of the groin/jetty and revetment.

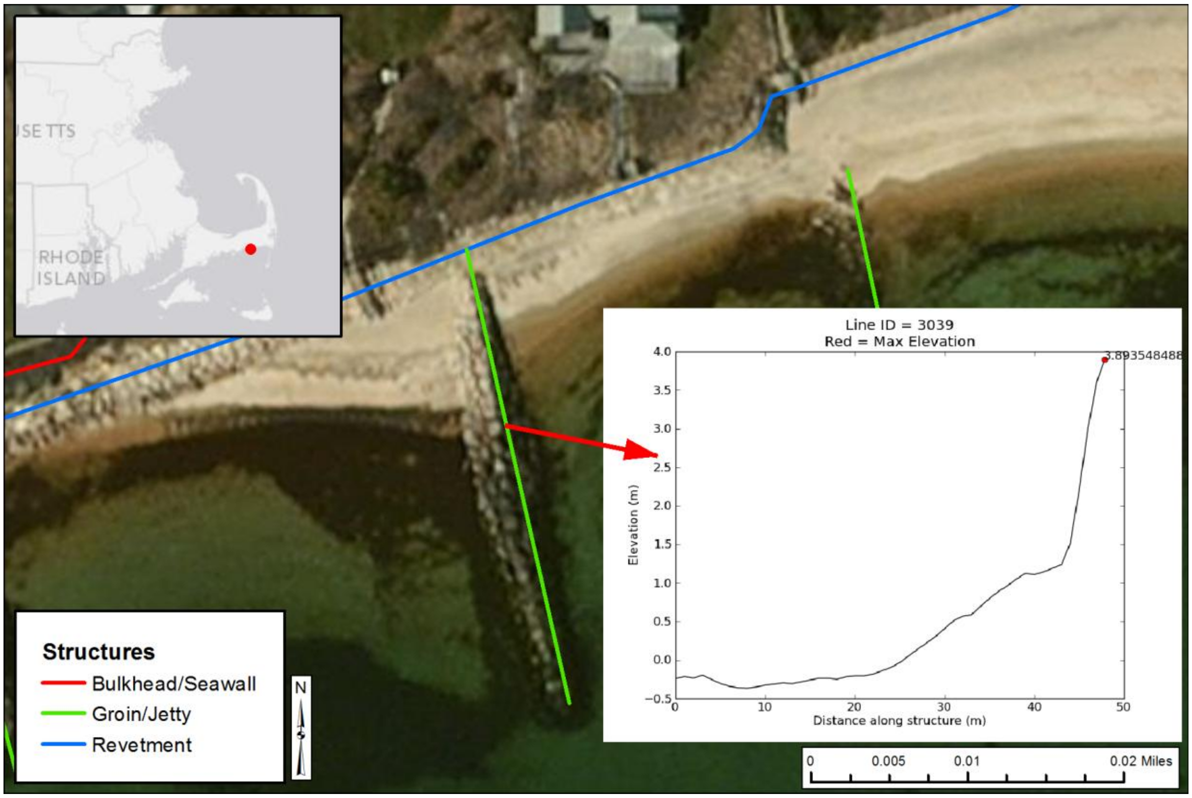

Figure 11. Example elevation profile for a groin tied into a perpendicular structure.

4.3.6 Structure Height

In addition to structure elevation, the above-ground height was estimated for coastal structures. Because height is measured relative to the true ground surface (as opposed to an orthometric datum), structure heights were determined from engineering plans and other descriptions that were included as part of the Chapter 91 license documents, as opposed to LiDAR data. The height of structures was determined by comparing the structure elevation with the ground surface elevation on the seaward side of the structure. Because of the relative scarcity of this information, only 5% of digitized structures were attributed with height information. The existing database schema contained two fields for recording structure heights, *PrimaryHeight* and *SecondaryHeight*.

Following the organization of previous studies, structure heights were typically entered in ranges of 5 feet, however, some structure plans listed multiple heights that spanned more than one 5-foot height range. For these cases, the complete range of heights was entered, where the minimum and maximum values were maintained in multiples of 5 feet (e.g., a structure with a height range of 3-7 feet would be assigned a height value 0-10 ft).

4.3.7 Ownership

For all structures the *PropertyOwnerDesc* and *StructureOwnerDesc* fields were set to “Private”. The individual owners of structures were not determined. The *PropertyOwner* and *StructureOwner* fields, which store a code for ownership, were all set to “1” (corresponding to private ownership).

4.3.8 Structure Coordinates

The structure location was saved as an attribute using latitude and longitude fields. The *PositionX* field stores the longitude and the *PositionY* field stores the latitude. Both coordinates are stored as decimal degrees. The coordinates were calculated using the ArcGIS mid-point function to calculate the mid-point of each structure, this ensures that the coordinates always fall on the line, regardless of its shape.

4.3.9 Remaining Attribute Fields

The remaining attribute fields in the structure feature class were not populated for this project, however, they were kept to maintain the field structure from previous phases. The fields listed in Table 4 were left empty (null).

Table 4. Fields not populated in the privately-owned structures database.

OwnerName	SecondaryPriority
Location	Repair
YearBuilt	EnterBy
BasedOn	EnterDate
BasedOnDesc	CrewBy
BasedOnComment	CrewDate
PrimaryCondition	Comments
SecondaryCondition	Details
PrimaryPriority	

4.4 Chapter 91 Licenses

4.4.1 Associating Licenses with Structures

The license shapefile provided by the Massachusetts Department of Environmental Protection (MassDEP) contains records for more than 5,600 Chapter 91 licenses that extend throughout the Commonwealth of Massachusetts. The location of each license is based on a geocoded address, which may not represent the exact location of the licensed structure. Figure 12 shows the locations (addresses) of all licenses present in the MassDEP shapefile.

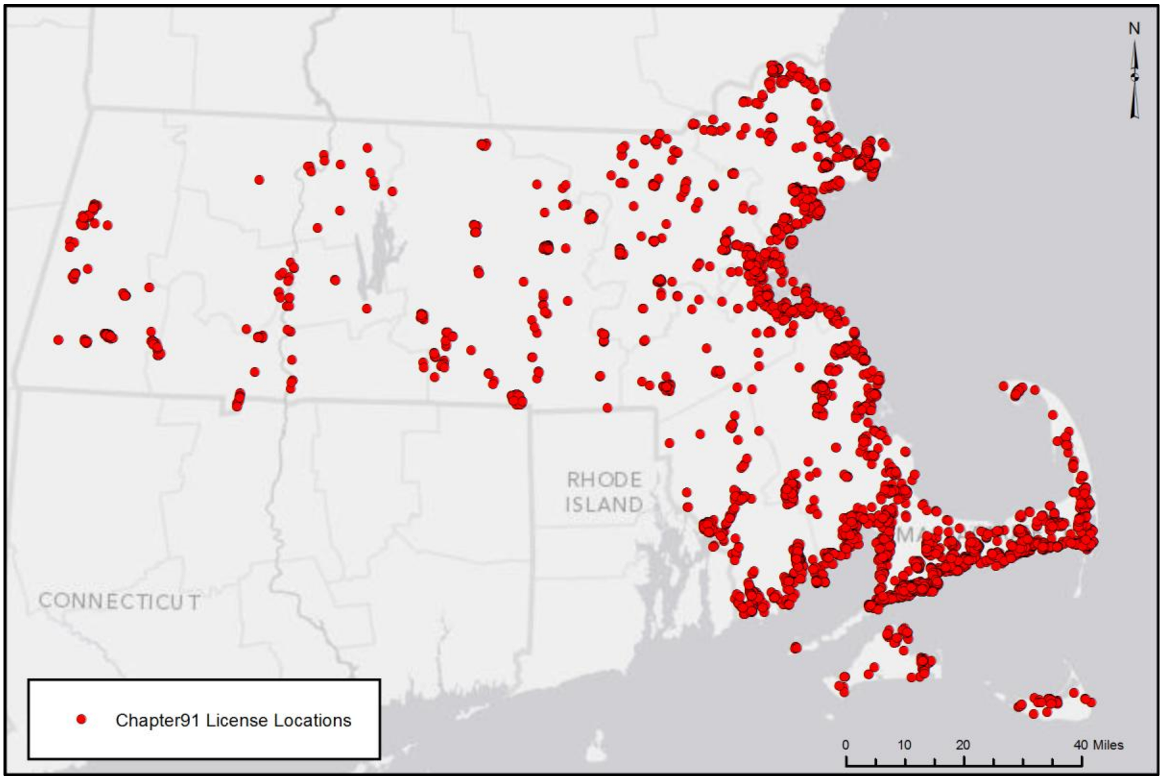

Figure 12. Chapter 91 license locations.

To identify licenses within the project area, the following steps were used to filter the data.

1. The shapefile was filtered based on the structure location. Licenses greater than 2 km from the project shoreline were removed, bringing the number of records to 3,118;
2. The shapefile was filtered based on the type of structures covered. Only licenses for relevant structure types were retained. Due to the large number of unclassified licenses, fields that were unfilled or unknown were also saved.

This filtering reduced the total number of valid records to 1,497. Paper copies of each license were obtained from the MassDEP archive and scanned to .PDF files. A total of 1,399 licenses were retrieved from the archive; the remaining 98 files were not located in the archive.

Each license was then manually linked to the corresponding digitized structure. By comparing license plans with tax parcel data, a parcel was identified for each license. Typically the license point and tax parcel were close to each other, although some were significantly apart. Several of the licenses covered structures that were outside of the project scope (structures inside bays and estuaries, and up rivers). These licenses were removed from further consideration.

Licenses that were found to correspond to private coastal protection structures within the project area were reviewed and the following information was recorded for each license:

- **Structure IDs –** a single license frequently included multiple digitized structures. Each structure present in the plans was recorded. Even if a license only applied to a specific feature, such as a dock, other relevant structures clearly shown and labeled in the plans were included.
- **Elevation(s) –** the elevation of each structure (in feet) was recorded when present. If multiple elevations were listed for a single structure, the full range was recorded. In some instances the elevation was estimated using a vertical scale bar or other scaled features. In these cases the elevation was flagged as 'estimated'.
- **Datum –** the vertical datum was recorded (when listed in the plans).
- **Height(s) –** the height of each structure (above the ground surface) was recorded when listed or when it could be interpreted from the plans. The exact height was typically not listed. In most cases, heights were estimated by comparing the elevation at the top and the base of each structure. In cases where the structure base elevation was not provided, the base elevation was estimated and the height range was recorded as estimated. In other cases the height was estimated using the scale bar included with the plans.
- **Notes –** Any interesting features in the plans were also recorded. Frequently these notes include any observed discrepancies between the structure type or material listed in the plans, and what was interpreted during the structure digitization.

The following figures show examples of digitized structures and their corresponding Chapter 91 license plans. Figure 13 shows a digitized concrete seawall (primary type) fronted by a stone revetment (secondary type). Figure 14 shows engineering plans from the corresponding Chapter 91 license (#8013), which include the location of the seawall and revetment, its materials, and the elevation and height of the structures.

Figure 13. Map of structure (digitized concrete seawall fronted by a stone revetment) with matching Chapter 91 license (Figure 14).

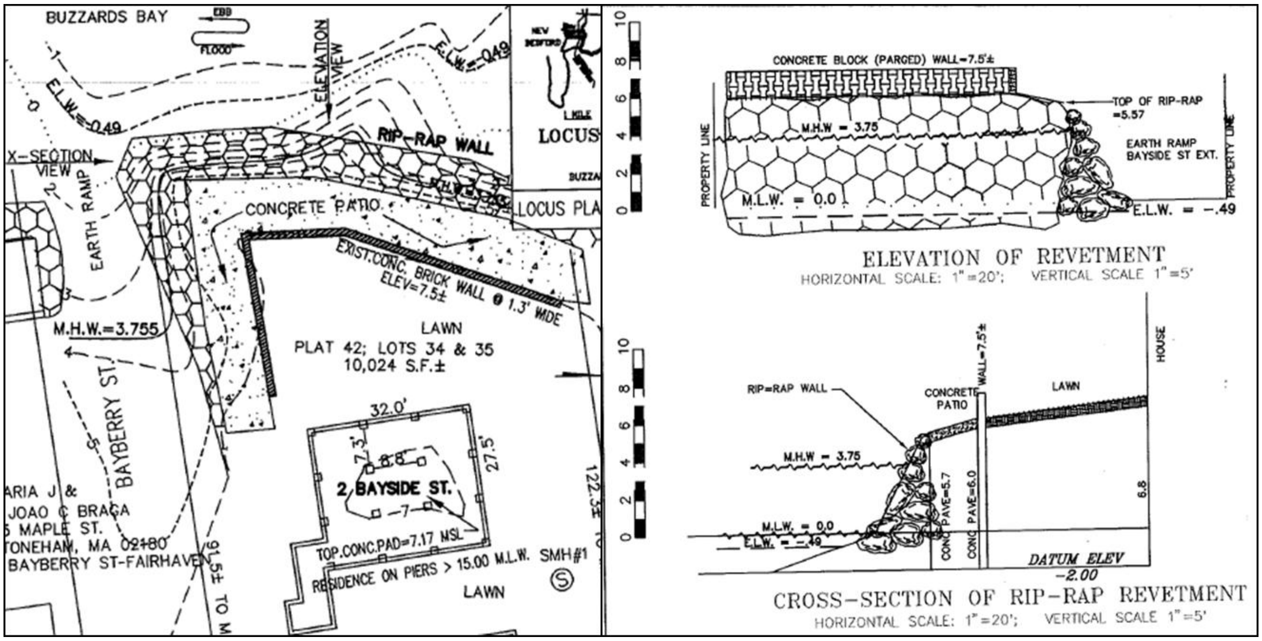

Figure 14. Engineering plans from Chapter 91 license corresponding to the structures in Figure 13.

Figure 15 shows several digitized structures, all of which are all covered by license #8097. Drawings included with the license (Figure 16) show the location of the structures, their type and material, and cross-sections and profiles that were used to determine height and elevation.

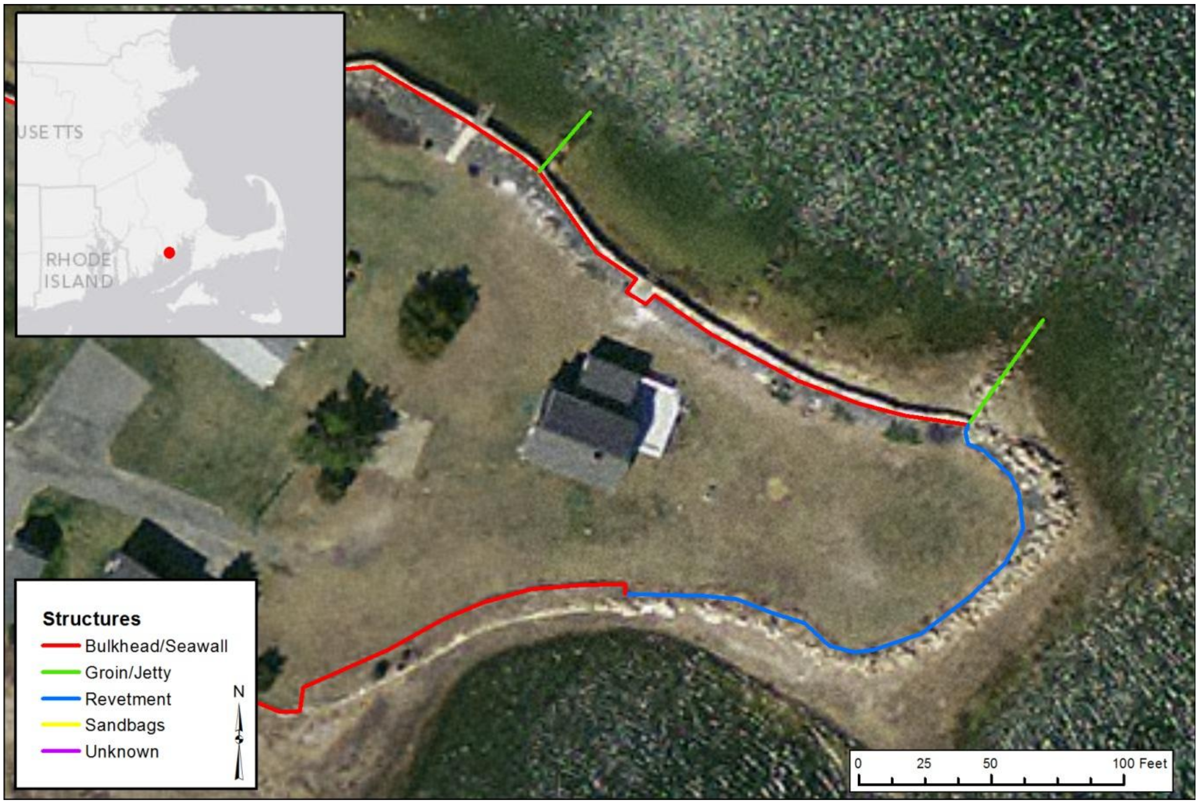

Figure 15. Map of structures (bulkhead/seawall, groins, revetment) with matching Chapter 91 license (Figure 16).

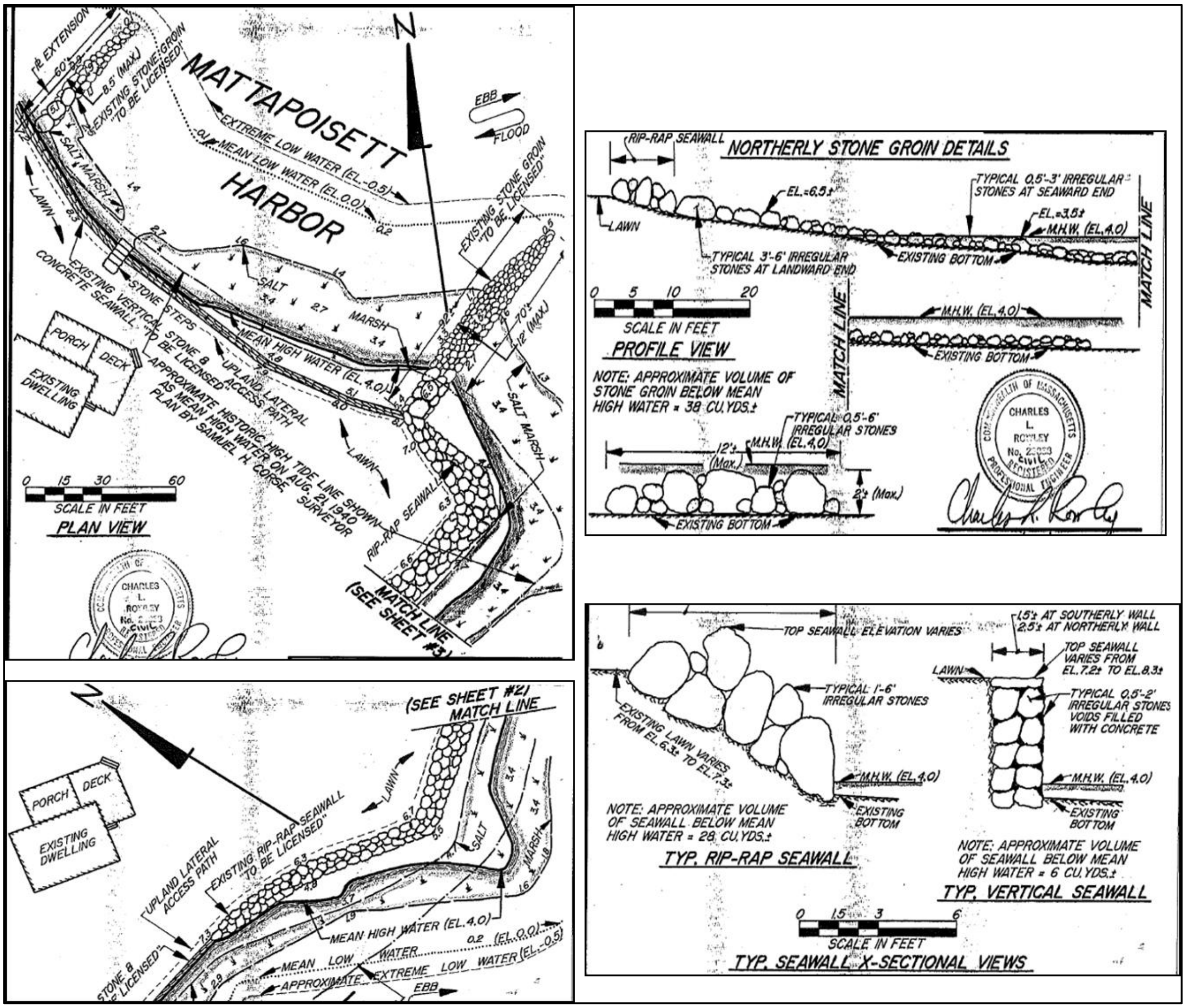

Figure 16. Engineering plans from Chapter 91 license corresponding to the structures in Figure 15.

4.4.2 Chapter 91 Table and Attributes Descriptions

All information from Chapter 91 licenses and plans was recorded in an ArcGIS FDGB table ("Chapter 91 License Table") located in the same database as the structures feature class. The table includes the following attributes:

- **LIC_NO –** License number.
- **StructureID –** Structure ID of the corresponding digitized structure.
- **Elev_FT_Recorded –** Structure elevation in feet, as it was recorded from the license. If multiple elevations were listed for a single structure, the range was recorded.

- **Elev_FT_Average –** Structure elevation in feet, represented as a single value. If a range of elevations was recorded, this value represents the mid-point.
- **Elev_Est –** Indicates that the elevation was estimated when the value is "Y".
- **Height_FT_Recorded –** Structure height (in feet) as recorded from the license. This can be a range or a single height value. Ranges were used if the exact value was not given, or when multiple values were listed.
- **Height_FT_Range –** Structure height (in feet) represented as a range where the minimum and maximum of the range are 5 foot intervals.
- **Height_Est –** Indicates that the height was estimated when the value is "Y".
- **Datum –** vertical datum used to measure the elevation (MLW = mean low water, MHW = mean high water, MSL = mean sea level).
- **ASA_Notes –** Notes recorded by RPS ASA personnel about the structure or plans.
- **Elev_NAVD88_M –** Elevation in meters using the NAVD88 vertical datum. This is the "Elev_FT_Average" value converted to NAVD88 using NOAA's VDatum tool (NOAA, 2012).

In addition, the following fields were appended directly from the MassDEP Chapter 91 point shapefile:

- FILE_NO
- NAME
- ADDRESS
- TOWN
- CH91_TOWN
- STATE
- ZIP
- REGION
- APPLICANT
- PERMITTYPE
- STRUCTYPE
- WATERBODY
- LIC_ISSUED
- LIC_EXPIRE

Because one license may correspond to multiple structures (and vice versa), this table is linked to the structures layer using a relationship class with one-to-many cardinality. A cardinality of one-to-many means that an origin record can relate to many destination records. For example, a given structure may be represented in multiple licenses. While licenses often contain multiple structures, a separate record was created in the Chapter 91 table for each structure in a given license. This allowed individual properties such as Structure_ID, Height, and Elevation to be recorded for each structure.

5 Final Database Structure

The final database is provided as an ArcGIS File Geodatabase (FGDB). It includes:

- a polyline feature class of the coastal structures;
- a table of the Chapter 91 licenses and attributes;
- the Chapter 91 licenses (included as attachments);
- a relationship class linking the structures to corresponding Chapter 91 licenses, and
- a relationship class linking the Chapter 91 license attachments to the Chapter 91 license table.

Figure 17 illustrates the database design. The Structures feature class uses a datum of North American Datum (NAD83) registered to the Massachusetts State Plane coordinate system, for the Mainland zone (FIPS 2001). The horizontal units are in meters. All elevations are referenced to meters NAVD88.

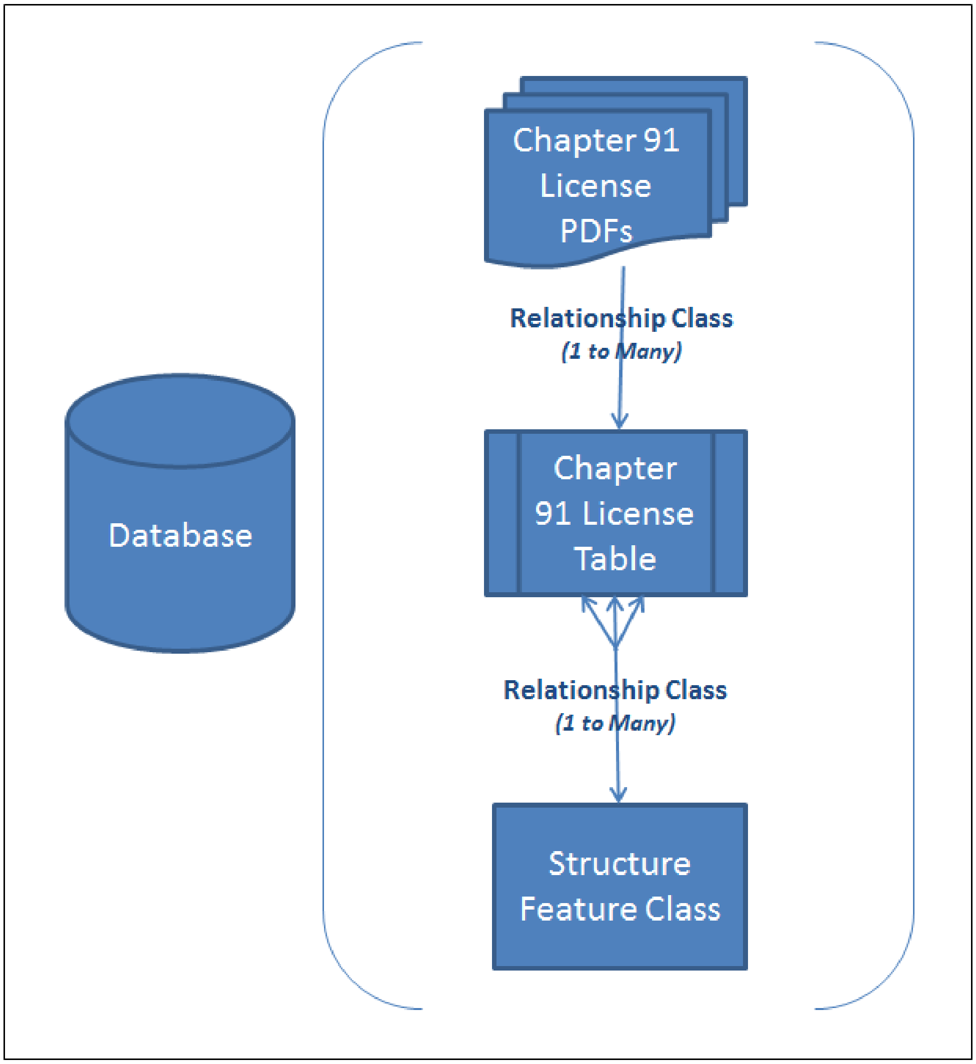

Figure 17. Privately-owned coastal structures database schema.

The simplest method to view the database is to load the structure feature class into ArcMap and to use the relationship classes to show associated data. When interrogating a structure that has a corresponding Chapter 91 license, the license record will appear in the "Identify" window tree-view. By expanding the tree for each structure, the list of associated licenses can be viewed. By selecting one of the licenses, all the attributes for that license record will be visible. The "Attachments" drop-down menu at the top of the Identify window will list the scanned document (PDF) for the selected license. The PDF can be opened by selecting the record from the drop-down list. An example of the "Identify" dialog tree-view and "Attachments" drop-down menu is shown Figure 18.

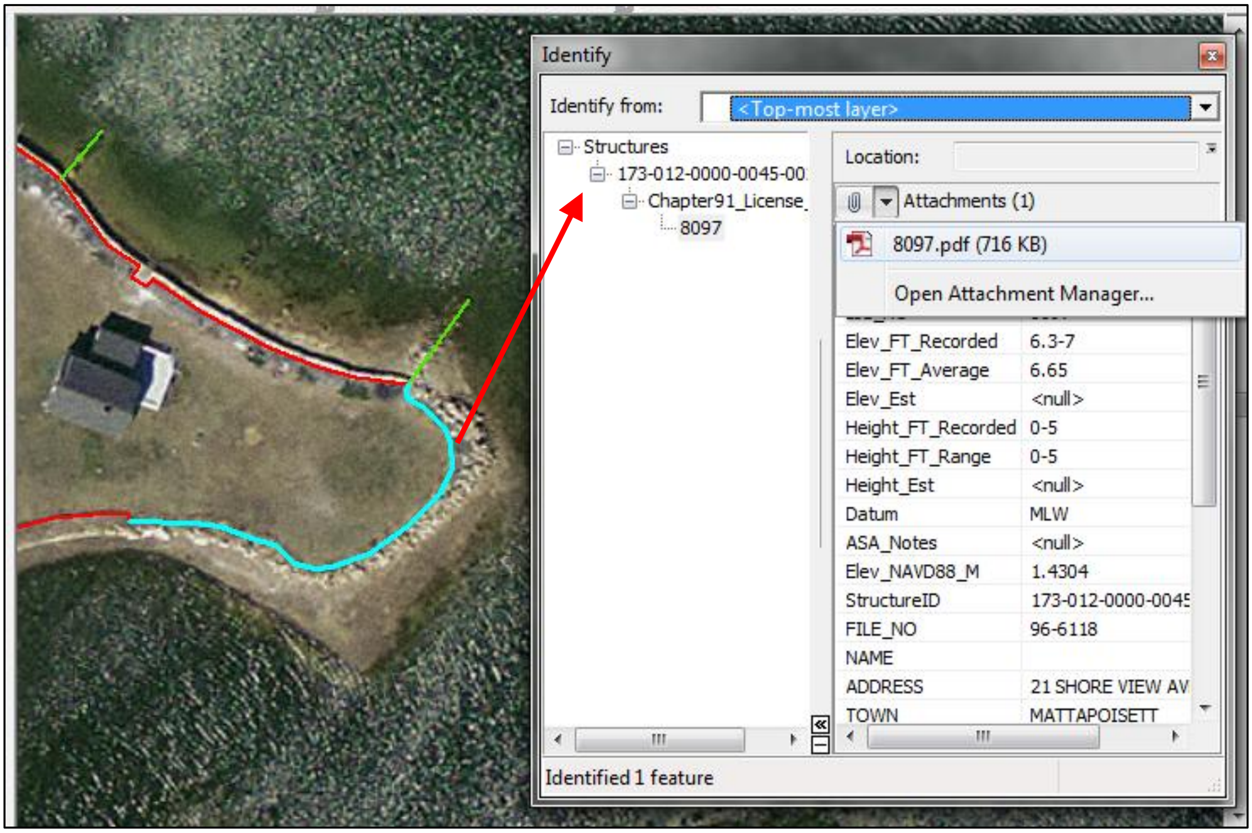

Figure 18. Using the "Identify" dialog to view structure and corresponding license attributes in ArcMap.

The license data can also be accessed directly by adding the standalone Chapter 91 license table to an ArcMap project or viewing the table directly using ArcCatalog. To open an attached license PDF, right click on a selected license record and select "Open Attachment Manager". Double-clicking the desired record will open the PDF document.

6 Results & Discussion

6.1 Statewide Summary

A total of 6,611 privately-owned coastal structures were mapped along Massachusetts' ocean-facing shoreline. The complete inventory of coastal structures includes:

- 2,967 bulkheads/seawalls;
- 1,660 revetments;
- 1,969 groins/jetties;
- 15 sandbag structures.

Figure 19 shows the full extent of mapped structures and their general distribution along the Massachusetts coastline. The frequency, elevation, and the type of structures are indicative of the physical processes that shape the coast, the underlying geomorphology, and the history of coastal development in each region. For example, cross-shore structures (groins) are most common in the sandy, micro-tidal environments south of Cape Cod, whereas the rocky headlands and isolated barriers of the North Shore are mainly protected by seawalls. Bulkheads are more common inside the highly developed Boston Harbor coastline and revetments are ubiquitous features throughout the Commonwealth, although they are less frequent for coastal reaches north of Boston. Coastal protection is mostly absent along the south-facing shorelines of Martha's Vineyard and Nantucket, the outer Cape, and the barriers north of Rockport. The highest coastal structures are found in the North Shore, Boston, and South Shore regions, where tidal range is also highest (Ramsey et. al, 2005). As the tide range decreases along Cape Cod and the South Coastal region, average structure elevations also decrease. The smallest tidal ranges, found in Buzzards Bay, correspond to the lowest structures.

The Commonwealth's ocean-facing shoreline, used to define the scope of work, extends for approximately 1,115 miles (1,794 km) between the border with New Hampshire in Salisbury and the Rhode Island border in Westport. Nearly 27% of this coastline is armored by some form of coastal protection[1]. This includes approximately 196 miles (316 km) of privately-owned coastal structures, and 103 miles (166 km) of public structures that are all oriented in an alongshore direction. Additionally, there are 67 miles (109 km) of structures that extend in the cross-shore direction (33 miles [55 km] of private groins/jetties and 34 miles [54 km] of public groins/jetties).[2] Table 5 provides the length of the ocean-facing shoreline within each MACZM region along with the breakdown of shore-parallel public and private structure lengths. Also shown is the percentage of the shoreline that is protected (percent armored by shore-parallel structures). Statewide statistics are included as the sum of all regions. Table 6 provides the total length of private and public shore-perpendicular structures by region and statewide.

[1] When referring to percentage of shoreline protected both statewide and regionally only the length of shore-parallel primary structures is considered.

[2] Summary statistics for public structures mapped during Phase 1 and Phase 2 exclude features outside scope of the current (private structures) project, and exclude dunes/beaches that were mapped during previous phases. The total length of public groins/jetties includes connecting (alongshore) pieces in some areas. Federal structures are included as public structures.

Table 5. Coastal structures length by MACZM region and statewide.

MACZM Region	Study Shoreline Length: Feet (Meters)	Private Structure Length: Feet (Meters)	Public Structures Length: Feet (Meters)	Percent Protected
North Shore	843,136 (256,989)	262,371 (79,971)	136,765 (41,686)	47.3%
Boston Harbor	303,350 (92,461)	64,088 (19,534)	110,616 (33,716)	57.6%
South Shore	682,977 (208,172)	150,564 (45,892)	157,294 (47,943)	45.1%
Cape Cod & Islands	3,248,303 (990,086)	344,856 (105,113)	66,270 (20,199)	12.7%
South Coastal	815,055 (248,429)	214623 (65,417)	72,936 (22,231)	35.3%
Total	**5,892,821 (1,796,137)**	**1,036,502 (315,927)**	**543,882 (165,775)**	**26.8%**

Table 6. Length of shore-perpendicular structures.

MACZM Region	Private Structure Length: Feet (Meters)	Public Structures Length: Feet (Meters)	Total Structure Length: Feet (Meters)
North Shore	2,567 (782)	5,592 (1,705)	8,159 (2,487)
Boston Harbor	5,880 (1,792)	24,934 (7,600)	30,814 (9,392)
South Shore	8,906 (2,715)	30,639 (9,339)	39,545 (12,054)
Cape Cod & Islands	102,940 (31,376)	105,508 (32,159)	208,448 (63,535)
South Coastal	58,616 (17,866)	10,630 (3,240)	69,246 (21,106)
Total	**178,909 (54,531)**	**177,304 (54,043)**	**356,213 (108,574)**

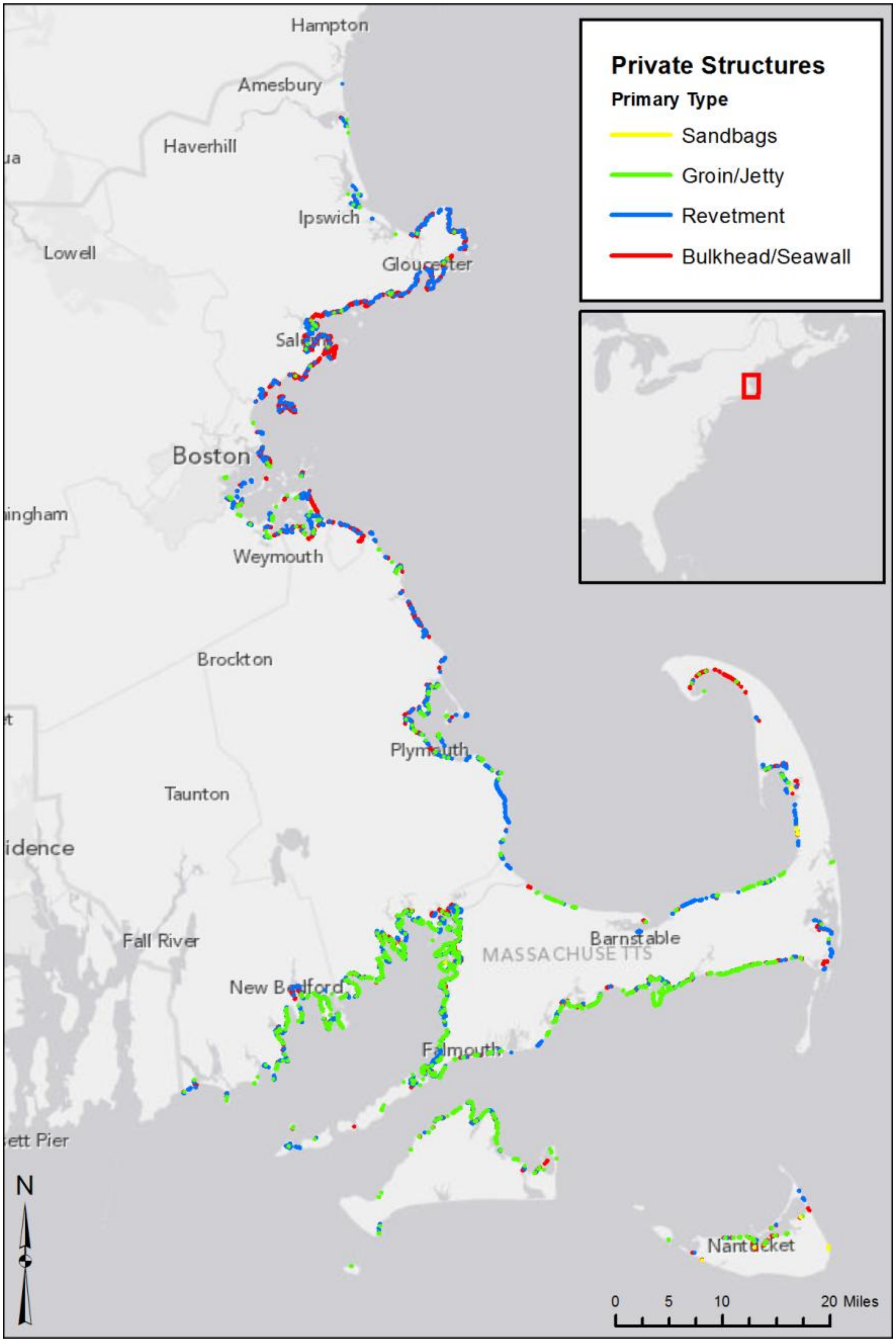

Figure 19. Private coastal structures (by type) along the ocean-facing shoreline of Massachusetts.

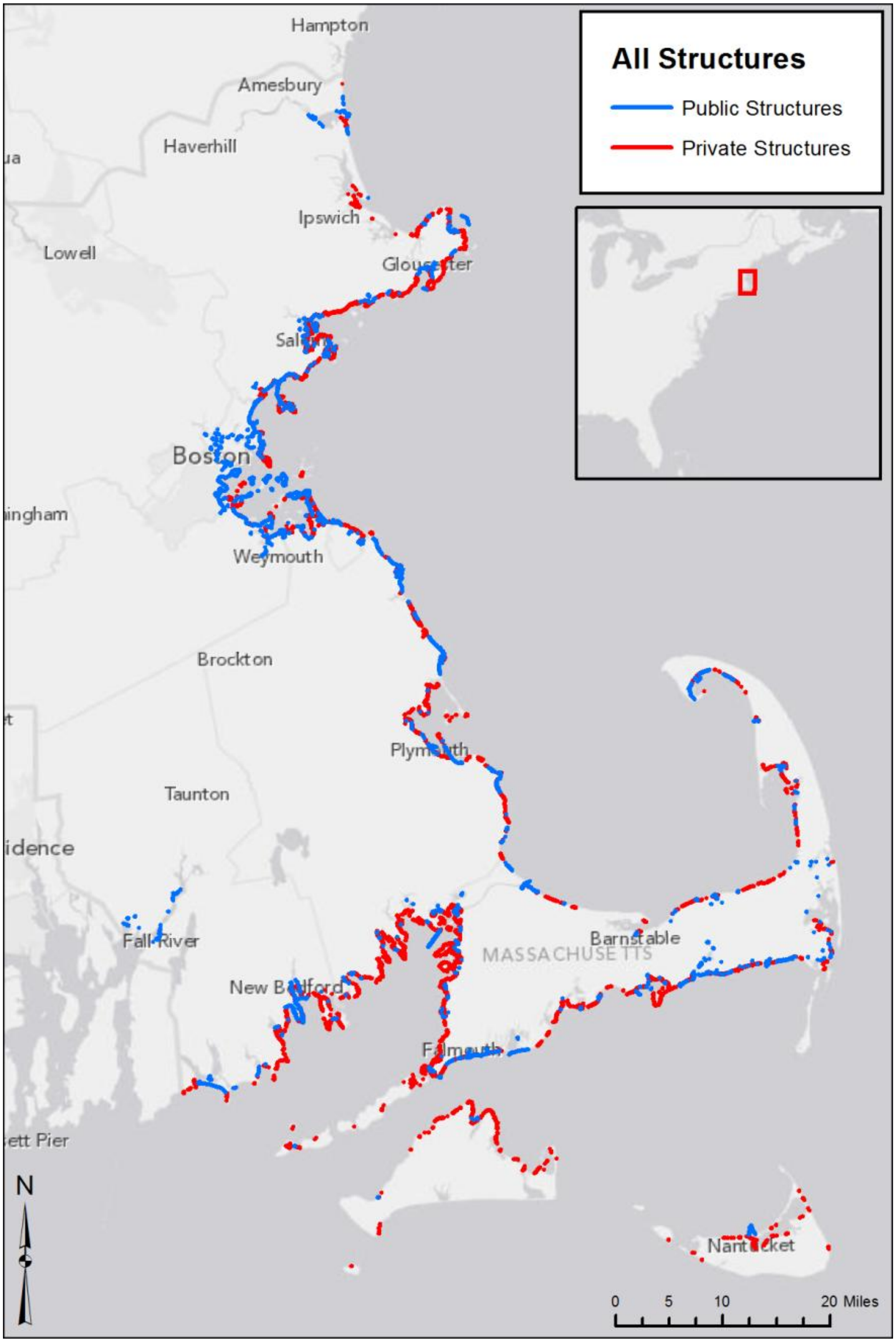

Figure 20. All coastal structures along the ocean-facing shoreline of Massachusetts.

For shore-parallel structures identified by this work, the mean (weighted by length)[3] elevation was approximately 12 feet (3.6 meters) above NAVD88; the mean elevation of shore-perpendicular structures (groins/jetties) was approximately 6 feet (1.7 meters) NAVD88. Figure 21 shows the distribution of elevations (in 2 foot bins) for all privately-owned structures, statewide. Groins and jetties (most of which extend only short distances onshore) are primarily in the 0-10 foot elevation range, while seawalls and other shore-parallel structures exhibit a much wider range of elevations. Elevations for 35 structures (34 groins/jetties, 1 shore-parallel structures) were not determined as these features are located entirely outside of the LiDAR coverage.

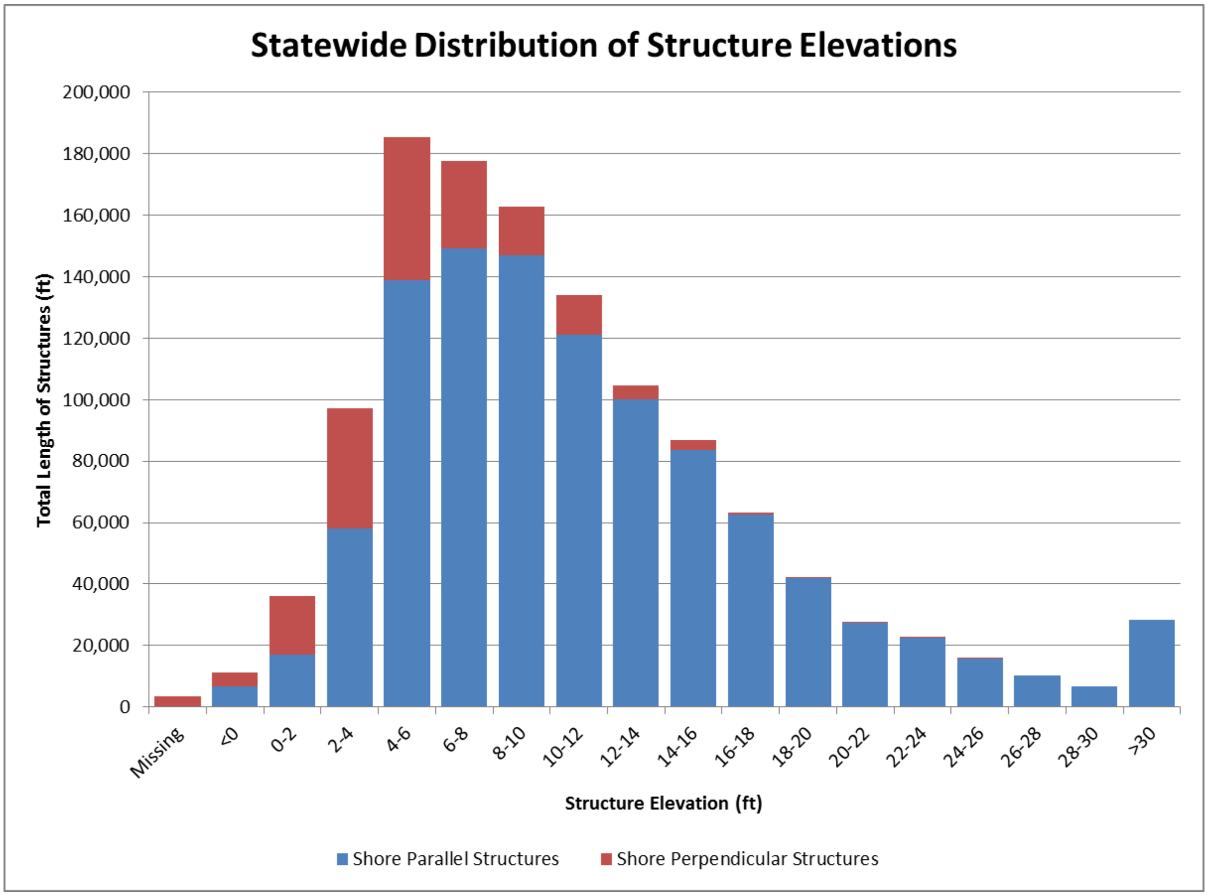

Figure 21. Distribution of elevations (2 foot bins) for Massachusetts' privately-owned structures, statewide.

[3] Summary statistics for structure elevations (here and in subsequent discussions) have been normalized by structure length. Length-weighted averages were presumed to be a better reporting metric given the variability in individual structure lengths. Mean elevation is calculated by multiplying each structure's elevation by the percentage of protected shoreline that structure represents, and summing the total. Similarly, percentages refer to the percent of total armored shoreline as opposed to the percent of individual structures.

6.2 North Shore

The North Shore region extends between the Massachusetts/New Hampshire border (at Salisbury) and Revere and includes approximately 160 miles (257 km) of ocean-facing shoreline. Just under 50 miles (80 km) of the coastline in this region is protected by privately-owned structures, the majority of which are bulkheads and seawalls (Table 7). Another 26 miles (42 km) are protected by public structures. In total, approximately 47% of the North Shore region is fronted by some form of coastal protection.

As shown in Figure 22, most of the privately-owned structures in the North Shore region were mapped in the communities south of Essex. North of Cape Ann the coastline is characterized by wide, sandy beaches and barriers and the relatively few coastal engineering structures are organized around inlets, harbors, and back beach environments. This region also contains the Parker River National Wildlife Refuge, which is predominantly undeveloped coastline. By contrast, the rocky headlands and pocket beaches that characterize the coastline south of Essex contain the vast majority of structures in the region (primarily bulkheads and seawalls). There are relatively few groins/jetties present in the North Shore region.

Figure 23 shows the distribution of structure elevations (in terms of total length) for the North Shore region. The data indicate that most of the coastal protection in this region occurs at an elevation above the statewide averages. For the North Shore region:

- The mean elevation of shore-parallel structures is 15.7 feet (4.8 meters) above NAVD88;
- Shore-perpendicular structures average 5.4 feet (1.6 meters) above NAVD88;
- 58% of shore-parallel structures (996 structures, 153,290 linear feet) are above the statewide average of 12 feet (3.6 meters) NAVD88;
- 52% of shore-perpendicular structures (14 structures, 1,334 linear feet) are above the statewide average of 6 feet (1.7 meters) NAVD88.

Table 7. Private coastal structure types and materials for the MACZM North Shore region.

Primary Structure	Primary Material	Total Structures	Total Length: Feet (Meters)
Bulkhead/Seawall	Stone	920	149,367 (45,527)
	Concrete	281	45,016 (13,721)
	Wood	17	2,017 (615)
	Steel	15	3,078 (938)
	Total	**1,233**	**199,477 (60,801)**
Revetment	Stone	289	62,130 (18,937)
	Structural Debris	3	764 (233)
	Total	**292**	**62,894 (19,170)**
Total Shore-Parallel Structures		**1,525**	**262,371 (79,971)**
Groin/Jetty	Stone	26	2,254 (687)
	Concrete	4	260 (79)
	Wood	1	53 (16)
Total Shore-Perpendicular Structures		**31**	**2,567 (782)**

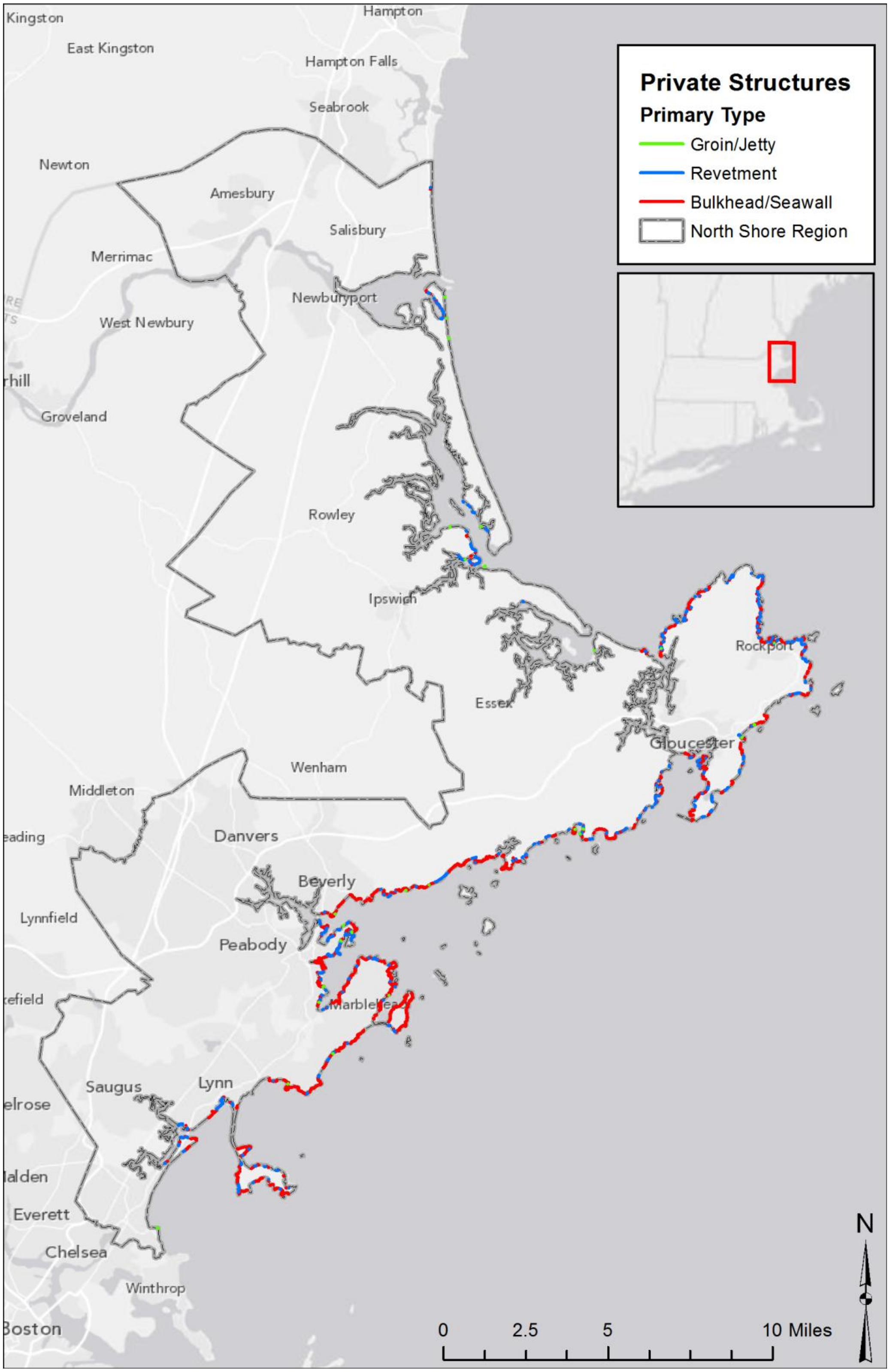

Figure 22. Private coastal structures (by type) for the MACZM North Shore region.

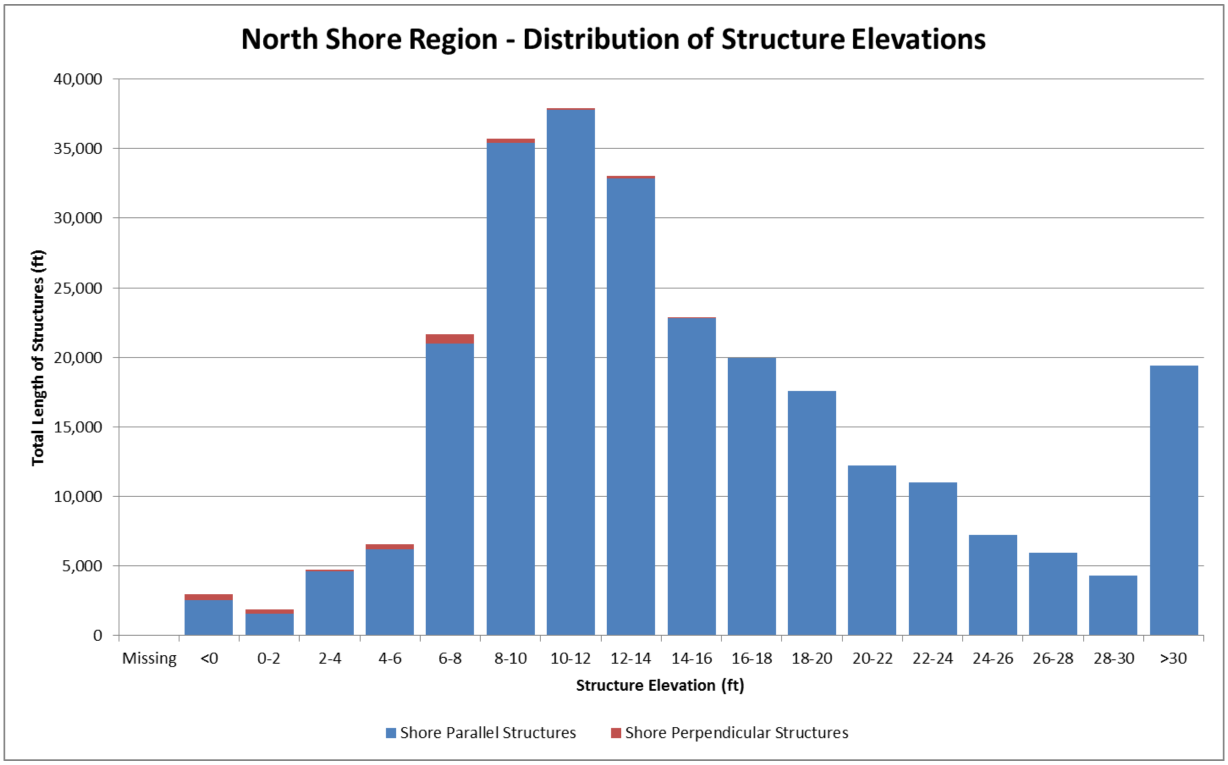

Figure 23. Distribution of elevations (2 foot bins) for privately-owned structures in the North Shore region.

6.3 Boston Harbor

The Boston Harbor region includes the densely-populated communities between Winthrop and Weymouth that surround the city of Boston. This region includes approximately 57 miles (92 km) of ocean-facing coast, of which, about 12 miles (19 km) are protected with privately-owned coastal structures (Table 8). Another 21 miles (34 km) of the coast are protected with public structures. The Boston Harbor region shoreline has the highest percentage of coastline fronted by some form of coastal protection (58%).

Figure 24 shows the location of private structures in the Boston Harbor region, classified by primary structure type. Given its smaller extent and the amount of public infrastructure that surrounds Boston Harbor, far fewer private structures were digitized here in comparison to other MACZM regions. Additionally, many of the interior portions of Boston Harbor fell outside of the study area. As with the North Shore, a high percentage of structures were identified as bulkhead/seawalls and revetments. There are relatively few groins/jetties present in this region.

Figure 25 shows the distribution of structure elevations in terms of total length for the Boston Harbor region. The data indicate that most of the coastal protection in this region occurs at an elevation above the statewide averages. For Boston Harbor:

- The mean elevation of shore-parallel structures is 15.1 feet (4.6 meters) above NAVD88;
- Shore-perpendicular structures average 7.4 feet (2.3 meters) above NAVD88;
- 55% of shore-parallel structures (99 structures, 35,307 linear feet) are above the statewide average of 12 feet (3.6 meters) NAVD88;
- 69% of shore-perpendicular structures (17 structures, 4,086 linear feet) are above the statewide average of 6 feet (1.7 meters) NAVD88.

Table 8. Private coastal structure types and materials for the MACZM Boston Harbor region.

Primary Structure	Primary Material	Total Structures	Total Length: Feet (Meters)
Bulkhead/Seawall	Concrete	111	22,571 (6,880)
	Stone	38	13,896 (4,235)
	Wood	9	1,584 (483)
	Steel	3	832 (253)
	Total	**161**	**38,882 (11,851)**
Revetment	Stone	60	25,206 (7,683)
Total Shore-Parallel Structures		**221**	**64,088 (19,534)**
Groin/Jetty	Stone	25	4,466 (1,361)
	Concrete	4	351 (107)
	Wood	4	1,063 (324)
Total Shore-Perpendicular Structures		**33**	**5,880 (1,792)**

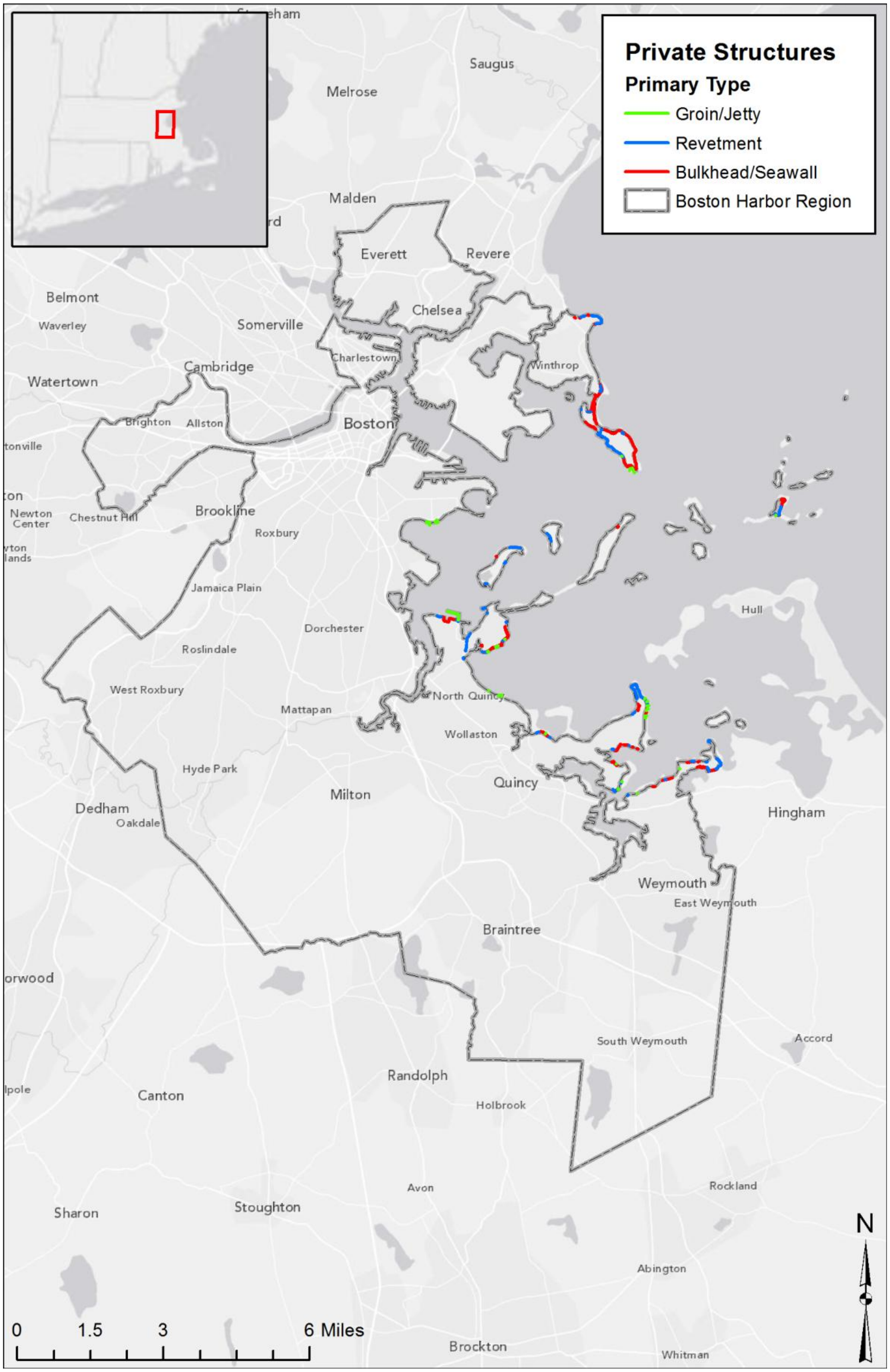

Figure 24. Private coastal structures (by type) for the MACZM Boston Harbor region.

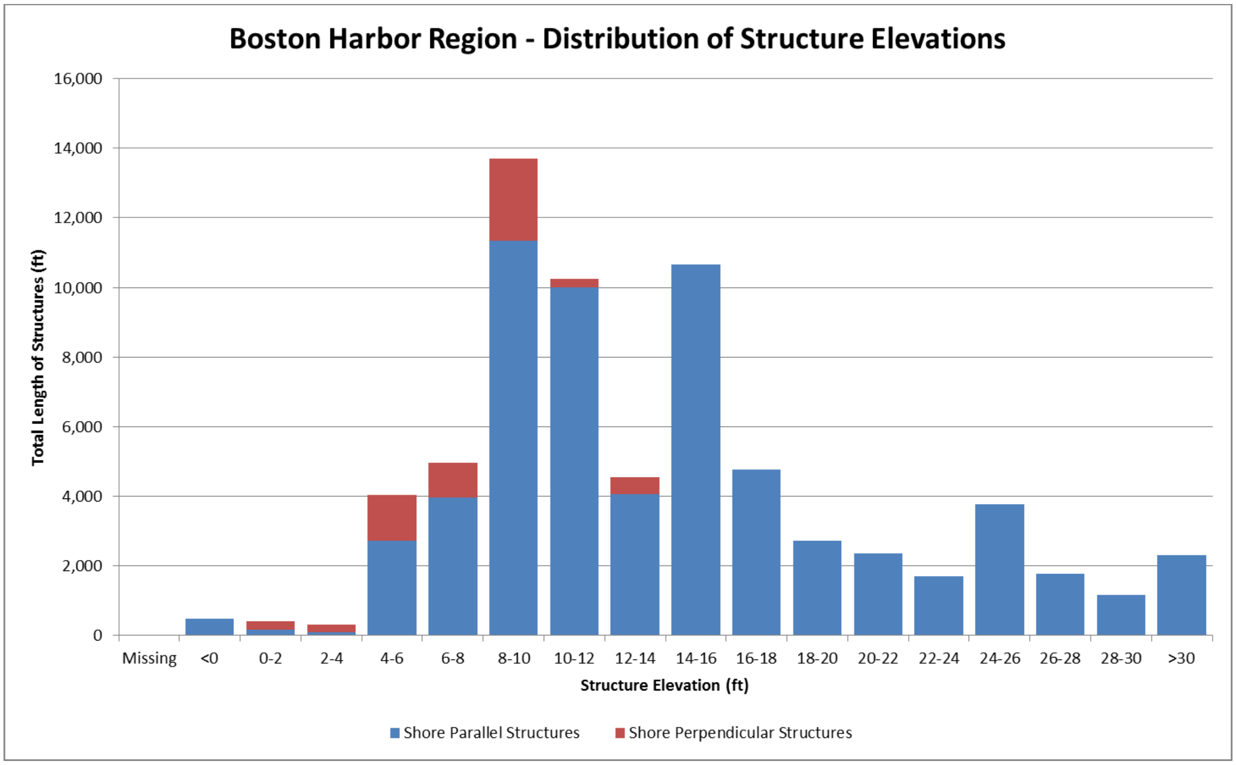

Figure 25. Distribution of elevations (2 foot bins) for privately-owned structures in the Boston Harbor region.

6.4 South Shore

The South Shore region extends from Hingham to Plymouth, and includes nearly 130 miles (209 km) of ocean-facing shoreline. Approximately 29 miles (46 km) of the coastline in this region is protected by privately-owned structures (Table 9). Another 30 miles (48 km) of the coast are protected by public structures. In total, 45% of the South Shore region is fronted by some form of coastal protection.

Most of the South Shore coastline (outside and to the south of Boston Harbor) is characterized by long, relatively narrow, headland beaches and headland-separated barrier spits. As shown in Figure 26, the most common structure type in this region is revetments, many of which consist of stone blocks placed at the base of eroding bluffs along these beaches. Bulkheads and seawalls are also quite common in the South Shore region. Shore-normal features (groins) occur more frequently than in the MACZM regions to the north.

Figure 27 shows the distribution of private structure elevations in terms of total length for the South Shore region. The data indicate that most of the coastal protection in this region occurs at elevations close to the statewide averages. For the South Shore region:

- The mean elevation of shore-parallel structures is 14.0 feet (4.3 meters) above NAVD88;
- Shore-perpendicular structures average 7.9 feet (2.4 meters) above NAVD88;
- 48% of shore-parallel structures (362 structures, 72,163 linear feet) are above the statewide average of 12 feet (3.6 meters) NAVD88;
- 69% of shore-perpendicular structures (56 structures, 6,132 linear feet) are above the statewide average of 6 feet (1.7 meters) NAVD88.

Table 9. Private coastal structure types and materials for the MACZM South Shore region.

Primary Structure	Primary Material	Total Structures	Total Length: Feet (Meters)
Bulkhead/Seawall	Concrete	256	40,749 (12,420)
	Stone	129	22,951 (6,995)
	Wood	26	4,061 (1,238)
	Steel	2	673 (205)
	Total	**413**	**68,434 (20,859)**
Revetment	Stone	322	81,593 (24,870)
	Concrete	2	196 (60)
	Structural Debris	2	272 (83)
	Total	**326**	**82,061 (25,012)**
Total Shore-Parallel Structures		**739**	**150,495 (45,871)**
Groin/Jetty	Stone	81	7,872 (2,399)
	Wood	16	883 (269)
	Concrete	2	196 (60)
Total Shore-Perpendicular Structures		**99**	**8,950 (2,728)**

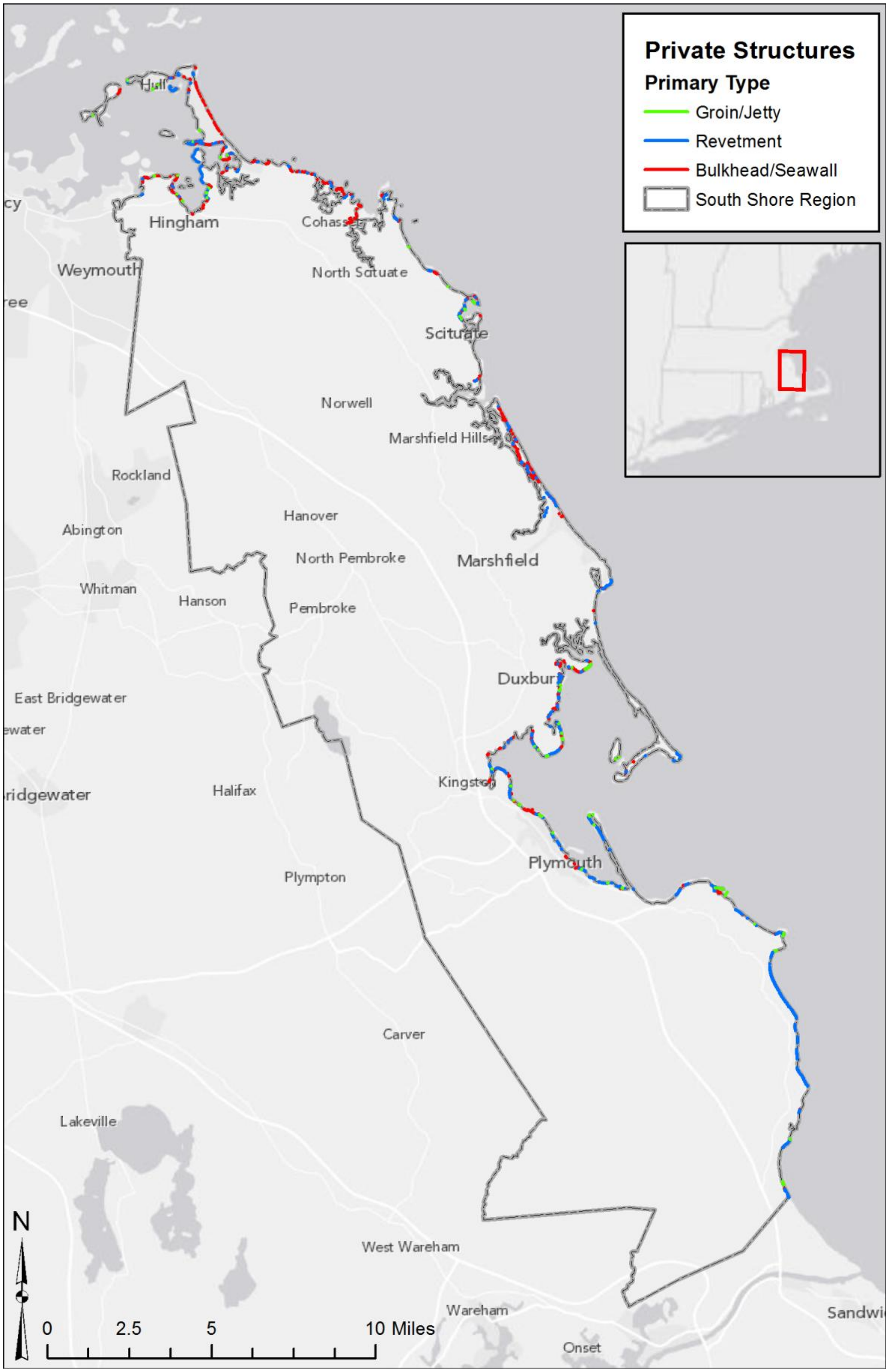

Figure 26. Private coastal structures (by type) for the MACZM South Shore region.

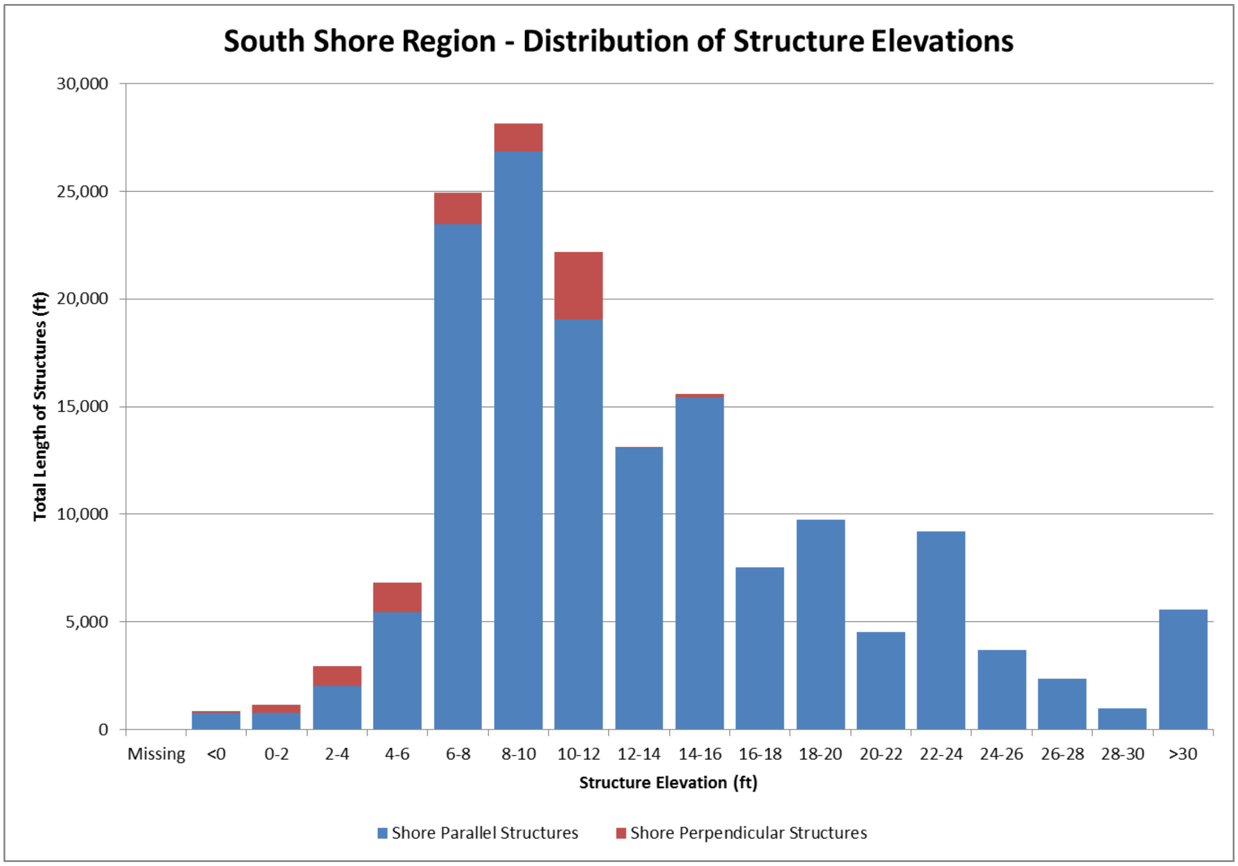

Figure 27. Distribution of elevations (2 foot bins) for privately-owned structures in the South Shore region.

6.5 Cape Cod and Islands

The Cape Cod and Islands region includes the 15 towns of Barnstable County, extending from Bourne to Provincetown, as well as Martha's Vineyard, Nantucket, and the Elizabeth Islands. This region includes approximately 615 miles (990 km) of ocean-facing shoreline, of which, about 65 miles (105 km) are fronted by privately-owned coastal structures (Table 10). Another 13 miles (20 km) are protected with public structures. The Cape Cod and Islands region has the lowest percentage of coastline fronted by some form of coastal protection, approximately 13%.

Figure 28 shows the locations of structures in the Cape Cod and Islands region, classified by primary structure type. The coastline of this region is geomorphically diverse, which is reflected in the type and occurrence of coastal structures within each community. For example, revetments are common along many of the elongated sandy beaches inside of Cape Cod Bay, while a combination of revetments and groins/jetties is widespread along the barrier spits of the south-facing coast. A substantial portion of this coastline also lies within the Cape Cod National

Seashore, which has almost no privately-owned coastal structures. The undeveloped, south-facing coastlines of Martha's Vineyard and Nantucket are equally devoid of coastal protection.

Figure 29 shows the distribution of private structure elevations in terms of total length for the Cape Cod and Islands region. The data indicate that most of the coastal protection in this region occurs at an elevation below the statewide averages. For the Cape Cod and Islands region:

- The mean elevation of shore-parallel structures is 10 feet (3.0 meters) above NAVD88;
- Shore-perpendicular structures average 5.9 feet (1.8 meters) above NAVD88;
- 36% of shore-parallel structures (373 structures, 122,500 linear feet) are above the statewide average of 12 (3.6 meters) feet NAVD88;
- 39% of shore-perpendicular structures (389 structures, 40,337 linear feet) are above the statewide average of 6 feet (1.7 meters) NAVD88.

Table 10. Private coastal structure types and materials for the MACZM Cape Cod and Islands region.

Primary Structure	Primary Material	Total Structures	Total Length: Feet (Meters)
Bulkhead/Seawall	Concrete	328	64,127 (19,546)
	Wood	174	40,349 (12,298)
	Stone	145	28,929 (8,817)
	Steel	34	16,147 (4,922)
	Total	**681**	**149,552 (45,583)**
Revetment	Stone	599	189,000 (57,607)
	Structural Debris	8	3,112 (949)
	Concrete	1	262 (80)
	Total	**608**	**192,374 (58,636)**
Sandbags		15	2,931 (893)
Total Shore-Parallel Structures		**1,304**	**344,856 (105,113)**
Groin/Jetty	Stone	1,061	98,314 (29,966)
	Wood	102	4,369 (1,332)
	Concrete	2	257 (78)
Total Shore-Perpendicular Structures		**1,165**	**102,940 (31,376)**

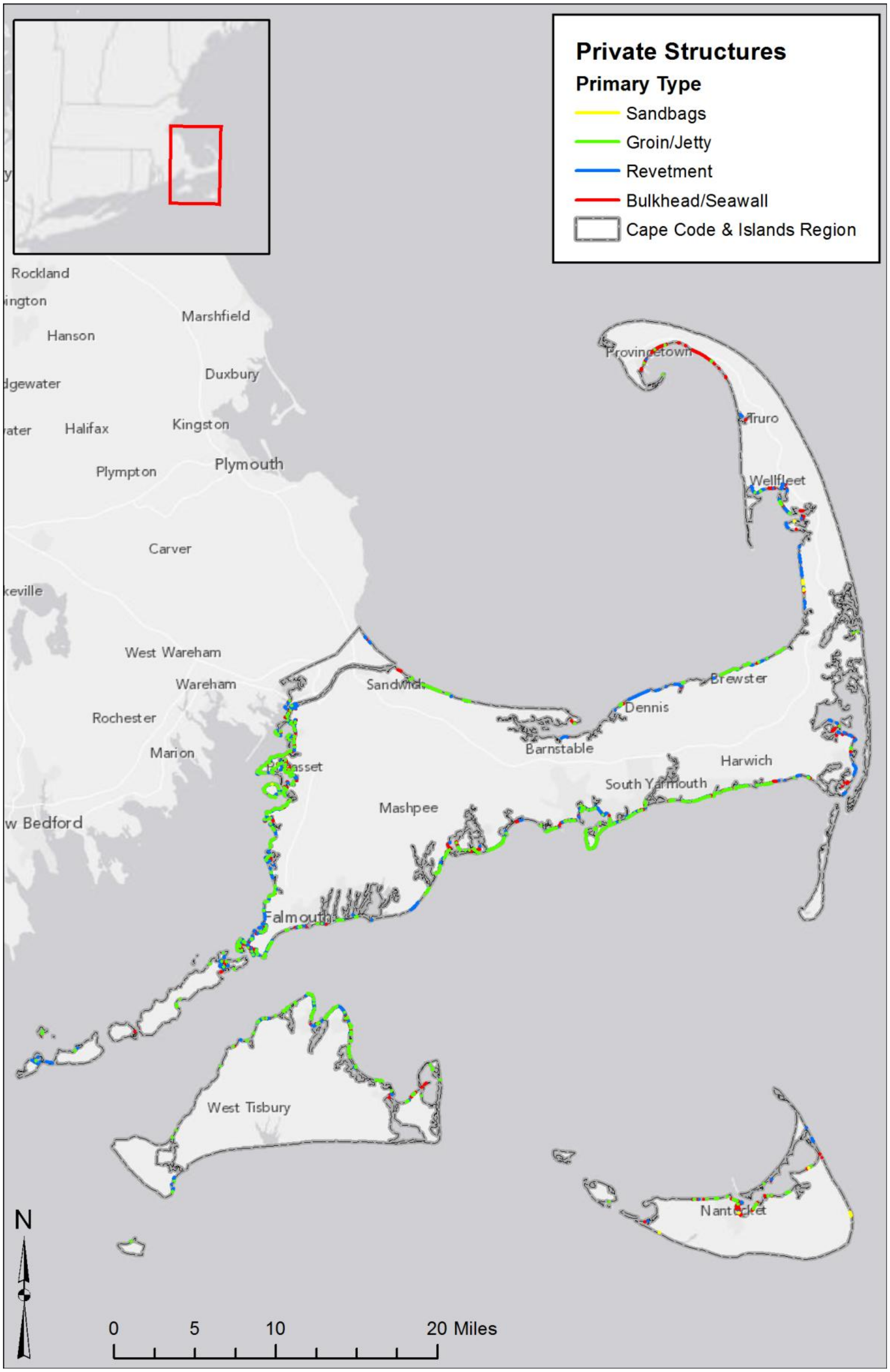

Figure 28. Private coastal structures (by type) for the MACZM Cape Cod and Islands region.

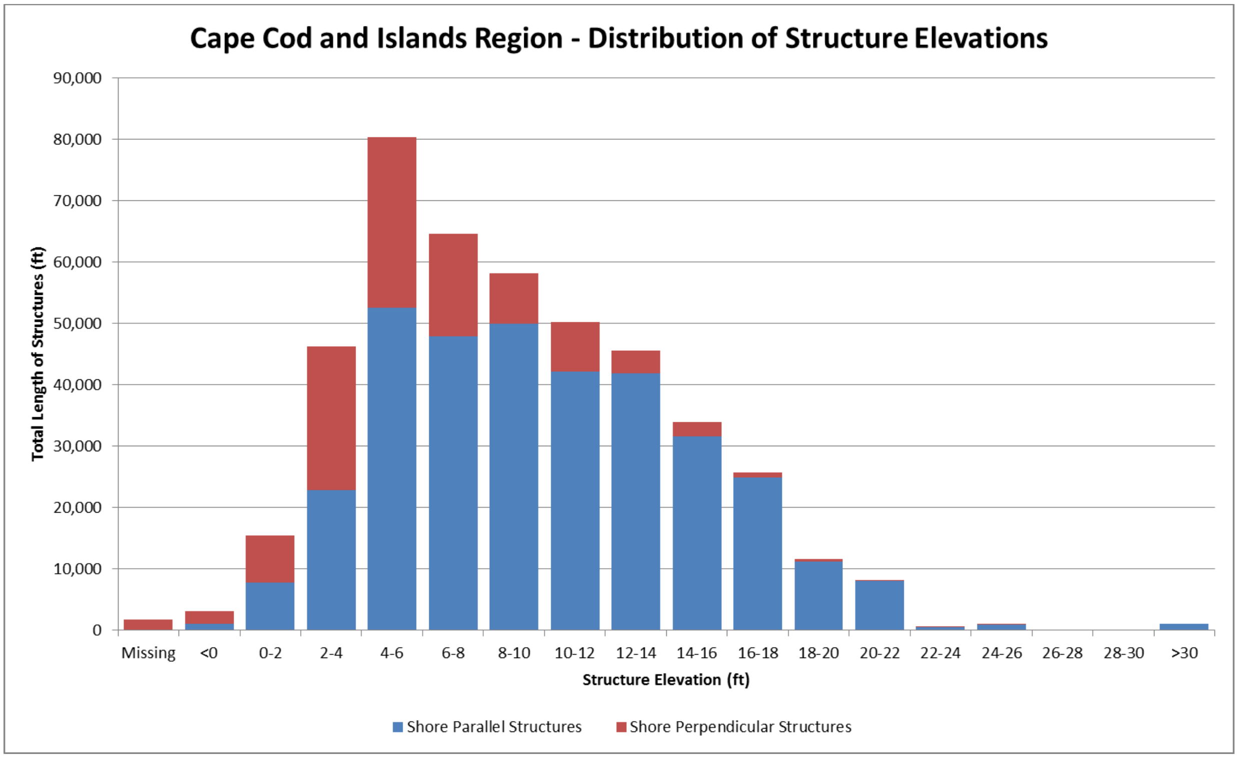

Figure 29. Distribution of elevations (2 foot bins) for privately-owned structures in the Cape Cod and Islands region.

6.6 South Coastal

The South Coastal region extends from Wareham to Seekonk, and includes the communities that make up the north and west coast of Buzzards Bay. This region includes approximately 154 miles (248 km) of ocean-facing shoreline, about 41 miles (65 km) of which are protected with privately-owned coastal structures (Table 11). Another 14 miles (22 km) of the coast are protected with public structures. In total, approximately 35% of the South Coastal region is fronted by some form of coastal protection.

The coastline between Wareham and the Rhode Island/Massachusetts border (shown in Figure 28) is characterized by numerous linear embayments separated by elevated headlands. The coastline is highly compartmentalized due to the glacial geology of Buzzards Bay (embayments resulting from drowned outwash channels) with isolated barriers and pocket beaches along the semi-protected shoreline segments. The region lacks significant sources of mobilized sediment, which likely accounts for the high percentage of sand trapping structures (groins) that were identified by this work. Revetments are also common features along this coastline.

Figure 31 shows the distribution of private structure elevations in terms of total length for the South Coastal region. The data indicate that most of the coastal protection in this region occurs at an elevation below the statewide averages. For the South Coastal region:

- The mean elevation of shore-parallel structures is 6.6 feet (2.0 meters) above NAVD88;
- Shore-perpendicular structures average 4.3 feet (1.3 meters) above NAVD88;
- 8% of shore-parallel structures (43 structures, 17,299 linear feet) are above the statewide average of 12 feet (3.6 meters) NAVD88;
- 25% of shore-perpendicular structures (139 structures, 14,714 linear feet) are above the statewide average of 6 feet (1.7 meters) NAVD88.

Table 11. Private coastal structure types and materials for the MACZM South Coastal region.

Primary Structure	Primary Material	Total Structures	Total Length: Feet (Meters)
Bulkhead/Seawall	Concrete	241	45,596 (13,898)
	Stone	212	53,057 (16,172)
	Wood	15	3,250 (991)
	Steel	10	5,167 (1,575)
	Brick	1	97 (30)
	Total	**479**	**107,168 (32,665)**
Revetment	Stone	370	107,079 (32,638)
	Structural Debris	4	377 (115)
	Total	**374**	**107,456 (32,753)**
Total Shore-Parallel Structures		**853**	**214,623 (65,417)**
Groin/Jetty	Stone	609	56,963 (17,362)
	Concrete	22	1,152 (351)
	Wood	9	501 (153)
Total Shore-Perpendicular Structures		**640**	**58,616 (17,866)**

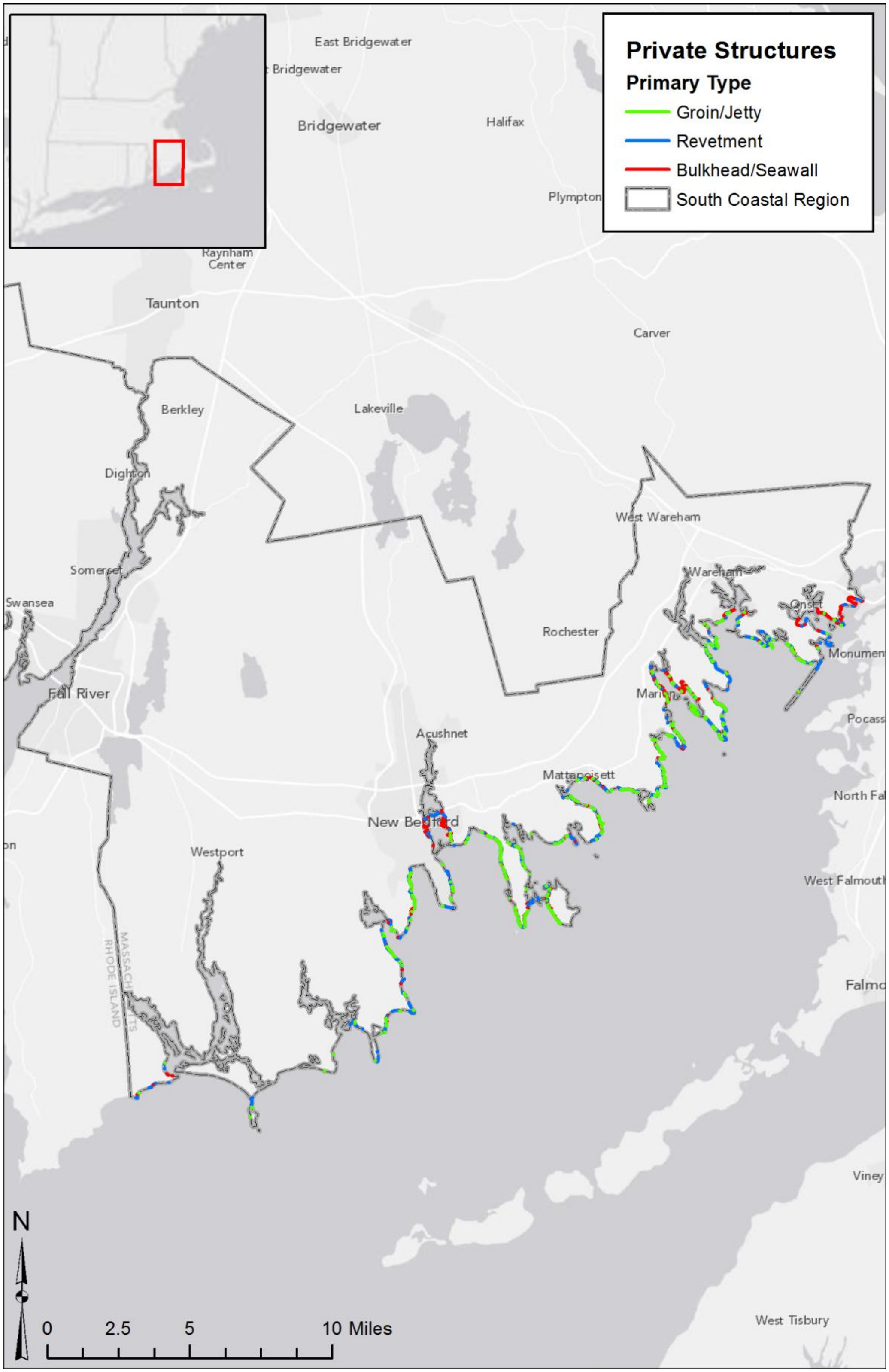

Figure 30. Private coastal structures (by type) for the MACZM South Coastal region.

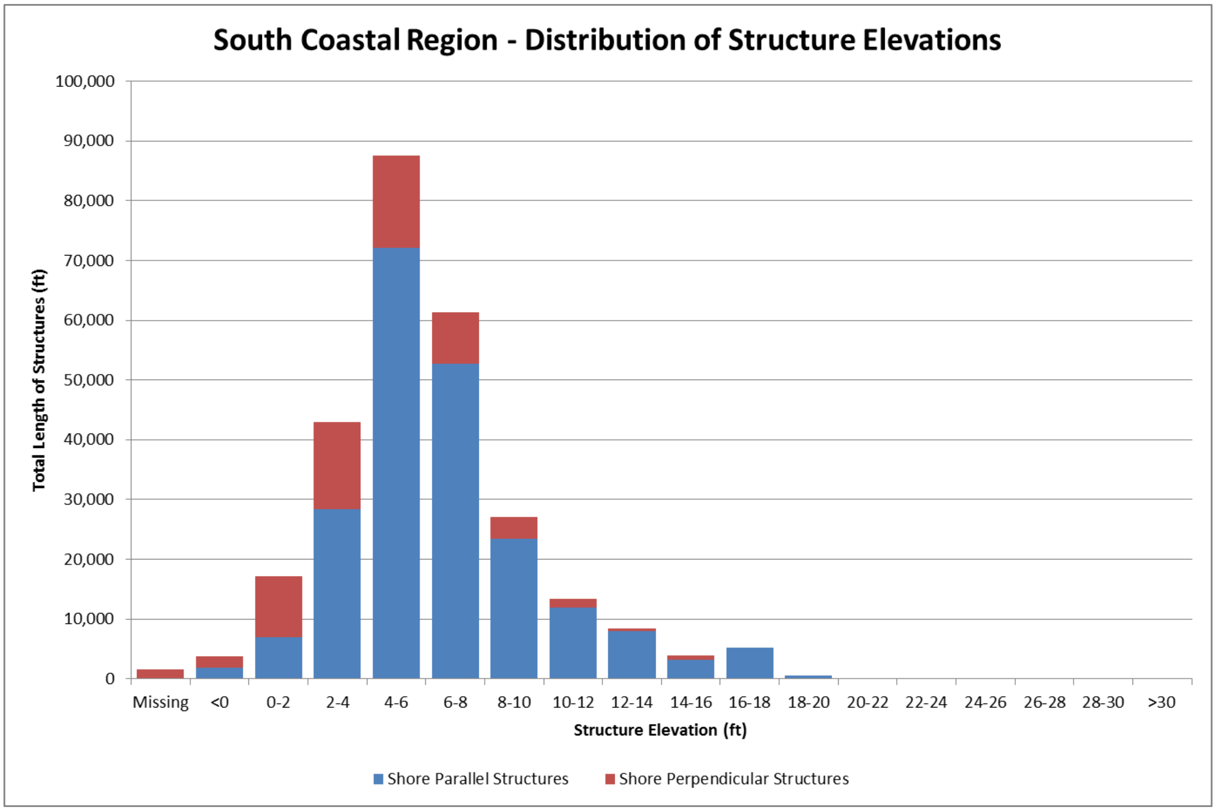

Figure 31. Distribution of elevations (2 foot bins) for privately-owned structures in the South Coastal region.

7 Future Considerations

Coastal structures, whether constructed to provide flood protection, maintain navigation channels, or to prevent shoreline migration, are designed based on specific criteria. The engineering of coastal structures takes into account the influences of tides, currents, and waves, which are all dependent on local water levels. As future sea level rise leads to higher global water levels (Rahmstorf, 2006), the functionality of coastal structures not designed to withstand these changes could be impacted. In fact, sea level changes along the mid-Atlantic and Northeast U.S. coastline (including Massachusetts) are increasing at a rate 3-4 times the global average (Sallenger et al., 2012). The consequences of such changes become acute during storms, as waves gain access to increasingly higher elevations over time.

To assess the potential for sea level rise to impact coastal structures, the elevation of each privately-owned coastal structure was compared with four plausible sea level rise scenarios representing increases in mean higher high water (MHHW) of 1, 2, 3, and 6 feet (0.3, 0.6, 0.9, and 1.8 m). MHHW represents the average of the highest tide of each tidal day observed over the 19 year National Tidal Datum Epoch. It can be thought of as an elevation that experiences tidal flooding once per day on average. Structure elevations were converted from NAVD88 to MHHW using NOAA's VDATUM tool (NOAA, 2012).

Table 12 summarizes the structures that become inundated by each of the four sea level rise scenarios. Groins and jetties, designed to trap sediment and stabilize channels, are impacted at much higher rate when compared with shore parallel structures, which are more typically constructed for flood protection. Even a very moderate sea level rise of 1 ft (0.3 m) impacts nearly 30% of groins/jetties, representing over 20% of their total length. The number of groins/jetties impacted grows quickly with higher sea level rise scenarios, reaching more than 80% if MHHW is increased by 6 ft (0.9 m). Shore parallel structures, which tend to have higher profiles, are affected to a lesser extent. The number and length of shore parallel structures impacted is 10% or less for sea level rise scenarios of 1 and 2 ft (0.3 and 0.6 m), but reaches approximately 15% for 3 ft (0.9 m) of sea level rise and approximately 45% with 6 ft (1.8 m) of sea level rise.

Table 12. Percent of privately-owned coastal structures (summarized by number and total length) with elevations less than 1, 2, 3, and 6 feet above MHHW.

Water Level (ft MHHW)	All Structures		Shore Parallel Structures		Groins/Jetties	
	Number	Length	Number	Length	Number	Length
1	12%	8%	6%	5%	28%	23%
2	20%	13%	10%	9%	43%	36%
3	28%	21%	16%	15%	57%	49%
6	57%	50%	45%	45%	84%	80%

8 Summary and Conclusion

The Commonwealth of Massachusetts has approximately 1,115 miles (1,794 km) of ocean-facing coastline containing a variety of engineering structures designed for shore protection and stabilization. Many of these were built prior to modern coastal management policies and regulations and until recently, no centralized database of coastal structures existed. For this reason, RPS ASA was contracted to develop an inventory of privately-owned coastal engineering structures for the Commonwealth's ocean-facing coastline. The work is a continuation of the Massachusetts Coastal Infrastructure Inventory and Assessment Project, previous phases of which were conducted between 2002 and 2009. Project tasks included "heads-up" digitizing of coastal structures, attribution of the mapped data (ownership, type, materials, length, elevation, and height), and additional research to relate digitized structures to publically available plans and permits. Coastal structures considered for this inventory included shore-parallel features designed to prevent shoreline migration (seawalls, bulkheads, revetments, and sand bags) as well as shore-perpendicular structures that restrict the alongshore movement of sediment or stabilize channels (groins/jetties). Please note that some structures identified in this inventory may not be considered functioning coastal engineering structures under the Massachusetts Wetlands Protection Act regulations and local wetlands bylaws. In summary:

- Structure identification and attribution were completed using a variety of public data sources. The project scope (extent) corresponds with the area mapped for recent shoreline change analysis. Data from previous phases of the project were used to mask the project area. Remotely sensed imagery and LiDAR were then used to identify remaining coastal structures and assign elevations.
- A total of 6,611 coastal structures not included in previous inventories of public structures were digitized and assumed to be privately owned. This includes approximately 196 miles (316 km) of shore-parallel structures and 34 miles (54 km) of shore-perpendicular structures. The inventory of private coastal structures includes 2,967 bulkheads/seawalls; 1,660 revetments; 1,969 groins/jetties; and 15 sandbag structures.
- Mapped structures were compared to Chapter 91 license documents maintained by MassDEP. Licenses that correspond with private structures were tabulated and linked to the structures layer using a "many-to-many" relationship class.
- All data is organized in a GIS database of privately-owned structures that is modeled on and compatible with the databases generated for the previous phases.

- The frequency and type of coastal structures is indicative of the physical processes that shape the coast, the regional geomorphology, and the history of coastal development. The Boston Harbor region (57 miles [92 km]) has the fewest structures, yet the highest percentage of coastline protected (58%). By contrast, the Cape Cod and Islands region (615 miles [990 km]) has the most structures, and the lowest percentage of coastline protected (13%).
- The mean (weighted by length) elevation of shore-parallel structures is approximately 12 feet (3.6 meters) NAVD88; shore-perpendicular structures (groins/jetties) average approximately 6 feet (1.7 meters) NAVD88.
- Considering both private and publically-owned structures, nearly 27% of Massachusetts' ocean-facing shoreline is armored with some form of coastal protection. This figure does not take into account an additional 67 miles (109 km) of structures that extend perpendicular to the coastline.

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