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FINAL MEMORANDUM

Date: **May 15, 2009**

To: **Bouchard 120 Shoreline TWG**

From: **John Ramsey, Mark Osler, and Trey Ruthven**

Subject: **Final Ram Island Shore Protection Alternatives Analysis and Wave Study**

This memorandum contains the initial assessment of shore protection alternatives for Ram Island, including an evaluation of various shore protection options. Initial discussions during the April 2008 site visit formed the basis for recommendations in the alternatives analysis. In addition to the alternatives analysis, the baseline information regarding waves and storm surge influencing coastal engineering design at Ram Island has been provided. Since the digital topographic information from the previous Massachusetts Division of Fisheries and Wildlife (MA DF&W) study was not available to Applied Coastal, the best available information was used to determine topographic information on the island (the 2000 NOAA LIDAR data set) as the basis for the alternatives analysis.

Initial assessment from the site visit has been repeated in this memorandum to illustrate the link between the initial assessment and the present alternatives analysis.

A. Initial Considerations on Shore Protection following the April 2008 Site Visit

From the perspective of shore protection, the site visit revealed some potential issues and/or concerns relative to methodologies that could be utilized to enhance the overall island stability. First, the southwest shoreline of the island consists of a natural cobble and boulder-strewn intertidal region that is interspersed with relatively sparse *Spartina alterniflora*. As shown in Figure 1, this region has relatively little relief. Potential shore protection options for the southwest shoreline may include:

- Boulder or other hard-engineered sill at the seaward limit of the salt marsh to reduce nearshore wave energy and potentially promote sediment accretion.
- Offshore structure to reduce wave energy; however, existence of nearshore eelgrass beds and overall cost may make this option infeasible.

At the southern terminus of the island, a small remnant salt marsh/mudflat exists within an island depression that retains some water (< 1ft) at low tide and has an inlet facing south. As shown in Figure 2, the fringing salt marsh in this depression is not contiguous and shows ongoing signs of episodic erosion. Observations indicate that tidal and wave action continues to cause erosion of underlying inorganic sediments, thereby destabilizing the salt marsh peat substrate. It may be possible to reconfigure the entrance to this mudflat/salt marsh area in a manner that allows sufficient tidal flushing, but reduces tidal currents and/or wave action during typical conditions. This could be accomplished by providing a slight restriction to the inlet with either boulders or other hard engineering methods. Again, this reduced channel should enhance sedimentation in the salt marsh/mudflat region, possibly leading to expansion of the existing fringing salt marsh.

Along the northeast shoreline of Ram Island, the shoreline consists of primarily cobble from the low tide line to the limit of typical wave uprush, with finer-grained sands and gravel landward of the cobble forming a low-crested dune feature (as shown in Figure 3). Based on NOAA LIDAR data from 2000, a contour plot of the upper dune feature is illustrated in Figure 4. It may be possible to enhance this existing dune feature (approximate limits shown by the area enclosed by the 6 ft NAVD contour), thereby enhancing tern nesting habitat, without negatively impacting other resource areas on the island. However, enhancement of this feature would utilize "soft" engineering techniques that likely would require more frequent maintenance. Some of the dune material would migrate into the salt marsh area over time; however, the benefit to the marsh likely would be negligible. Possible shore protection options along the northeast shoreline include:

- Mixed cobble/gravel/sand dune nourishment that would provide sediment to the island following storm events that caused reconfiguration of the dune. Depending on the grain size distribution, the longevity/sustainability of this technique could be limited.
- A cobble dune that would provide longer-term shoreline stability, but would not provide soil that would benefit tern nesting habitat.
- Additionally, it may be possible to add a sand/gravel substrate along the landward edge of the dune feature. Assuming the dune can significantly reduce storm overwash, finer-grained substrate may be more stable in this region than recent history dictates.
- Due to the relatively significant wave energy of the site, Applied Coastal agrees with the overall conclusions of the 14 May 2007 site visit indicating that coir logs and sand tubes likely would provide ineffective long-term protection for the island shoreline.

Figure 1: Boulder and cobble intertidal region with interspersed *Spartina alterniflora.*

Figure 2: Remnant salt marsh and intertidal flat consisting of sand/gravel/cobble/boulder material near southern terminus of Ram Island.

Figure 3: Cobble, gravel, and sand beach (foreground) and dune (background) along the northeast shoreline of Ram Island.

Figure 4: Elevation of the dune feature on Ram Island illustrating features that have elevation of 6 or more feet NAVD.

B. Overview of Shore Protection Alternatives Evaluation

Based on discussions held during the site visit and supported by the analysis of wave and storm surge conditions at Ram Island, standard coastal engineering structures that protect the upland from being submerged and/or overtopped during a severe storm event (i.e. the 25-year return period) would substantially alter the existing island topography. This type of structure and fill project would be costly and require significant damage to both existing dune/beach resources, as well as complete removal of the fringing salt marsh. Rather than development of shore protection design utilizing standard coastal engineering design methodologies, the aim of the design is to utilize appropriate shore protection measures to enhance the habitat of the island that includes salt marsh and beach/dune, while helping to sustain the longevity of the island. Coastal resources on the island consist of salt marsh, rocky intertidal shore, coastal beach, and coastal dune. The evaluation of alternatives focused on developing a plan to sustain the function of the island and maintaining and/or enhancing the existing coastal resource areas where practicable.

As part of the alternatives analysis, regulatory constraints were considered to ensure that technically feasible solutions from an engineering perspective were developed in a manner that would be consistent with existing state and federal environmental regulations associated with coastal resources. In general, 'hard' coastal engineering structures are problematic to permit because of their adverse environmental impacts directly to the resource areas or indirectly to downdrift areas. 'Soft' measures such as dune enhancement, beach nourishment, or biodegradable coir fiber rolls are preferred by regulatory agencies, since the adverse environmental impacts are minimal or even self-mitigating in some cases. For example, dune nourishment is often considered 'self-mitigating', since it periodically adds sand to the beach system that existed prior to placement of the artificial dune feature. Due to the importance of Ram Island to the endangered Roseate tern population, as well as the numerous efforts that have in to protecting this nesting habitat within the Buzzards Bay region, it is possible that regulatory agencies could relax restrictions that normally limit the use of hard structures in areas consisting of coastal beach, coastal dune, and salt marsh resources.

C. Description of the Screening Process for Alternatives

Prior to eliminating alternatives from further consideration, it is important to develop a more formal screening process to describe the benefits and disadvantages associated with the full range of available alternatives. This process ensures that the most appropriate shore protection options are carried forward to the conceptual design phase. The primary emphasis of the shore protection selection process is screening, where the process is to identify the most appropriate alternative(s) based upon a series of exclusionary and discretionary criteria. There are no numerical thresholds that identify the best alternative; rather, the screening process is designed to assess a wide range of potential shore protection options, and through comparative analysis, narrow the list of options until only the most appropriate remain. Appropriate is defined as those alternatives that best meet the "federal" Least Environmentally Damaging Practicable Alternative (LEDPA) standard, that are permittable under federal and state environmental regulations and which can be considered cost-effective. An overview of the screening process for alternatives is shown in Figure 5.

Screening criteria are characterized as either exclusionary or discretionary. Exclusionary criteria reflect potential available shore protection measures that are not technically feasible or are prohibited by state/federal regulations. For example, if Ram Island was located within an Area of Critical Environmental Concern (ACEC) that prohibits coastal engineering structures under state law, this exclusionary criterion for potential structural options would eliminate further evaluation of these options. Based on the series of options evaluated below, no alternatives were categorically eliminated based upon exclusionary criteria.

Discretionary criteria are those that determine, when applied as a group, the shore protection alternatives which are least or best suited for the site. For example, the potential impacts to shellfish and fin-fish habitat (e.g., eel grass beds) are evaluated under discretionary criteria. The presence of such habitat potentially impacted by an alternative would not automatically exclude the shore protection option from further consideration, but it would identify that option as less desirable than one in which such habitat was not adversely impacted. The application of discretionary criteria is the main component of the screening process, and it is the process by which the shore protection alternatives are compared amongst themselves, using site-specific information to prioritize alternatives.

Potential alternatives then are reviewed using the discretionary criteria and assigned a relative ranking. Alternatives that have significant limitations receive low marks; alternatives with fewer limitations receive higher marks. Some examples of potential impacts that would receive low marks include:

- filling of salt marsh that provides essential fish habitat and shore bird foraging;
- direct and long-term adverse effects on benthic communities that may be associated with placement of shore protection structures or fill;
- alteration of sediment characteristics of the island that affect the nesting habitat quality for Roseate Terns.

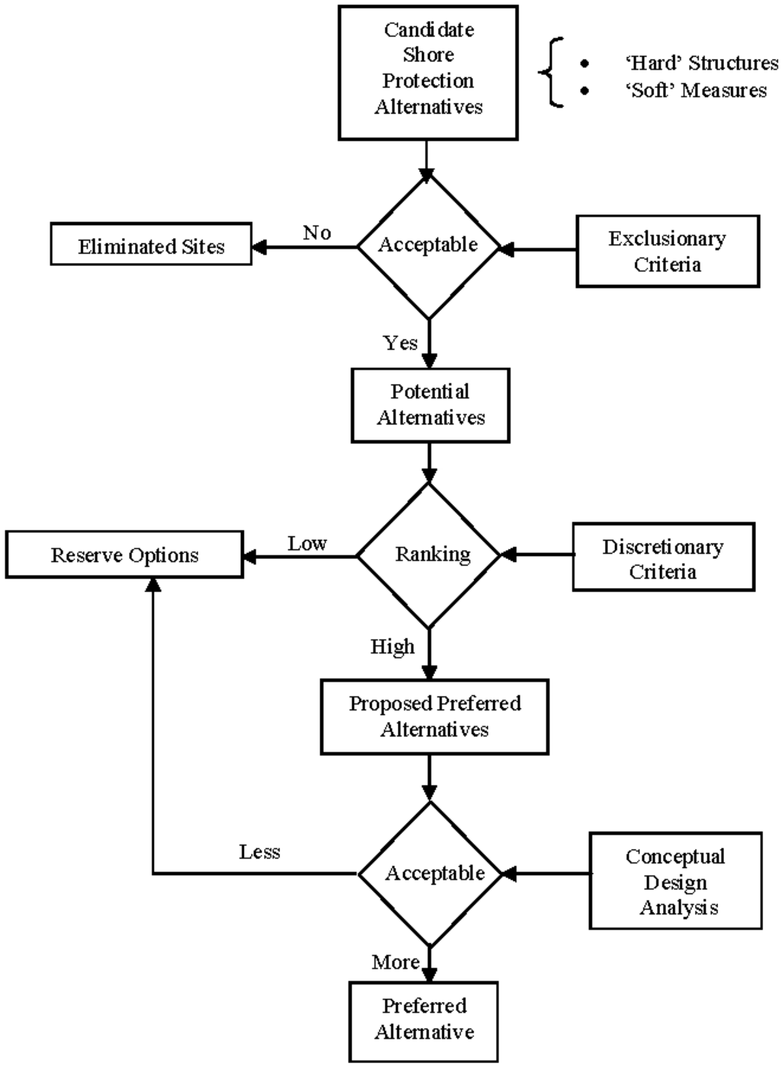

Figure 5. Screening process flowchart for shore protection alternatives.

All identified structural and non-structural alternatives were then examined and tested against the discretionary criteria. The following lists the alternatives that potentially could be utilized for shoreline stabilization at Ram Island and provides a brief summary of available information. In addition, Table 1 lists key details associated with the analysis of discretionary criteria for each alternative. It should be noted that the regulatory constraints are similar for each shore protection alternative, where non-structural measures likely are permitable if potential adverse impacts are minimized and structural measures will require a variance under the Massachusetts Wetlands Protection Act. The regulatory process for all shore protection alternatives will require Section 7 endangered species consultation due to the Roseate tern habitat and will impact EFH due to the coastal beach, salt marsh, and sub-tidal resources surrounding the island.

1. No Build

It has been acknowledged that continued stability of Ram Island is critical to the survival of endangered Roseate terns in Massachusetts, since one half of North America's breeding pairs of the Roseate terns can be found on Bird and Ram Islands in Buzzards Bay (http://www.mass.gov/dfwele/dfw/nhesp/conservation/birds/tern_restoration.htm). Additionally, both Bird and Ram Islands have eroded significantly during the past 100 years. Figure 6 illustrates the reduction in the area of Ram Island since 1935, where the land loss rate for the most recent time-period is ~0.05 acres per year. Based on the assumption that this rate of land loss continues in the future (as a result of erosion and relative sea-level rise), Ram Island will likely disappear within the next 40 years.

Therefore, if no action is taken to eliminate and/or reverse the observed land loss process on Ram Island, this valuable nesting habitat (primarily utilized by the endangered Roseate tern) will be lost. For this reason, this alternative was determined to have unacceptable adverse long-term environmental impacts.

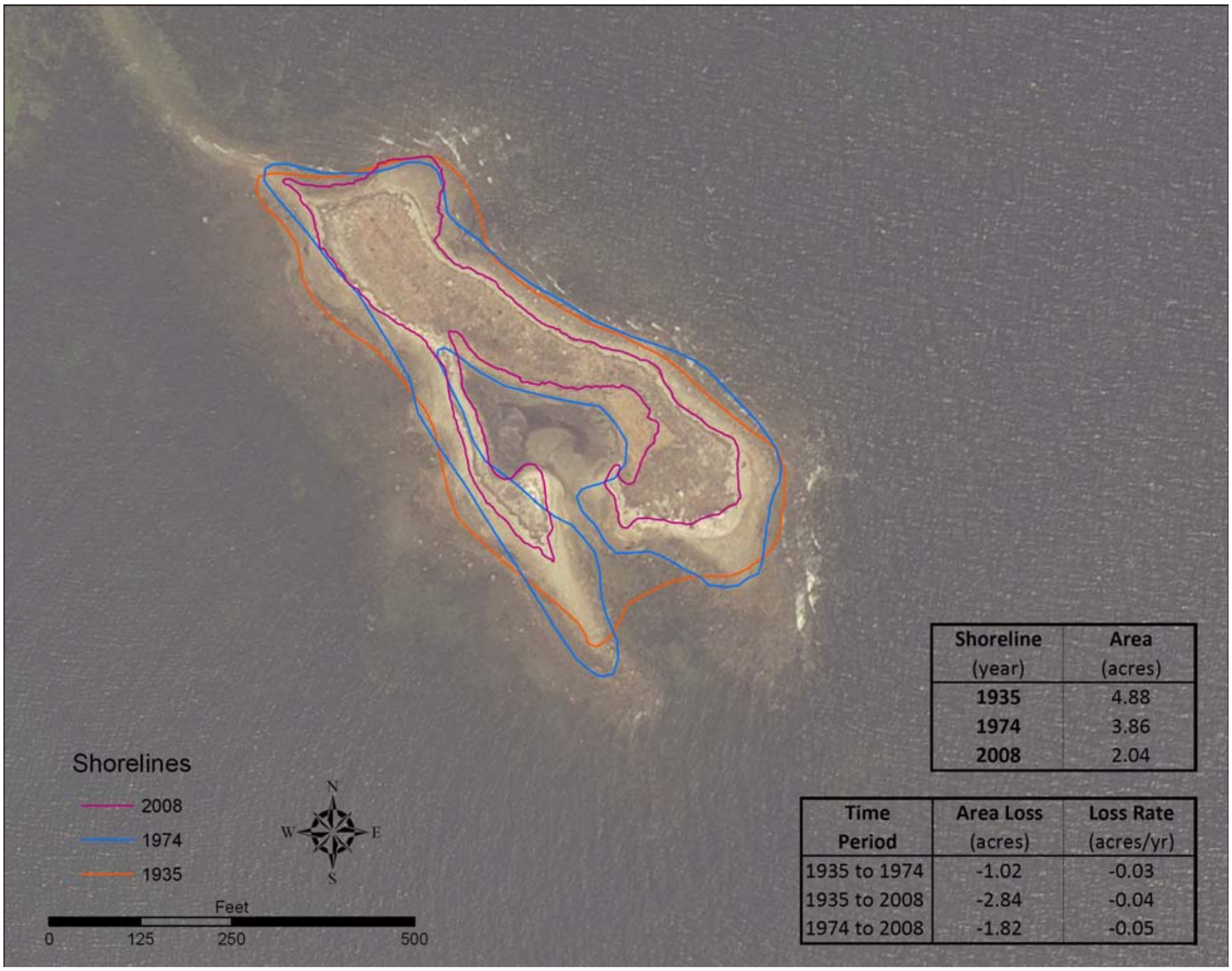

Figure 6: High water shorelines developed from NOAA T-sheets (1935 and 1974) or surveyed by Applied Coastal using differential GPS equipment.

2. Beach/Dune Nourishment

- erosion protection - good with proper design and compatible sediment source
- potential environmental impacts - low to significant depending on local aquatic, intertidal, and subaerial resources impacted
- constructability is straight-forward using hydraulically placed sand, but is logistically complex for coarse-grained material placement

- periodic renourishment is required (likely on ~5- year cycle to maintain island nesting area)
- protection of upland beach and dune resources only

Placement of beach/dune fill is a logical means for improving the longevity of the island and to expand the existing tern habitat. The loss of land area on the island is postponed by raising the elevation and/or extending the shoreline into Buzzards Bay. Due to the ‘soft’ nature of this shore protection measure, the longevity of this approach is limited and periodic renourishment must be anticipated. Hence, a combination of nourishment with other erosion mitigation measures may be more cost-effective for extending the life of the beach/dune fill. Since no other methodology raises the elevation and adds volume to Ram Island, nourishment is the only option that potentially increases shore bird habitat. In addition, an influx of sediments is required to allow the island to keep up with ongoing relative sea-level rise; therefore, adding material to the island is required to maintain the general characteristics of the island habitat.

Nourishment material may be obtained from an onshore or offshore borrow site. However, recent regulatory decisions by the New England District of the U.S. Army Corps of Engineers have made future use of offshore sand/gravel resources (i.e., sand mining) problematic. Therefore, realistic borrow sources for Ram Island nourishment likely would be limited to beneficial re-use of dredged material associated with navigation projects or upland source alternatives. An upcoming dredging project in Woods Hole for the Northeast Fishery Science Center berth could provide a significant volume of coarse-grained material (sand/gravel/cobble) for the island; however, much of this material is slated for offshore disposal in Rhode Island in late 2008 or early 2009. Other potential offshore sources are the coarse-grained material dredged from the Cape Cod Canal and the sand/gravel from the Confined Aquatic Disposal Cell construction in New Bedford Harbor.

Fill material utilized at Ram Island should be compatible with *in situ* sediments. Based on observations from the site visit, much of the inter-tidal area is covered with cobble and boulder, forming a ‘cobble pavement’ that protects the mixture of glacial till sediments underneath. In addition, the subaerial sediments range from fine-grained sand (with some organic material) in the marsh area and a low-lying region near the northwest end of the island to coarse-grained dune features primarily consisting of gravel and cobble. Therefore, dune/beach nourishment on Ram Island should consist of a range of sediment grain sizes between sand and rounded cobble. However, to enhance the primary features that withstand wave action, the material comprising the core of the dune should consist of primarily gravel and cobble.

The nourishment design elements associated with the existing MADFW program directed at increasing the island elevation at two critical regions consists of sand-sized material. The advantage of this approach is that sand can be hydraulically placed on the island via a pipeline; however, design life will be short. Use of a pipeline limits the amount of construction activity on the island, especially the requirement for significant heavy equipment. To deliver coarse-grained gravel and/or cobble to the island will require significantly more complex logistics for delivery. It is possible that a shallow-draft barge can be used with a portable conveyor system for delivery. Spreading of the material and placement of the conveyor system will require more substantial construction equipment on the island, with the potential for increased short-term impacts.

Environmental concerns related to beach/dune nourishment projects include potential for temporary water quality impacts when sediments are deposited (if they are placed hydraulically), and natural habitat (e.g., salt marsh) may be disturbed when depositing the dredged material. Since environmental concerns may limit the dredging window, costs for beach nourishment in Massachusetts may be relatively high. The primary issues involve disruption of both finfish and/or shellfish habitat at the beach fill site (typically utilized by juvenile fish during the summer months).

Due to the relatively minor environmental impacts and the significant benefits associated with this shore protection alternative, it is recommended that this option be considered for shore protection at Ram Island. Specifically, the existing dune system that runs along the northeastern shoreline of the island (Figure 7) could be enhanced with a sand/gravel/cobble dune nourishment program.

3. Upland Stone Dike

- erosion protection - good since it prevents migration of island sediment; however, it may exacerbate loss of sediment on the long run due to increased wave reflection
- potential environmental impacts – significant both during construction and in the long-term
- constructability is complex and will require heavy equipment to operate on the island
- limited maintenance required as island and dike subside
- protection of upland beach and dune resources only

Stone dikes have been utilized on a number of barrier beach systems throughout the U.S. as a means of fixing the location of the natural feature. In general, the dike will reduce and or eliminate wave action behind the structure during severe storm events. Locally, Plymouth Long Beach has been armored by a dike since 1900 and the U.S. Army Corps has considered lengthening a dike on nearby Cuttyhunk to stabilize the barrier beach system adjacent to the harbor entrance. Due to the natural migration of dune and beach features, dikes on these natural systems have proven to be ineffective in the long-term. For example, a portion of the barrier beach system on Plymouth Long Beach has migrated landward of the dike system, leaving the structure stranded in the inter-tidal area. Once the dike is compromised in this manner, the structure can actually exacerbate erosion of the beach/dune system due to increased wave reflection. Without the addition of sediment to the island, long-term coastal processes (relative sea-level rise and continues wave action on the island) will cause long-term subsidence of the island and impact the integrity of a stone dike. Periodic maintenance (frequency of every 10-20 years as indicated in Table 1) would be required for this type of stand-alone structure.

From a construction perspective, placement of large armor stone on the island would require construction of a temporary offloading pier, as well as use of large construction equipment (trucks, excavators, and cranes). Due to the scale of the project and the limited space on the island, it is likely that a portion of the salt marsh system would be impacted and possibly destroyed.

Due to the limited benefits substantial environmental impacts and the associated with this shore protection alternative, this option was eliminated from further consideration.

4. Nearshore Stone Dike

- erosion protection – limited as a stand-alone option; however, reduction in wave heights at the shoreline can enhance salt marsh stability and help retain finer-grained sediment on the island
- potential environmental impacts – relatively insignificant if dike can be placed in the area between the seaward extent of the salt marsh and the landward limit of an submerged aquatic vegetation beds.
- to simplify construction, a shallow draft barge with a crane will be required to place the stones at the proper location
- limited maintenance required due to wave action and relative sea level rise
- protection of fringing marsh with limited protection of upland beach and dune resources

The design concept for an offshore stone dike is similar to the existing stone wall that originally protected Bird Island Lighthouse in the northern part of Buzzards Bay. As sea level has risen, the low-lying seawall protecting the lighthouse became an inter-tidal dike, which helped retain sediment on the island and formed an area protected from open-bay wave conditions. This wave protection allowed development of a stable salt marsh on Bird Island. For Ram Island, this concept could be designed to serve the same purpose, where a low-lying dike could be constructed in the vicinity of the low water line (between -1 ft and -2 ft NAVD) and have a height that would protect the island from waves during most daily tidal conditions (dike height ~4 feet). As a stand-alone shore protection option, this dike would have limited benefits to overall island stability; however, combined with dune/beach nourishment, this structural enhancement would extend the longevity of the dune and island habitat. In addition, the dike would reduce wave heights at the shoreline, providing enhanced stability of the fringing salt marsh system.

Construction of an offshore dike feature is directly dependent on the stone size required, the nearshore water depths in the region of placement, and the ability for a barge-mounted crane to place the material at the proper location. Based on the wave height information, wave heights during the peak of a 25-year event are 6.1 and 5.5 ft for the east and south sides of the island, respectively. Therefore, appropriate individual stone sizes that would resist movement during a 25-year event would need to be excess of 5 tons. This relatively large sized stone likely would require use of a shallow draft jack-up barge equipped with a crane.

The offshore dike described above could either be placed in a contiguous fashion or be made up of a series of shore sections with gaps to improve tidal circulation. From a shore protection perspective, a contiguous structure is preferable, since it inhibits wave action to the maximum extent possible. However, a contiguous structure is the most expensive option and the dike can be designed with reasonable gap widths that provide adequate wave damping and improved tidal circulation.

One additional area where a nearshore dike could be utilized to enhance island stability is at the entrance of the salt marsh system located at the southeastern end of the island. This boulder-strewn area around the inlet could be enhanced and protected using a series of short shore dikes. The stone dike sections could represent a significant reduction in channel cross-sectional area but with properly designed gaps and alignments between sections of the dike, there will be no adverse affect on tidal circulation. Nearshore dikes in this region would reduce wave action and the on-going loss of marsh sediments at this location. Due to the more wave-protected nature of this location, smaller armor stones could be utilized to constrain the size of this tidal channel.

Due to the significant benefits and the relatively minor environmental impacts associated with this shore protection alternative (assuming placement directly on either salt marsh or nearshore eelgrass resources can be avoided), it is recommended that this option be further considered for shore protection at Ram Island. Specifically, the southwestern shoreline of the island that presently consists of ‘cobble pavement’ (Figure 7) could be enhanced with an offshore stone dike and related nourishment. In addition, use of armor stone to reduce the cross-section of the marsh channel at the southeastern side of the island also should be considered as an appropriate method to enhance shore protection at Ram Island.

5. Offshore Breakwaters

- erosion protection – good since wave heights during all but the most extreme conditions would be reduced substantially
- potential environmental impacts – significant both during construction and in the long-term

- constructability is straight-forward with the appropriate heavy equipment to place the armor units from a barge
- limited maintenance required
- protection of fringing marsh with limited protection of upland beach and dune resources

Offshore breakwaters have historically been utilized throughout the world as a method to reduce wave energy at the shoreline and they are often incorporated with beach nourishment programs to enhance the longevity of a fill project. If adequate littoral sediments are available, a "salient" or "tombolo" often accretes in the shadow of a breakwater, due to the re-direction and attenuation of wave energy landward of the structure. One regional example are the "Five Sisters" offshore of Winthrop Beach, Winthrop, Massachusetts where the series of breakwaters helps maintain a relatively wide beach that has provided shore protection since the 1930s. Another local example is the breakwater offshore of Round Hill Beach, in Dartmouth where the structure actually has had an adverse impact on the stability of the tidal inlet.

Offshore breakwaters typically are emergent by several feet at high tide to ensure that transmission of wave energy is inhibited for all but the most severe wave conditions. This design allows stability of the shoreline landward of the structure. Lower profile breakwaters that become submerged at high tide can allow as much as 90% of the wave energy to propagate to the shoreline under normal wave conditions; therefore, submerged structures are generally no effective for shore protection.

From a construction perspective, placement of large armor stone in the offshore region will necessitate use of large construction equipment (barges and cranes). Depending on the water depth and height of the structure, the 'footprint' of a breakwater can be significant. As discussed during the Ram Island site visit, the subtidal waters surrounding Ram Island contain dense healthy beds of eelgrass. Therefore, construction of offshore breakwaters in the sub-tidal region will have substantial permanent impacts on these submerged aquatic vegetation beds.

Due to the substantial environmental impacts associated with this shore protection alternative, this option was eliminated from further consideration.

6. Groins

- erosion protection – good if beach nourishment is added to protect the upland and/or dune at the landward end of the structures. This also requires that the upland is above the water level anticipated for design conditions
- potential environmental impacts – significant both during construction and in the long-term
- constructability is straight-forward with the appropriate heavy equipment to place the armor units on the island
- limited maintenance required and the longevity of the beach fill can be enhanced by making the groins with a "T-head"
- protection of upland beach and dune resources with associated beach nourishment; however, this intertidal nourishment could cover fringing salt marsh

For the purposes of this analysis, groins are defined as shore perpendicular structures that extend from the upland dune/beach to seaward of the low tide line. Stone groins have historically been utilized along much of the Buzzards Bay and Cape Cod shorelines to prevent loss of material to downdrift beaches. They are often incorporated with beach nourishment programs to enhance the longevity of a fill project. If adequate littoral sediments are available to keep the groin compartments filled to entrapment, the structures have limited adverse impacts to downdrift beaches. However, an island system like Ram Island does not lend itself for design of a groin system since a substantial volume of fill would be required to ensure that the landward end of the structures does not become compromised during a significant storm event.

Groins typically stand by several feet above the high tidal line to ensure that they block longshore sediment transport in all but the most severe wave conditions. From a construction perspective, placement of large armor stone on the island would require construction of a temporary offloading pier, as well as use of large construction equipment (trucks, excavators, and cranes). Due to the requirement that these structures cross the intertidal zone, both the structures and the associated beach nourishment would permanently destroy the salt marsh surrounding the island.

Due to the substantial environmental impacts and the design difficulties associated with this shore protection alternative, this option was eliminated from further consideration.

7. Geotubes and/or Coir Fiber Rolls

- erosion protection – poor
- potential environmental impacts – minor if placed in areas that avoid existing salt marsh
- constructability is straight-forward with limited equipment on the island necessary to move the measures into place
- significant maintenance required
- protection of upland beach and dune resources with possible temporary protection of fringing salt marsh

In recent years, biodegradable coir fiber rolls and geotubes have become more accepted as methods of 'soft' erosion protection in quiescent wave environments. They have been used with some success in enclosed embayments such as Pleasant Bay (Chatham) and Cotuit Bay (Barnstable). However, the wave and storm surge analysis for Ram Island indicated that this location is not suitable for either geotubes or coir fiber rolls. Specifically, geotubes will become compromised rapidly by wave-driven flotsam. Storm surge combined with small waves would rapidly destroy the coir fiber rolls at this site.

Due to the inability for these shore protection options to survive the wave and storm surge climate of the site, these alternatives was eliminated from further consideration.

8. Intertidal Cobble Nourishment

- erosion protection - good with proper design and compatible sediment source
- potential environmental impacts - significant due to existence of intertidal salt marsh on cobble beach
- constructability is logistically complex for coarse-grained material placement
- periodic renourishment is required (likely on ~5- year cycle to maintain upland protection
- protection of upland beach and dune resources, with possible protection of fringing marsh depending on rate of migration

Similar to beach/dune nourishment, placement of intertidal cobble fill is a logical means for improving the longevity of the upland and to expand the existing tern habitat. Specifically, the western side of the island that consists of an intertidal cobble beach and salt marsh could be enhanced with introduction of a cobble berm. Due to the 'soft' nature of this shore protection measure, the longevity of this approach is limited and periodic renourishment must be anticipated. In addition, placement of this feature in the lower half of the intertidal zone (between mean low water and mean tide level) would minimize direct impacts to existing salt marsh resources.

Therefore, an approximate 40 ft wide region of cobble nourishment placement is possible, potentially allowing a berm height of ~5 feet. Migration and natural profile adjustment of the cobble berm will generally exhibit a milder foreshore slope after equilibration. Following fill placement, this profile adjustment will cause some migration of the fill material into the sub-tidal region. According to Komar et al. (2003), the slope of natural cobble beaches along the west coast of the U.S. are approximately 1:5 (vertical:horizontal). Following equilibration of the cobble berm, the coarse cobble material at the crest of the feature forms the steepest slope, generally steeper than 1:2 (v:h). Therefore, waves will alter the shape of a cobble nourishment following placement by flattening the seaward portion of the profile and generally steepening the crest of the berm. Depending on storm frequency, overwash of the berm crest can lead to landward migration of the cobble nourishment and episodic covering of salt marsh resources landward of the berm.

However, similar to beach/dune nourishment, intertidal cobble nourishment raises the elevation and adds volume to Ram Island. This influx of sediment serves to protect the fringing salt marsh from direct wave attack during normal tide conditions and prevent erosion of the upland. This short-term protection of the salt marsh needs to be balanced with the infrequent overwash of a cobble nourishment that will cause burial of the salt marsh.

Fill material utilized at Ram Island should be compatible with *in situ* sediments. Based on observations from the site visit, much of the inter-tidal area along the western shoreline is covered with cobble, forming a 'cobble pavement' that protects the mixture of glacial till sediments underneath. Therefore, a shore protection berm will consist primarily of cobble and gravel sized material. Similar to the description of delivery methods for beach nourishment above, delivery of coarse-grained gravel and/or cobble to the island will be logistically complex. It is possible that a shallow-draft barge can be used with a portable conveyor system for delivery. Spreading of the material and placement of the conveyor system will require more substantial construction equipment on the island, with the potential for increased short-term impacts.

Environmental concerns related to a cobble berm nourishment project include potential for some direct disturbance to natural habitat (e.g. salt marsh) when depositing the fill material. In addition, fill migration from natural equilibration of the berm may cover both nearshore eelgrass and island salt marsh resources. Due to the relatively short design life, the potential for adverse environmental impacts, and the likelihood that fill along the western shore of the island can be stabilized with intertidal headland structures that ultimately would have a more substantial design life with similar cost and environmental impacts (see below), the cobble berm concept is not recommended.

9. Intertidal Headlands or Breakwaters

- erosion protection - good with proper design placement and dimensions
- potential environmental impacts – relatively insignificant if headlands can be placed in the area between the seaward extent of the salt marsh and the landward limit of an submerged aquatic vegetation beds. However, state environmental regulations prohibit new coastal engineering structures that may adversely impact coastal beach and/or salt marsh resources, so a variance would be required.
- to simplify construction, a shallow draft barge with a crane will be required to place the stones at the proper location. Alternatively, the structures could be constructed from the upland by working during the period between approximately low tide and mean tide level without directly impacting the existing salt marsh resources.
- limited maintenance required due to wave action and relative sea level rise
- protection of fringing marsh with limited protection of upland beach and dune resources

To reduce potential construction costs, as well as environmental impacts associated with standard offshore breakwaters, shore protection for the Ram Island shoreline could be provided by smaller intertidal breakwaters or headlands. Similar to offshore breakwaters and the nearshore stone dike described above, the primary purpose of the structures would be to reduce wave energy reaching the shoreline. This will provide direct protection of the fringing salt marsh along the western shoreline of the island. Intertidal headlands would be designed to be emergent at high tide; therefore, they would provide wave protection similar to offshore breakwaters. Due to their larger cross-shore footprint, intertidal headlands are more effective than the nearshore stone dike at reducing wave energy at the shoreline.

If adequate littoral sediments are available, a “salient” or “tombolo” often accretes in the shadow of an intertidal headland or breakwater, due to the re-direction and attenuation of wave energy landward of the structure. Regardless of the sediment supply, these structures will generally cause a reshaping of the beach in the lee of the structures as a result of wave re-direction (diffraction). The relatively quiescent environment formed in the shadow of the structures may allow for establishment of a more stable fringing marsh system; however, this may require enhancement of the beach sediment supply (as described below). As a stand-alone option, intertidal headlands are not recommended primarily due to their cost relative to the protection provided. In addition, existing environmental regulations prohibit coastal engineering structures in areas where they can potentially impact coastal beach and salt marsh resources. However, this shore protection technique may have merit if incorporated with nourishment (see below).

10. Intertidal Headlands or Breakwaters with Nourishment

- erosion protection - good with proper design placement and dimensions
- potential environmental impacts – relatively insignificant if headlands can be placed in the area between the seaward extent of the salt marsh and the landward limit of any submerged aquatic vegetation beds. However, state environmental regulations prohibit new coastal engineering structures that may adversely impact coastal beach and/or salt marsh resources, so a variance would be required.
- to simplify construction, a shallow draft barge with a crane will be required to place the stones at the proper location. Alternatively, the structures could be constructed from the upland by working during the period between approximately low tide and mean tide level without directly impacting the existing salt marsh resources. Similar to cobble nourishment, delivery of fill material is logistically complex.
- limited maintenance required due to wave action and relative sea level rise
- may initially cover fringing salt marsh; however, this combined shore protection technique will provide long-term enhancement of fringing marsh and protection of upland beach and dune resources

By incorporating beach nourishment with compatible sediments (likely dominated by gravel and cobble) with the intertidal headland concept, shore protection along the western shoreline of Ram Island can be provided to both the fringing marsh and the upland beach and dune system. Initially, placement of beach nourishment material may cover a portion of the salt marsh within the existing cobble beach system. However, it is anticipated that a more stable environment for the salt marsh will be established in the relatively quiescent region landward of the breakwaters. An example of this technique is shown in Figure 7, where small breakwaters were placed on an intertidal mud flat with nourishment. Environmental monitoring of this project has indicated an expansion of the existing *Spartina alterniflora* marsh in the lee of the breakwaters (personal communication with Christopher Creed, Olsen Associates).

As a shore protection solution, the combination of intertidal headlands and beach nourishment is recommended as an option that should be further considered at Ram Island. Existing environmental regulations prohibit coastal engineering structures in areas where they can potentially impact coastal beach and salt marsh resources. Regardless, it may be possible to justify this shore protection option due to its long-term shore protection viability for stabilizing the Roseatte tern habitat on Ram Island.

Figure 7: The Fish Haul Creek Stabilization Project in Hilton Head South Carolina was constructed in the fall of 2006 and included beach fill and a series of detached breakwaters that were placed on the intertidal mudflat (2005 Photo: Town of Hilton Head, SC), 2007 Photo: Aerial and Architectural Photo, Inc.).

Table 1: Assessment matrix for shore protection alternatives for Ram Island.

Alternatives	Regulatory Constraints	Environmental Impacts	Potential Resource Benefits	Constructability	Longevity	Sustainability	Ease of Maintenance	Cost of Construction (per linear foot)	Cost of Life Cycle	Overall Ranking
Beach/Dune Nourishment	Permitable with minimization of adverse impacts	Low	Protection for interior upland portions of the island along with adding material to intertidal regions	Sand fill is relatively straight-forward; however, gravel/cobble will require more complex and costly delivery	3-5 years	Fair-to-Good With Periodic Nourishment	Moderately Complex	$500 - $1,000	Moderate To High	High (east side)
Upland Stone Dike	Significant, WPA Variance Required	Significant	Protection for interior upland portions of the island	Constructability is complex and will require heavy equipment to operate on the island	10-20 years	Good	Complex	> $1,000	Moderate	Low
Nearshore Stone Dike	Significant, WPA Variance Required	Moderate (if placed appropriately)	Protection for fringing salt marsh with limited protection of upland beaches and dune resources	A shallow draft barge with a crane will be required to place the stones at the proper location	~20 years	Good	Complex	$400 - $800	Moderate	Moderate (west side and marsh entrance)
Offshore Breakwaters	Significant, WPA Variance Required	Substantial	Protection for fringing salt marsh with limited protection of upland beaches and dune resources	Constructability is straight-forward with the appropriate heavy equipment to place the armor units from a barge	25-50 years	Good	Moderately Complex	> $2,000	Low	Low
Groins	Significant, WPA Variance Required	Substantial	Protection of beach and dune resources with associated beach nourishment; however, this intertidal nourishment could cover fringing salt marsh	Constructability is straight-forward with the appropriate heavy equipment to place the armor units on the island	25-50 years (nourish every 3-5 years)	Fair-to-Good With Periodic Nourishment	Complex	> $1,000	Moderate To High	Low
Geotubes or Coir Fiber Rolls	Permitable with minimization of adverse impacts	Low To Moderate (if placed appropriately)	Protection of beach and dune resources with possible temporary protection of fringing salt marsh	Constructability is straight-forward with limited equipment on the island necessary to move the measures into place	Less than 1 year	Poor	Simple	Not Applicable	High	Low
Intertidal Cobble Nourishment	Permitable with minimization of adverse impacts	Significant	Protection of beach and dune resources, with possible protection of fringing marsh depending on rate of migration	The delivery and placement of gravel/cobble will require heavy equipment to operate on the island	3-5 years	Fair-to-Good With Periodic Nourishment	Complex	$500 - $1,000	Moderate	Low
Intertidal Segmented Breakwaters	Significant, WPA Variance Required	Moderate to Substantial	Protection of fringing marsh with limited protection of upland beach and dune resources	A shallow draft barge with a crane will be required to place the stones at the proper location or heavy equipment to operate on the island	25-50 years	Good	Moderately Complex	> $1,000	Low	Low
Intertidal Segmented Breakwaters with Nourishment	Significant, WPA Variance Required	Substantial	Protection of beach and dune resources with initial impacts to fringing salt marsh	A shallow draft barge with a crane will be required to place the stones at the proper location and heavy equipment to handle the nourishment on the island	25-50 years (nourish every 5-7 years)	Good With Periodic Nourishment	Moderately Complex	$1,500 - $2,000	Moderate	Moderate (west side)

D. Preliminary Shore Protection Recommendations

Based on the assessment of the alternatives summarized in Table 1, two possible shore protection strategies have been developed to protect the fringing salt marsh and upland island resources. Both plans include enhancement of the dune and upper beach with compatible material along the path of the existing dune ridge shown (in green) in Figures 8 and 9. In addition, both options include placement of armor stones to constrain the tidal channel leading to the lagoon (purple line shown in Figures 8 and 9). To protect the western shoreline, to different recommendations have been provided: Option 1 consists of a nearshore dike along the approximate mean low water line (red line in Figure 8) and Option 2 consists of intertidal headland structures placed near the high water line combined with nourishment in the lee of the structures (blue line in Figure 9). The shore protection recommendations are designed to be complimentary and implementation of the three options shown in either Figure 8 (Option 1) or Figure 9 (Option 2) should be performed together to maximize longevity of the upland and protection of the fringing salt marsh system.

The dune feature (shown in green on Figures 8 and 9) should consist of a mixture of sand, gravel, and cobble. Once reworked by the waves, it likely will readjust into a series of cobble-dominated ridges at the limit of storm wave uprush. The remaining surficial sediments along the seaward edge will tend toward the coarser range of the grain size and the landward side will likely contain the finer-grained component (likely dominated by wind-blown material). The length of the dune would be approximately 750 feet, with an average width of approximately 70 feet. Natural migration of the dune feature will supply sediments to the low-lying areas associated with the tidal flat in the middle of the island. Creation of this dune will gradually increase the elevation of this region (shown as "lagoon area" on Figure 8 and 9). It is anticipated that the crest of the dune feature would be somewhere between the 10-year and 25-year flood elevation (8.2 ft to 11.4 ft MLW). This should allow limited migration of the feature during typical storm conditions. Based on the cross-sections shown in Figures 10 and 11 (2000 data), fill depths along the eastern side of the island would be approximately 3 to 5 feet. The renourishment interval is estimated to be 3-5 years; however, this is strongly dependent on material grain size and storm frequency.

As mentioned above, armor stones also can be utilized to constrain the tidal channel leading to the lagoon. Due to the relatively small size of the lagoon, it is possible to reduce the channel cross-section significantly without adversely impacting the health of the marsh system. Placement of armor stones across a portion of the entrance will nearly eliminate wave activity in the lagoon and prevent continued loss of sediments from this region.

The first option to protect the western shoreline (Option 1) consists of a nearshore armor stone dike. This feature is intended to provide the recommended protection from predominate southerly and westerly waves during normal conditions. Due to the lack of existing dune feature along the western side of the island, the recommendation for shore protection along this shoreline is a low-lying dike in the vicinity of the mean low water line. This dike would consist of a single row of ~5 ton stones (approximately 4-to-5 feet in diameter) that would shelter the shoreline from waves during the range of typical daily tidal conditions at Ram Island. This should consist of a semi-contiguous row of stones to maximize shore protection without interfering with nearshore tidal circulation and habitat use by fish and other organisms. The length of the semi-contiguous structure would be approximately 1000 feet, with an average width of 5-to-8 feet depending on boulder placement.

Option 2 provides more substantial protection along the western shoreline by providing emergent armor stone headlands placed near the mean low water line. These breakwater features would extend a minimum of 2 feet above mean high water to nearly eliminate wave transmission over the structures during normal tidal conditions. As shown, approximately six 75 ft long structures would be required along the western shoreline, totaling approximately 450 feet of total structure length. Nourishment material would be placed in the lee of each structure and wave action would create the shoreline shape depicted by the light blue lines in Figure 9. As discussed in the Screening Process for Alternatives, the series of headland structures combined with the beach nourishment would provide more substantial protection from wave action for both the fringing marsh and the island interior.

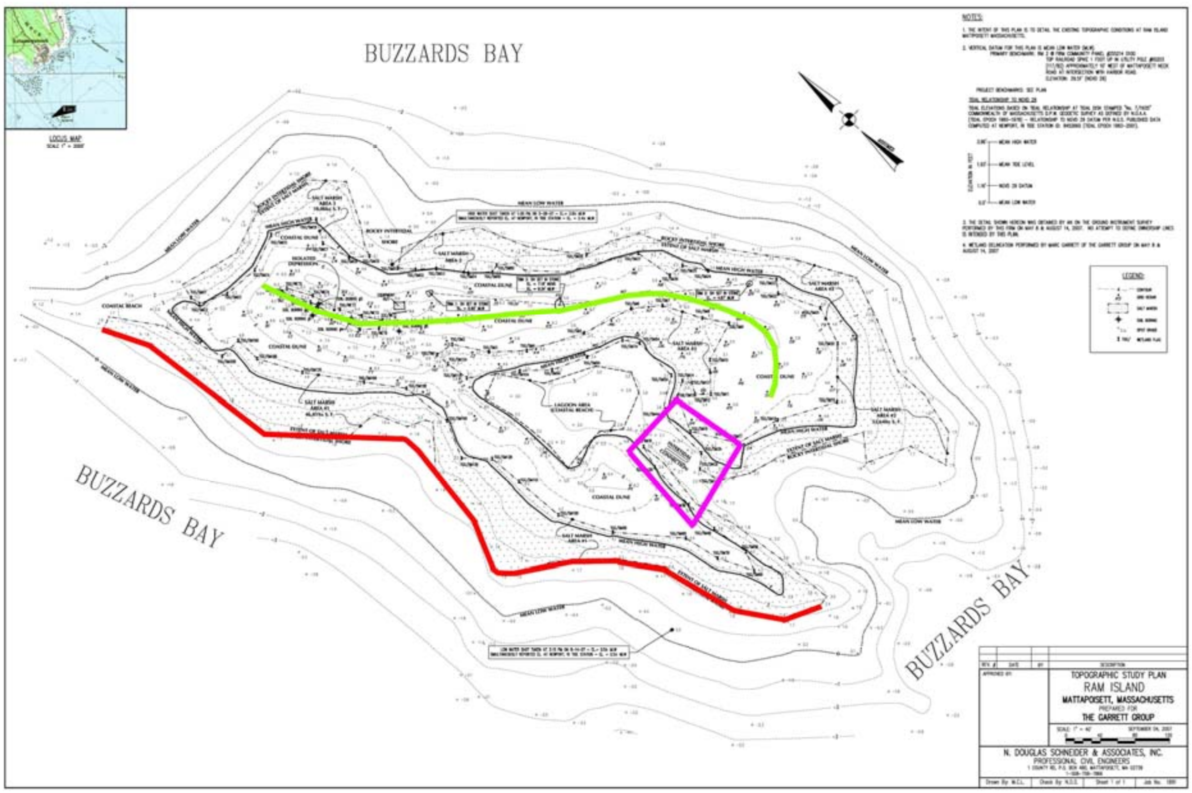

Figure 8: Option 1 shore protection at Ram Island include: (a) enhancement of dune and upper beach with sand/gravel/cobble nourishment (green line), (b) placement nearshore armor stones to constrain tidal channel into the lagoon area (general area shown by purple line), and (c) placement of a nearshore dike along the approximate mean low water line along the western side of the island to reduce wave action and enhance the existing salt marsh resource (red line).

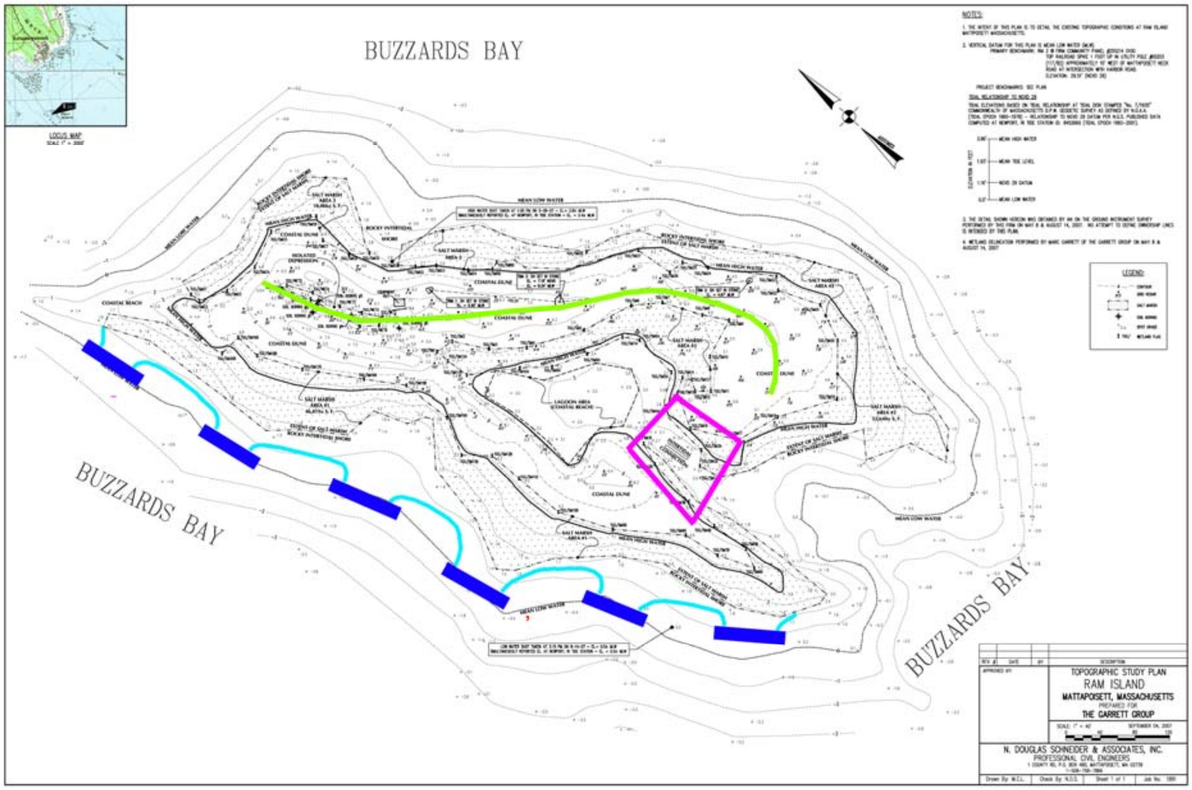

Figure 9: Option 2 shore protection at Ram Island include: (a) enhancement of dune and upper beach with sand/gravel/cobble nourishment (green line), (b) placement nearshore armor stones to constrain tidal channel into the lagoon area (general area shown by purple line), and (c) placement of a series of intertidal headlands/breakwaters (blue lines) backed by beach nourishment along the western shoreline (seaward limit shown as light blue lines).

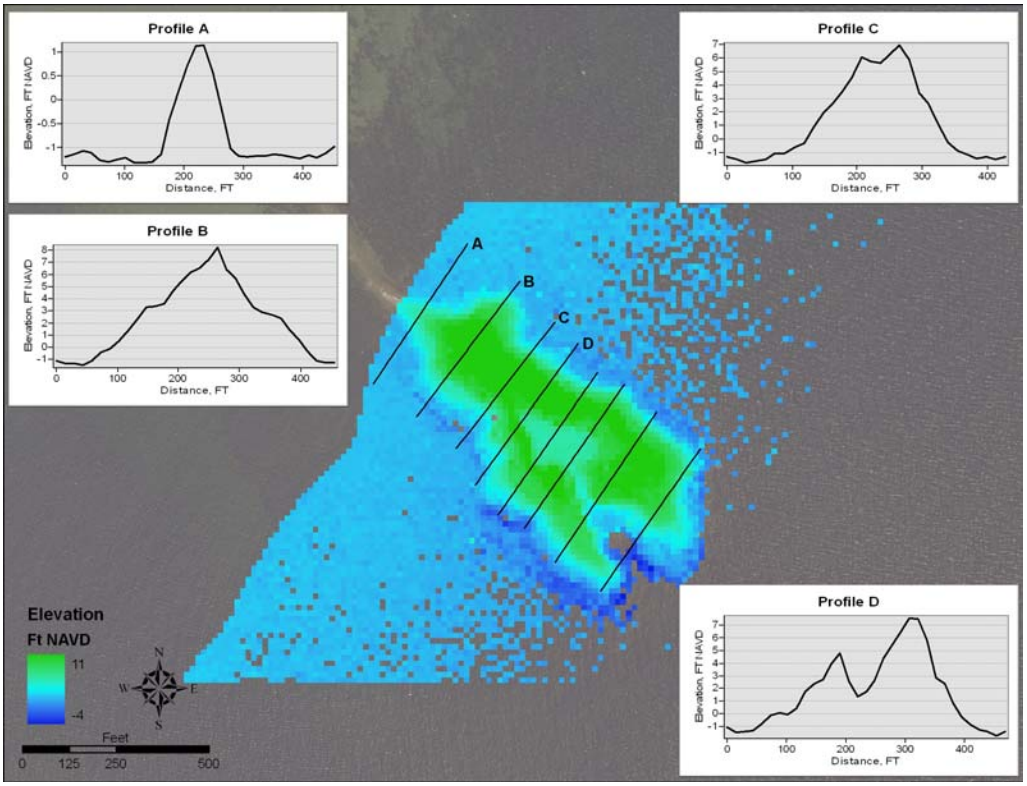

Figure 10: Selected cross-sections developed from the 2000 NOAA LIDAR data set.

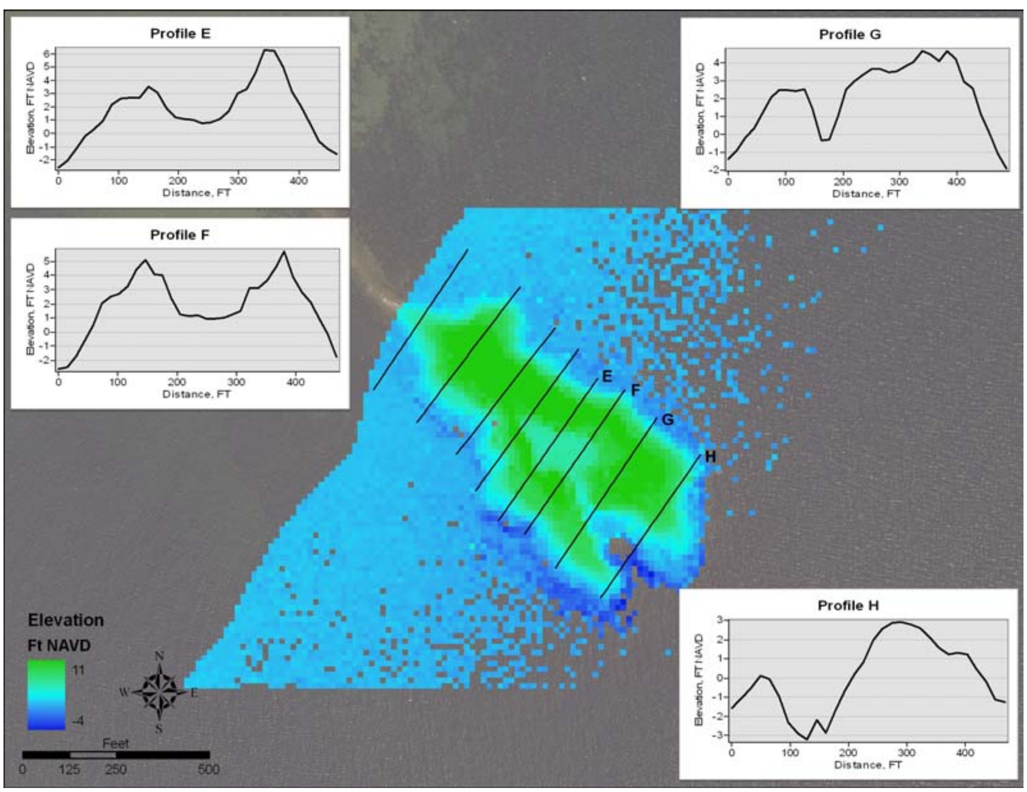

Figure 11: Selected cross-sections developed from the 2000 NOAA LIDAR data set.

F. Final Shore Protection Recommendations

After reviewing the Screened Alternatives and the Preliminary Shore Protection Recommendations the Technical Working Group recommended four (4) of the options for further consideration. The four alternatives selected are:

- Nearshore stone dike along the western side of Ram Island.
- Intertidal armor stone dikes within the entrance channel to the lagoon.
- Intertidal segmented headlands with nourishment in the lee of the structures along the western side of the island.
- Dune and upper beach enhancement with compatible nourishment material along the existing dune on the eastern side of Ram Island.

A nearshore armor stone dike along the western side of Ram Island would provide protection from predominate southerly and westerly waves during normal conditions. This would offer protection to fringing marsh with limited protection of upland beach and dune resources. The armor stone dike may also help to retain sediment eroded along the western side island in the area protected from open-bay wave conditions by the dike.

The armor stone dike would be a low-lying segmented structure constructed in the vicinity of the mean low water line (between -1 ft and -2 ft NAVD). The dike would consist of a single row of ~5 ton stones in order to resist movement up to a 25-year event. The armor stones would be approximately 4-to-6 feet in diameter and would shelter the shoreline from waves during most daily tidal conditions. Small gaps between the segments of the dike should be constructed to allow for nearshore tidal circulation and habitat use by fish and other marine organisms. The gaps can be designed to allow for minimal wave transmission beyond the structure. The overall structure would be approximately 800 to 1000 feet in length, with an average width of 5-to-8 feet depending on boulder placement. Figure 12 shows a conceptual layout of the nearshore armor stone dike. By creating a quiescent area landward of the structure, fringing Spartina alterniflora will become more stable along the southwestern shore of the island.

Construction of the dike would likely require use of a shallow draft jack-up barge equipped with a crane due to the armor stone size. The material could be delivered to the island by barge and either stock piled or placed directly in position on a continuous basis. An advantage of this construction method is the limited disturbance to the islands interior and fringing salt marsh since most construction activities would be water based. Placement of the armor stones along the approximate MLW contour will prevent direct long-term impacts to eelgrass beds surrounding the island. In addition, the use of jack-up barges will minimize temporary impacts to eelgrass beds, since the foot print of the “spuds” is negligible. The cost to construct the nearshore dike is approximately $325,000 to $400,000.

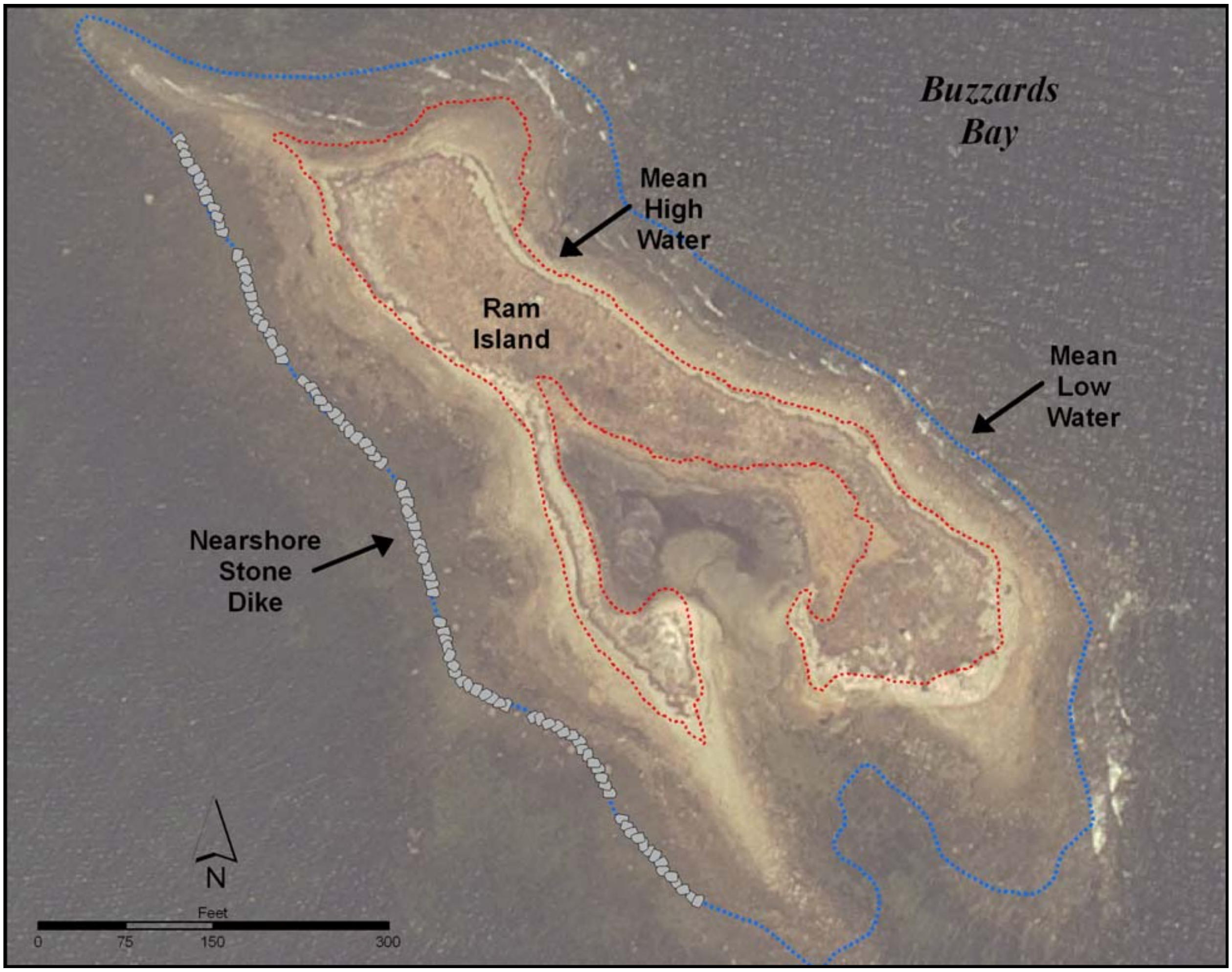

Figure 12: Nearshore stone dike protecting the shoreline of Ram Island. The dike is located along the western side of the island approximately at mean low water line to reduce wave action and enhance the existing salt marsh.

Constraining the inlet channel to the lagoon will reduce the channel cross-section significantly without adversely impacting the health of the marsh system. At present, the inlet to the lagoon is significantly larger then necessary for effective tidal exchange allowing wave energy to erode upland sediments. Placement of armor stones across a portion of the entrance will nearly eliminate wave activity in the lagoon and lessen the continued loss of sediments from the interior of the island. Protecting the interior of the lagoon will help to stabilize the fringe salt marsh and enhance the habitat. However, the stabilization of the inlet will not help to stabilize and reduce erosion along the perimeter of the Ram Island.

The inlet will be constrained using a series of low profile stone dikes within the lagoon channel. Figure 13 shows a conceptual layout of the stone dikes. The overlapping structures protect the interior of the lagoon while preserving the natural tidal exchange of water in the lagoon.

The cost associated with constraining the inlet is the lowest of the four alternatives presented, due to the limited amount of materials and time required to construct the project. Though the project will require similar complex and costly logistics involved with transporting materials and equipment to the island that the other alternatives require, which keep the costs relatively high when considering the overall area protected. Constraining the inlet would be most beneficial if combined with the construction of one of the other alternatives. The other three alternatives require significant volumes of material to be delivered to the island. By sharing the logistical costs with one of the alternatives that stabilizes a larger percentage of the island, dikes in the lagoon entrance channel become more cost effective.

The cost developed for constraining the inlet is approximately $35,000 to $45,000. This assumes that a landing craft can be utilized to deliver a small front end loader and stone to the island without constructing a pier for offloading. If a more complex delivery method (barges, piers, etc.) is required, the cost will increase substantially.

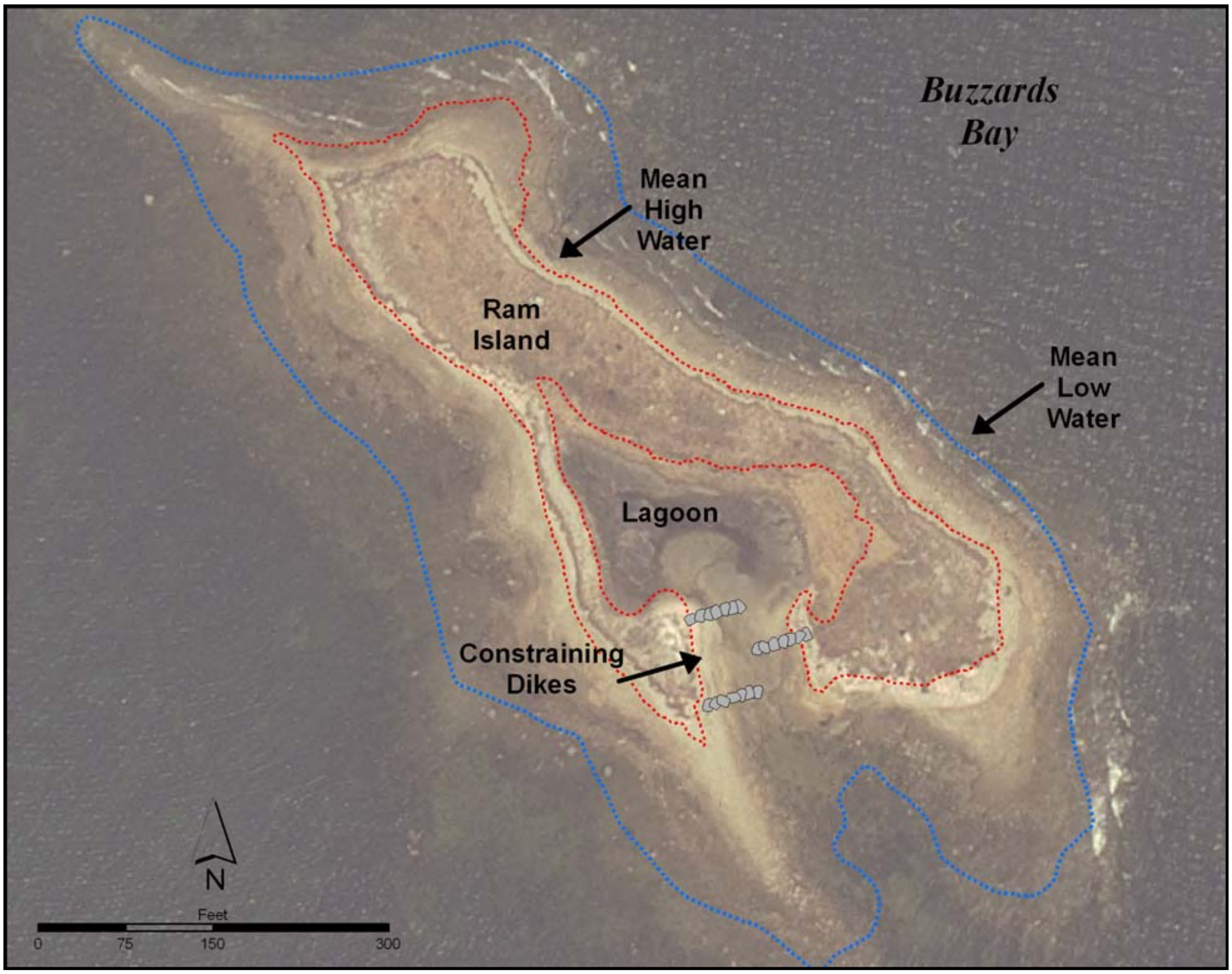

Figure 13: Constraining dikes protecting the inner lagoon on southwest side of Ram Island. Stone dikes will constrain tidal channel into the lagoon area protecting the area from wave intrusion.

Intertidal segmented breakwaters (or headlands) with nourishment in the lee of the structures along the western side of Ram Island would provide the most substantial shoreline protection for Ram Island. The emergent armor stone breakwaters would be placed in the vicinity of the mean low water line and would extend a minimum of 2 feet above mean high water to nearly eliminate wave transmission over the structures during normal tidal conditions. There would be 6 individual breakwaters; each breakwater would be approximately 75 feet in length. The nourishment material would be placed in the lee of the structures and allowed to naturally redistribute. Waves would defract in the lee of the breakwaters, redistributing the material into the crenulate shoreline shapes depicted by the yellow line in Figure 14. After equilibration of the nourishment, the breakwaters combined with the nourishment would provide substantial protection from wave action for both the fringing marsh and the island interior. In addition, the expanded shoreline in the lee of the structures will create a quiescent region for further establishment of salt marsh.

Construction of the breakwaters would be completed in a similar manner to the nearshore dike. A shallow draft jack-up barge equipped with a crane would be used to construct the breakwaters. Once construction of the breakwaters is completed the shoreline along the western side of the island would be nourished. Due to the coarse grained nature of the nourishment material (cobble, gravel, and sand) mechanical delivery of material is more likely than hydraulically pumping from a hopper or barge. The nourishment will require approximately 5,800 to 6,200 cy of material to fill the lee of the structures to approximately 2 feet above mean high water. Delivery of that volume of material is logistically complex, requiring a temporary pier and conveyor system to move the material onto the island. A front end loader will be utilized on the island to place and grade the nourishment material. The estimated cost for the breakwater and fill is approximately $1,400,000 to $1,700,000.

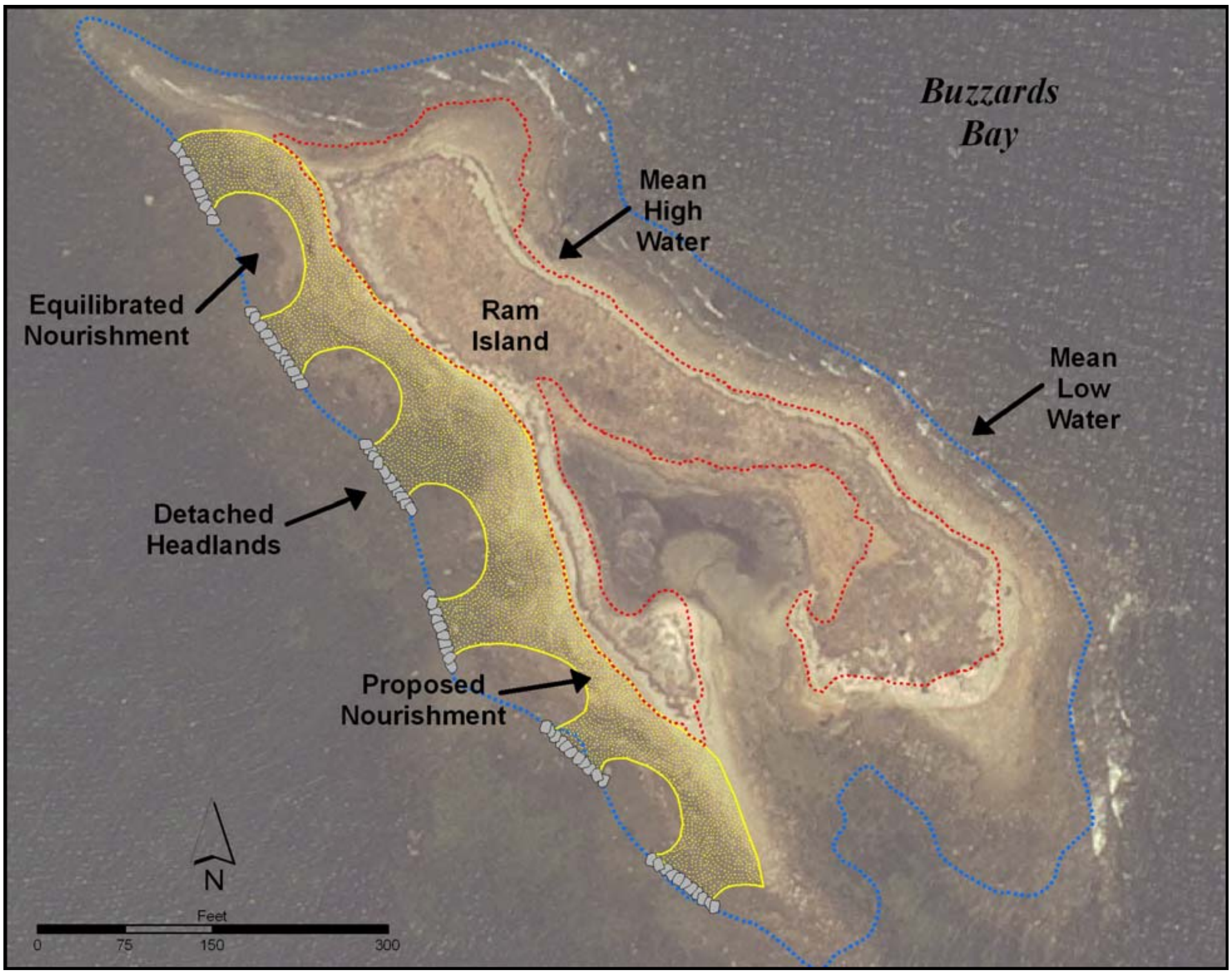

Figure 14: Nearshore breakwaters (headlands) with sand and cobble nourishment in the lee of the structures.

The upper beach and dune enhancement along the eastern side of Ram Island should consist of a mixture of sand, gravel, and cobble. Over time the material will be naturally reworked by waves, readjusting across the active profile into a series of cobble-dominated ridges at the limit of storm wave uprush. The remaining material on the seaward face will be sorted across the profile into smaller ridges depending on grain size. Along the landward side of the dune, material will periodically migrate into the low-lying areas of the island. The dune would run the length of the eastern side of island (approximately 750 feet), with an average width of approximately 70 feet. The crest of the nourishment would fall slightly below the 25-year flood elevation at an elevation of +10 feet NAVD with a 30 foot crest width. The initial fill template would have 3H:1V slopes transitioning into the natural profile of the island. Figure 15 shows a typical cross section of the island with the construction template for the nourishment, a plan view is shown in Figure 16. The approximate volume of nourishment would be 6,000-7,000 cy of material. This would provide a renourishment interval of approximately 3-5 years; however, this is strongly dependent on material grain size and storm frequency. It is anticipated that the renourishment volume would be approximately 50-percent of the initial fill volume.

Construction of the upper beach and dune nourishment would require the construction of temporary pier and conveyor system to facilitate the delivery of nourishment material onto the island from delivery barges. Hydraulically pumping the nourishment material into place would be difficult due to the coarse nature of the material required; therefore a mechanical means will likely be used. A front end loader would be required to transport and grade the nourishment material. The use of the loader could be limited to the eastern side of the island to minimize the disturbance to the interior and fringing marsh along the western side of the island. After the placement of the nourishment, the crest of the dune could be planted with natural vegetation to reduce erosion and aid in the restoration of the natural habitat. The estimated cost for the upper beach and dune nourishment is approximately $540,000 to $650,000.

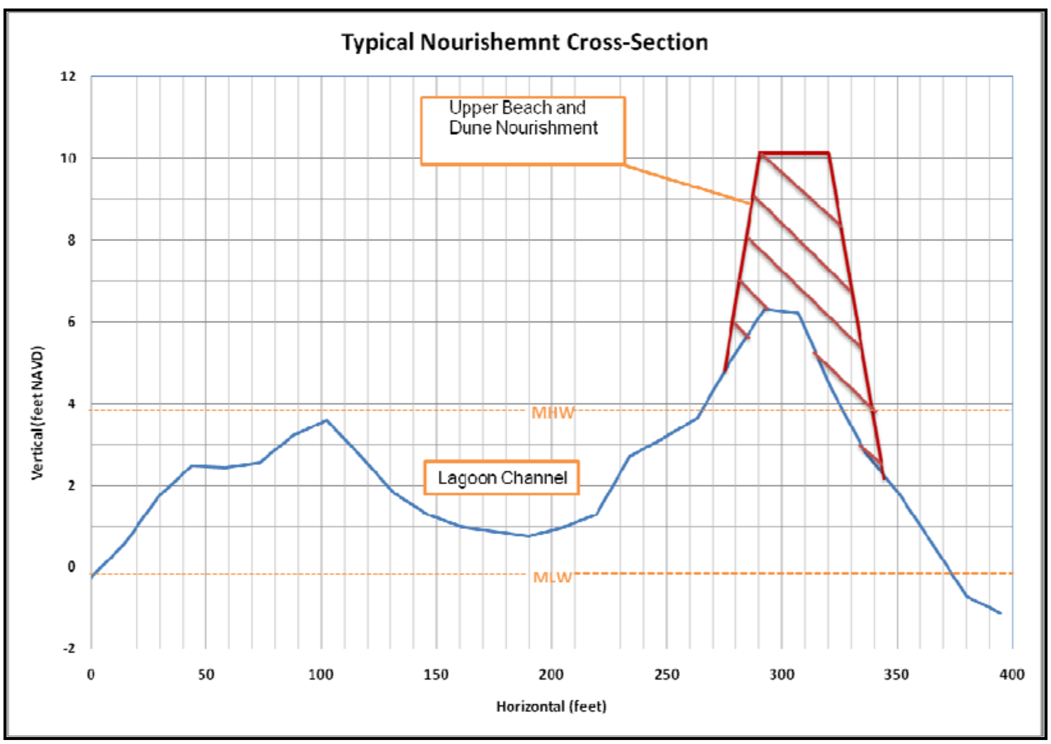

Figure 15: Typical nourishment cross section for dune and upper beach enhancement along the eastern side of Ram Island.

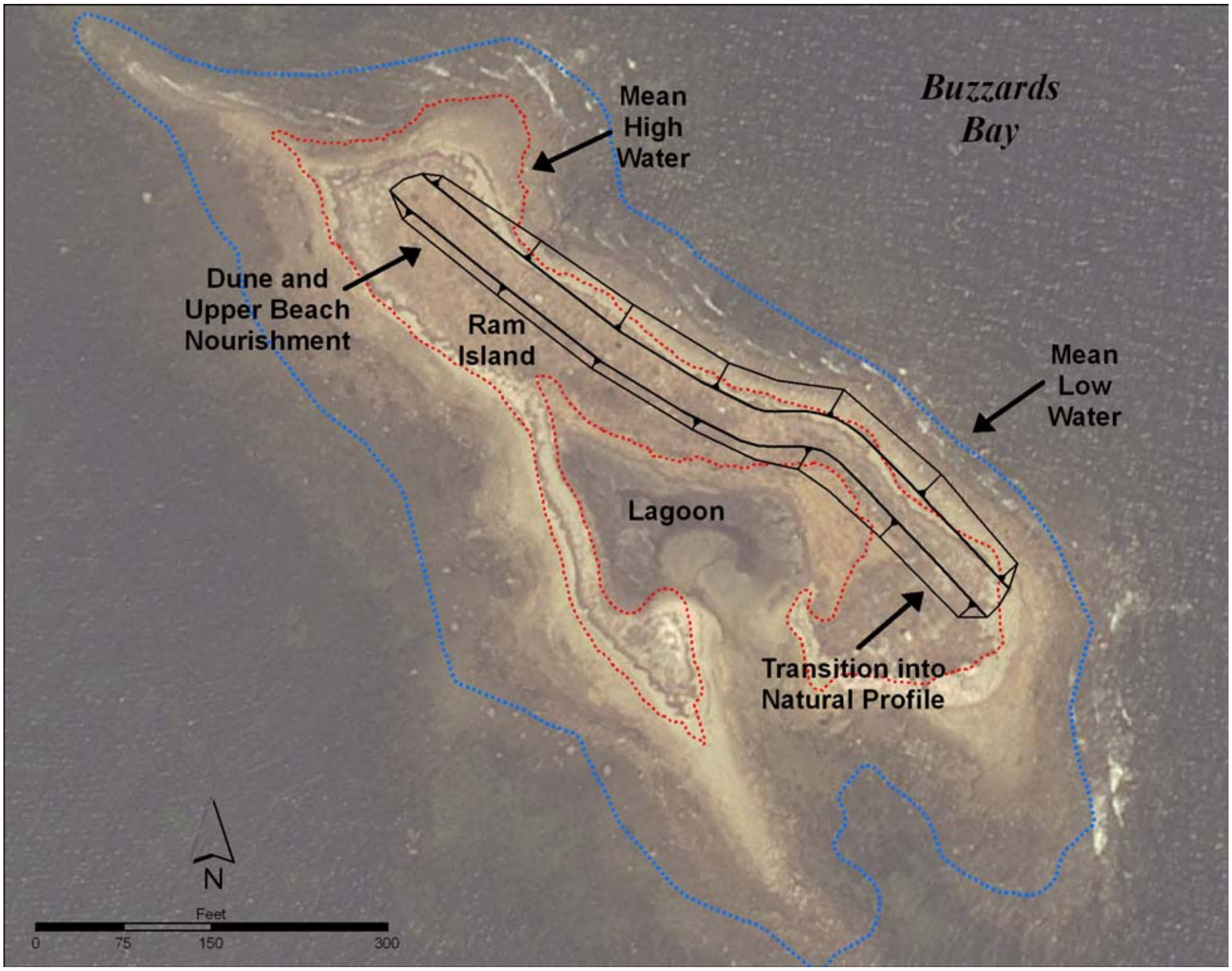

Figure 16: Dune and upper beach enhancement with compatible nourishment material along the existing dune on the eastern side of Ram Island.

Each alternative could be constructed as a stand-alone shore protection project; however that approach would have limited benefits to overall island stability. A combined approach with upper beach and dune nourishment along with structural enhancements would extend the longevity of the island and the unique nesting habitat of Ram Island. Without action to stabilize and restore Ram Island, the island will likely disappear over the next 40 to 60 years. The recommend approach for stabilizing and enhancing Ram Island is to incorporate the upper beach and dune nourishment with the intertidal breakwaters and nourishment. Both the eastern and western sides of Ram Island will be afforded protection during typical wave conditions and even during minor coastal storms. The addition of approximately 12,000 cy of nourishment will temporary offset the continued loss of material from the island and allow the island to more readily respond and recover from significant storm events.

Existing environmental regulations will make permitting the breakwater structures problematic, due to the potential impacts to land under the ocean and salt marsh resources. Regardless, it should be possible to justify the structures due to the long-term shore protection afforded to Ram Island and more importantly the protection and enhancement of roseate tern habitat.

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Appendix A. Wave Study

Wave Modeling Analysis

For the wave analysis portion of the study, nearshore wave heights and directions within Buzzards Bay were estimated using the SWAN wave model. The wave model was used to simulate the propagation of offshore waves and the generation local wind waves to the shoreline fronting Ram Island. Wind and offshore wave data available from U.S. Army Corps of Engineers Wave Information Study (WIS) were used to derive input wind and wave conditions for SWAN. The results of the wave modeling were used to gain a general understanding of the nearshore wave conditions under different storm conditions. The resulting wave heights and directions were used to inform the discussion of alternatives contained in the main report.

The interaction of wind with the water surface generates waves. The forces of gravity, and to a lesser extent surface tension, allow waves to travel long distances across the sea surface. Waves are primarily responsible for sediment transport in the nearshore zone and for subsequent shoreline change; therefore, waves are of fundamental interest to determine the potential effects and stability of any proposed modifications to the shoreline.

As waves enter the nearshore zone, varying seafloor topography causes the characteristics of waves (e.g., height and direction of travel) to change. As waves enter shallow water, their height increases (shoaling), and the direction of travel bends toward the coast so that wave crests become more parallel to the shoreline (refraction). As waves approach the shore, shoaling and wavelength modifications cause the wave height to increase and waves to steepen. Eventually wave steepness causes the wave to become unstable and break, which dissipates wave energy. Energy also is distributed along a wave crest by a process called wave diffraction. Together, wave shoaling, refraction, diffraction, and breaking can focus wave energy on particular areas, depending upon the characteristics of nearshore bathymetry.

In general, waves that impact the shoreline at Ram Island are generated locally by winds blowing across the water surface of Buzzards Bay. Ocean waves and swell can propagate into Buzzards Bay from the southwest. However, the relatively narrow entrance, complex bathymetry and irregular coastline (bays, peninsulas, and rocky outcroppings) of Buzzards Bay result in a significant amount of energy dissipation as waves travel to the northeast. Is this sense, Ram Island is relatively sheltered by its location far up the bay and close to the northern shoreline.

Wave Model Boundary Conditions

To quantify the impact of both the offshore waves and locally generated wind waves, both wind and wave information from the US Army Corps of Engineers Wave Information Study (WIS) was utilized to define the boundary conditions for the SWAN wave model. WIS contains time series information of spectrally-based, significant wave height, peak period, peak direction, and wind speed and direction produced from a computer hindcast model for the period 1980-1999. The data obtained from WIS allowed for the specification of localized wind conditions (within Buzzards Bay) along with offshore wave (ocean) conditions along the southern and western boundaries of the model. Figure A shows WIS Station 79 (purple marker) which was selected to define the boundary conditions within the wave model.

Plots of the wave height and wind data for the 20-year WIS record, from 1980 to 1999, are shown in rose plots contained within Figure B.

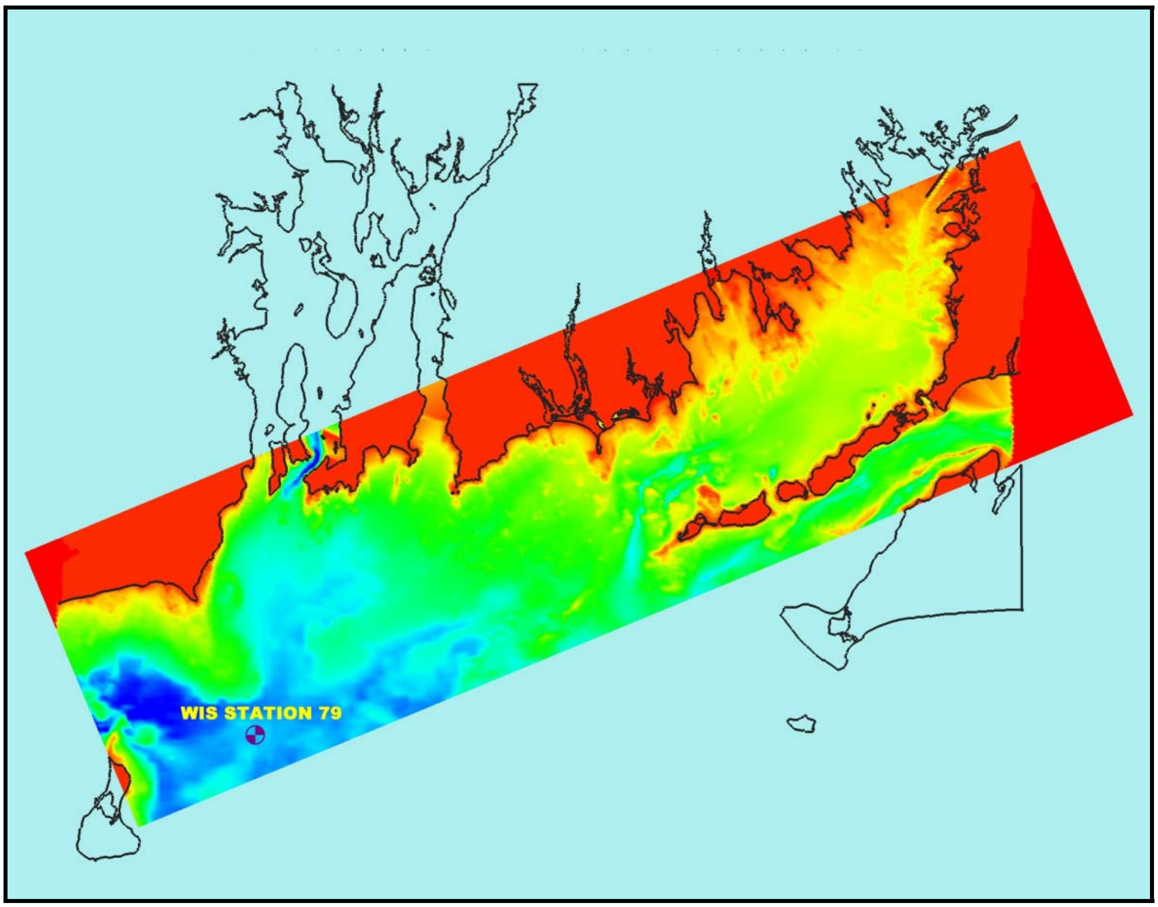

Figure A. Location of the WIS station used to define the boundary conditions for the wave model.

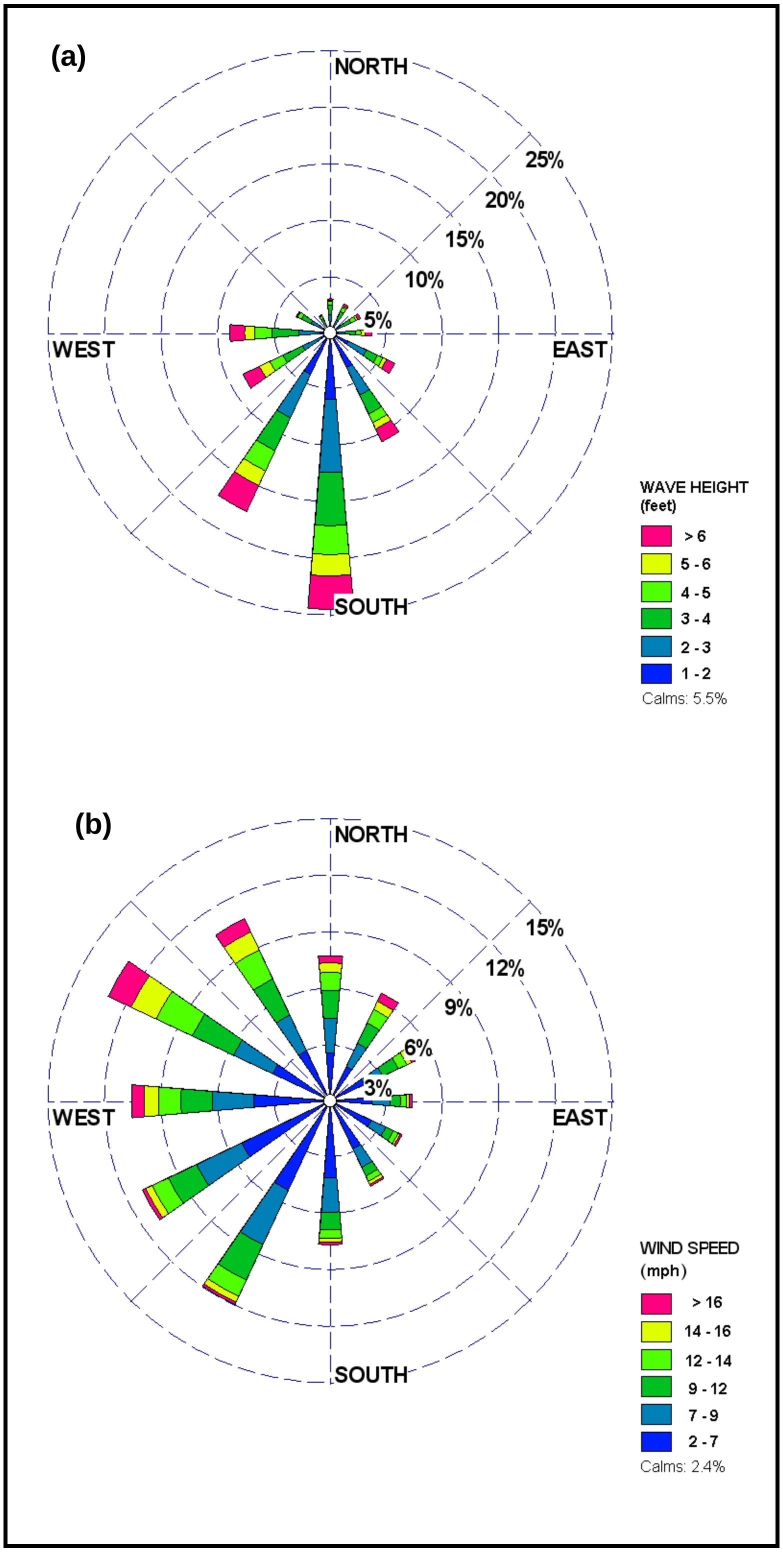

Figure B. Rose plots showing (a) wave height and (b) wind speed for WIS station 79 from 1980 to 1999.

The wave rose plot clearly shows that a majority of the offshore wave energy approaching the southern coastline of Massachusetts is incident from the south and the southwest. Wave energy approaching from the east and north directions are significantly reduced due to the limit fetch distances and sheltering from land that occurs in those directions. Offshore waves from the remaining directions are not a concern at Ram Island due to the sheltering provided by the Elizabeth Islands and the coastline of southern Massachusetts.

The winds are more evenly distributed directionally, with a predominance of wind conditions approaching out of the western reaches. With the shoreline orientation at Ram Island, winds from WSW around to E are capable of generating waves that will impact the shoreline.

The boundary conditions for the coarse wave model were based on the wind data in the WIS dataset. The initial step in defining the boundary conditions involved sorting the wind records from the WIS dataset by direction into 45 degree angle bins. With the wind data sorted into bins, a return period analysis was performed on wind velocities for each of the 8 directional bins. The hindcast wave heights associated with each of these return period wind conditions was also extracted from the WIS dataset. To be exact, these wave heights are not the 2-, 5-, 10-year etc. return period wave heights, rather they are the hindcast waves associated with the return period winds from each angle band at the location of WIS Station 79. The results of this analysis are shown below in Table A.

Table A - Return Period Wind Speed and Associated Wave Heights per Angle Band for WIS STATION 79

Return Period (years)	Wind Direction							
	N	NE	E	SE	S	SW	W	NW
	Wind Speed (mph)							
2	41.1	41.0	38.5	36.2	38.5	37.6	42.0	41.7
5	46.6	46.4	47.1	40.1	43.3	42.0	45.2	46.3
10	50.2	50.0	52.9	42.7	46.4	44.8	47.4	49.4
25	54.8	54.4	60.1	46.0	50.4	48.5	50.0	53.3
50	58.2	57.8	65.5	48.5	53.4	51.1	52.0	56.1
100	61.6	61.1	70.9	50.9	56.3	53.8	54.0	59.0
Return Period (years)	Wind Direction							
	N	NE	E	SE	S	SW	W	NW
	Wave Height (feet)							
2	7.6	8.7	11.7	12.2	13.8	14.2	11.5	8.2
5	9.3	11.2	14.5	15.2	16.8	17.4	14.7	10.1
10	10.4	12.8	16.4	17.2	18.7	19.6	16.7	11.4
25	11.7	14.8	18.7	19.7	21.2	22.3	19.4	13.0
50	12.8	16.4	20.5	21.5	23.0	24.4	21.3	14.1
100	13.8	17.9	22.2	23.4	24.8	26.4	23.3	15.3

In addition to wind and wave conditions at the model boundary, water level also plays a major role in influencing wave heights at Ram Island. The Feasibility Report prepared by the Garrett Group reports the common tidal datum values in addition to the 10-, 50-, and 100-year return period water levels. These return period water levels were checked against the USACE Flood Profiles for New England and were found to be accurate. For this report, additional analysis was performed to provide the intermediate return period water levels for the 2-, 5- and 25-year events. A summation of this data is provided in Table B below.

Table B – Return Period Water Levels for Ram Island	
Return Period, years	Elevation (ft), MLW
100	14.8
50	12.9
25	11.4
10	8.2
5	7.6
2	5.9
1	5.5
MHW	3.9
NGVD	1.2
MLW	0

To augment the investigation of water levels at the site, an extremal analysis of water levels at Woods Hole was performed to determine the return period of the ten highest annual water levels recorded at that station. Hourly tide data from the Woods Hole station only span 50 years but maximum storm surge elevations available for historical storm events between the 1930's and 1950's extend the span of this records. The annual maximum tide elevations together with the supplementary storm data provided the basis for this analysis. The ten highest annual water levels where determined for the Woods Hole station. These elevations are listed in Tables C together with the return period determined for each individual event. It is apparent in the listed storm events that extreme water levels at Woods Hole are heavily influenced by hurricanes. This is in contrast to water levels along the Cape Cod and Massachusetts Bay shorelines, where northeasterly events play an equal role in extreme water levels. The data from Woods Hole show that for Buzzards Bay extreme water levels are relatively infrequent and are associated with hurricanes, while the more frequent and less severe events are from the east and northeast.

Table C - Ten highest maximum annual water elevations from the tide record from Woods Hole. Return periods are based upon the published elevations of the FEMA analysis for Falmouth, MA (FEMA, 1986).		
date	ft, NGVD	return period (yr)
September 21, 1938	10.5	77
August 31, 1954	9.9	61
September 14, 1944	6.8	20
August 19, 1991	6.3	16
September 12, 1960	5.2	11
December 2, 1974	4.8	9
January 10, 1997	4.7	9
January 23, 1987	4.7	9
January 9, 1978	4.7	9

The final scenarios chosen for the wave modeling were the 2-, 5- and 25-year return period events. Both the wind speed, direction and wave height were input to the coarse model grid for each of the three return periods. In addition, the relevant water level for each return period was used in the model. Understanding that the highest point on Ram Island is just greater than 7' MLW, the 2-year water level (see Table B above) falls more than a foot below this point, while the 5-year water level creates a condition where the entire Island becomes submerged. The final 25-year water level sees Ram Island submerged under nearly 4 feet of water. Of particular interest in the formulating the design recommendations are the incident wave heights on the east and southwest faces of Ram Island under these varying water levels and wave conditions.

Wave Model Setup

SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. SWAN was developed by the Delft University of Technology. Version 40.51 of the model incorporates the state-of-the-art formulations for the deep water processes of wave generation, dissipation and the quadruplet wave-wave interactions from the WAM model (Komen *et al*., 1994). In shallow water, these processes have been supplemented with the state-of-the-art formulations for dissipation due to bottom friction, triad wave-wave interactions and depth-induced breaking. SWAN is fully spectral (in all directions and frequencies) and computes the evolution of wind waves in coastal regions with shallow water and ambient current. SWAN accounts for the following physics:

- wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth, wave generation by wind.
- Three- and four-wave interactions.
- White-capping, bottom friction and depth-induced breaking.
- Wave-induced set-up.
- Propagation from laboratory up to global scales.
- Transmission through and reflection against obstacles.
- Diffraction.

The wave modeling consists of a regional coarse model grid (200m x 200m grid cells) covering Buzzards Bay as well as a fine grid (25m x 25m grid cells), which provide a detailed solution in the area around Ram Island. The solution from the coarse wave model is transferred onto the offshore boundary of the fine grid, providing a detailed and spatially varying boundary condition for the fine grid runs.

The southern and western limits of the coarse grid (the largest rectangle in Figure C) were chosen so that the offshore waves approaching from the southern directions would be able to propagate into Buzzards Bay. The remaining lateral extents of the grid were chosen to encompass the extents of Buzzards Bay that would be significant for locally generated wind waves. The boundaries of the coarse grid are taken far enough away from the fine grid so as to ensure that the solution at the boundary of the fine grid is free of any edge effects. The solution from the coarse wave grid was used only to formulate the boundary conditions for the fine wave grid.

The fine wave model grid domain was chosen to provide sufficient amount of detail in the area around Ram Island to closely examine the wave patterns along the shoreline. The grid is comprised of 25m x 25m grid cells, which allows for sufficient resolution to describe the island, the complex bathymetry, and the irregular shoreline along this section of coastline.

Bathymetry data were obtained from National Ocean Service (NOS) Office of Coast Survey data hydrographic survey archive. The NOS bathymetry data were interpolated into the Cartesian grids for both the coarse and fine grids. The grids were then used as the basis for the wave simulations. The final interpolated grid bathymetries for the coarse and fine grids are presented in Figure D and Figure E, respectively.

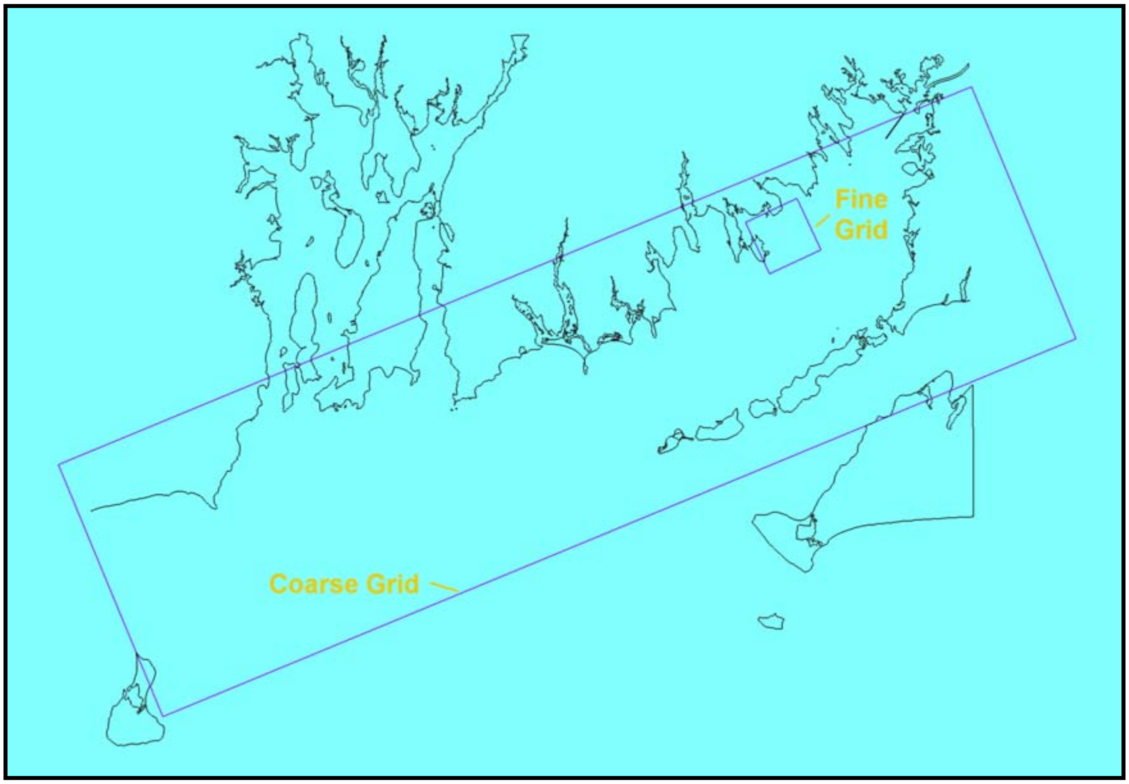

Figure C. The extents and domains of the coarse and fine wave model grids.

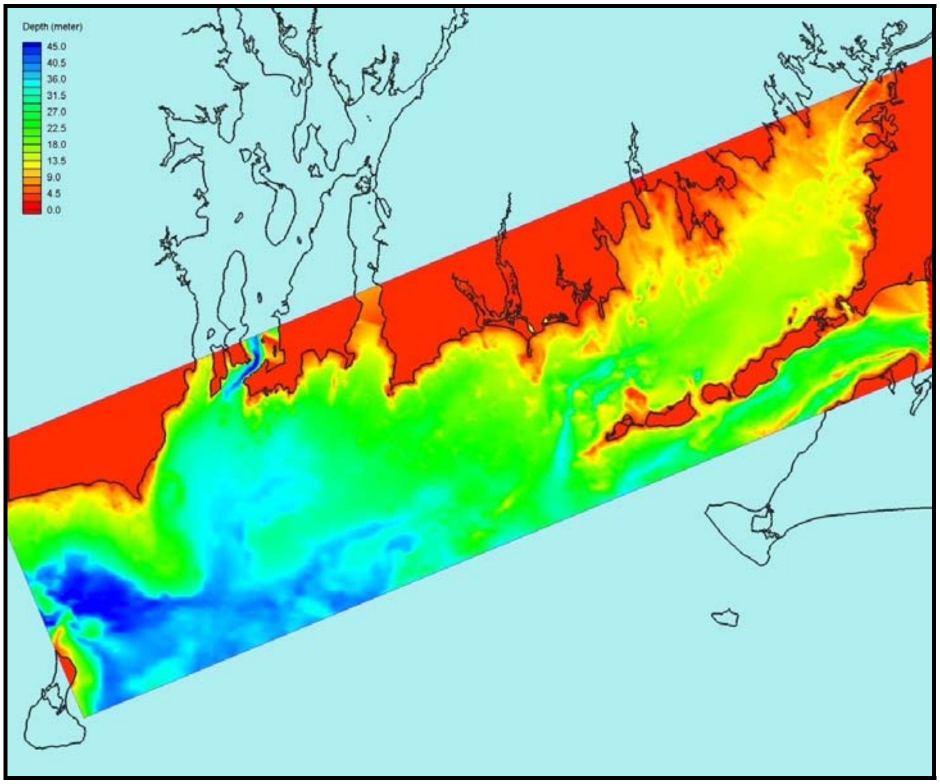

Figure D. NOS bathymetric data interpolated to the coarse wave model grid. Depths are in meters.

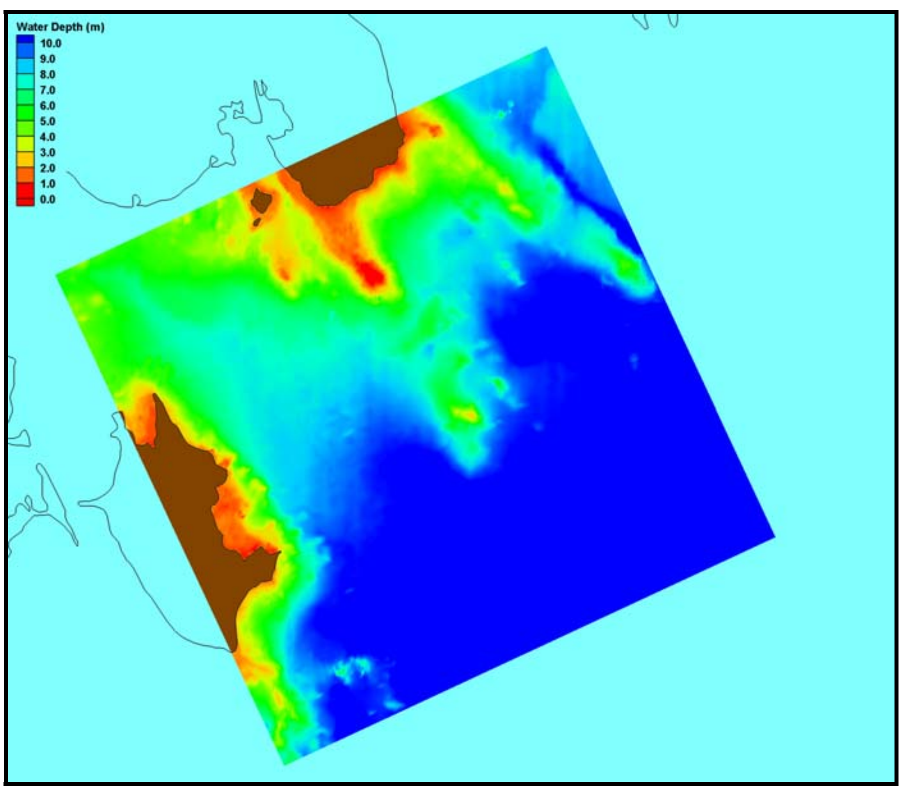

Figure E. NOS bathymetric data interpolated to the fine wave model grid. Depths are in meters.

Wave Model Results

The results from the coarse wave grid were used solely to provide boundary conditions for nested model grid. However, examining the results of the coarse model provides useful insight into the propagation of waves into Buzzards Bay.

Figures F and G, show waves throughout Buzzards Bay and Rhode Island Sound under southwest and northeasterly conditions respectively (2-yr return period). For the southwest conditions (Figure F), waves entering Buzzards Bay from Rhode Island Sound are quickly dissipated due to refraction along the north and south sides of the Bay. The complex shoreline and bathymetry limits the contribution of ocean waves and swell to the overall wave climate within the central and northern reaches of Buzzards Bay. This results in conditions where the wave climate in the upper Bay is dominated by waves generated locally rather than what has traveled in from Rhode Island Sound. This figure also demonstrates the significant sheltering effect provided by Elizabeth Islands. Ram Island is situated in the upper reaches of the bay and experiences significant reductions in wave energy compared to the shorelines to the west along the Rhode Island coast.

Figure G shows a northeasterly condition where the landmass of Cape Cod provides immediate sheltering for Buzzards Bay. The limited fetch and relatively narrow width of the Bay serve to hinder wave growth, with wave heights only increasing significantly south and west of Cuttyhunk Island at the mouth of Buzzards Bay.

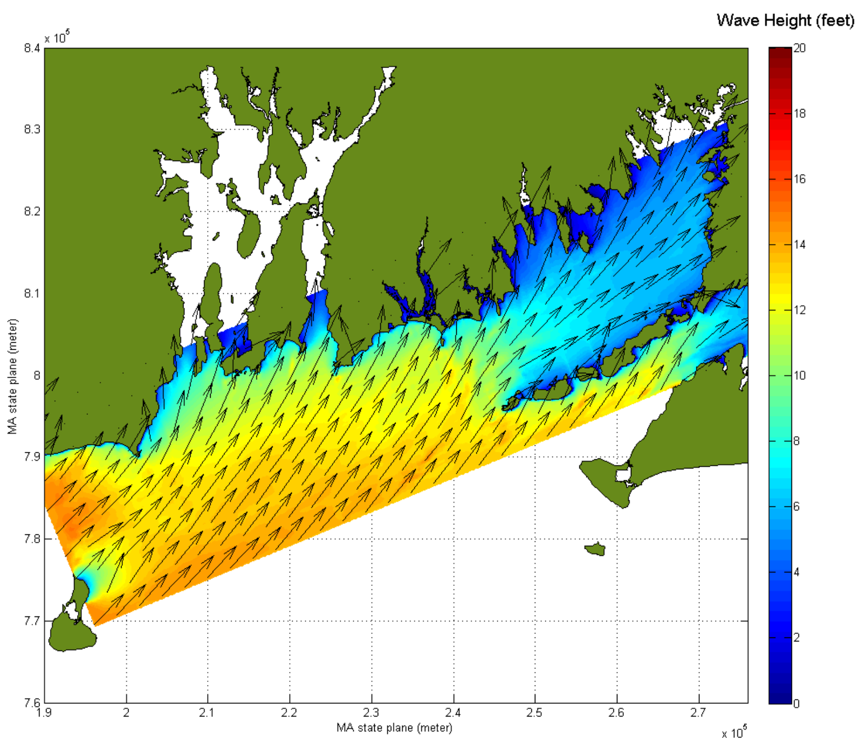

Figure F. Coarse grid model results. 2-yr event from the southwest.

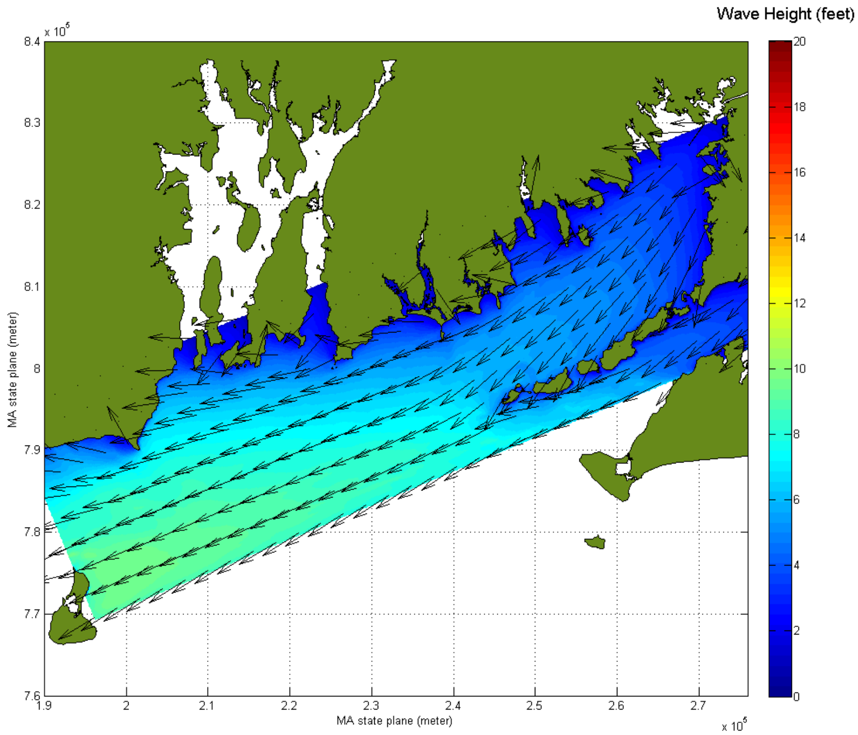

Figure G. Coarse grid model results. 2-yr event from the northeast.

Figure H below shows the fine model results for the same 2-yr southwest conditions as Figure F above (Note: there are different limits for the color scale bars on the coarse and fine wave model figures). This figure shows the important role that West Island plays in sheltering Nasketucket Bay and Ram Island from waves incident from the southwest quadrant. For the conditions shown in Figure H, Ram Island falls right along the boundary of higher wave heights further to the southeast and the fully sheltered waters to the west. This indicates that wave conditions at Ram Island are highly dependent on incident direction as well as water level. It is also clear that whichever side of the island is windward will understandably be subjected to higher wave heights than those parts of the island which remain somewhat sheltered.

Figure I below shows the fine model results for the same 2-yr northeast conditions as Figure G above. Wave heights on the whole are smaller throughout the area primarily due to the limited fetch to the northeast. Despite the lower wave climate in the area in general, the eastern face of Ram Island is actually subject to higher wave heights (3.1 feet) under these conditions, when compared to the southwest case above (Figure H) where the eastern face sees wave heights of only 2.2 feet. Conversely, the southwest face of Ram Island is subject to wave heights of 2.5 feet when winds are from the northeast but 3.3 feet with winds from the southwest.

For comparison with the 2-year conditions, some results from the 25-year wind and water level conditions are presented in Figures J and K. Winds from due east result in the largest wave heights impacting the eastern shore of Ram Island. Figure J shows the wave heights and directions for the 25-year event from the east where a wave height of 6.1 feet is incident on the east side of Ram Island. To the east of Ram Island wave heights are uniformly at 7-8 feet. Despite a surge level of 11.4 feet above MLW, the limited fetch across the width of Buzzards Bay limits the height of the waves impacting Ram Island.

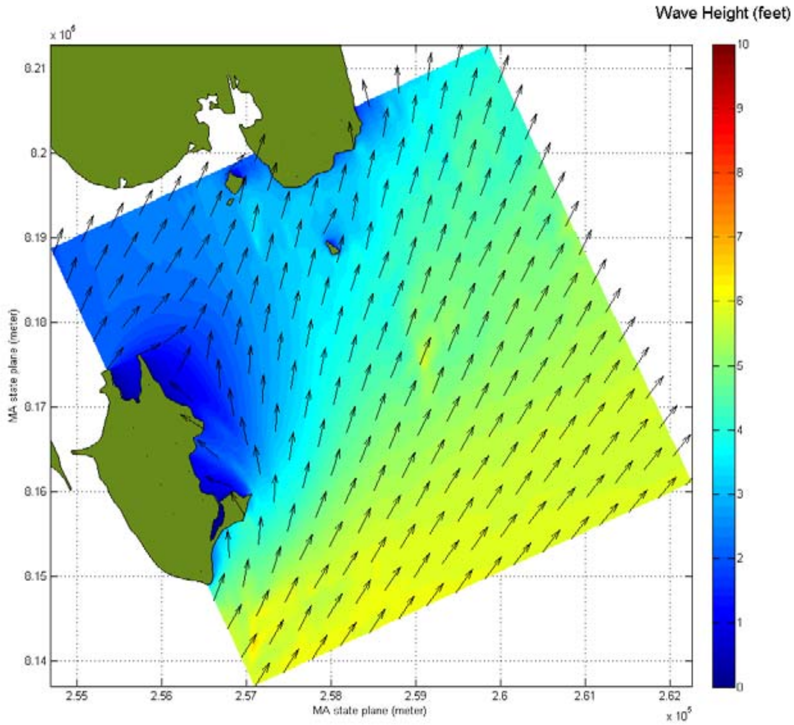

Figure H. Fine grid model results. 2-yr event from the southwest.

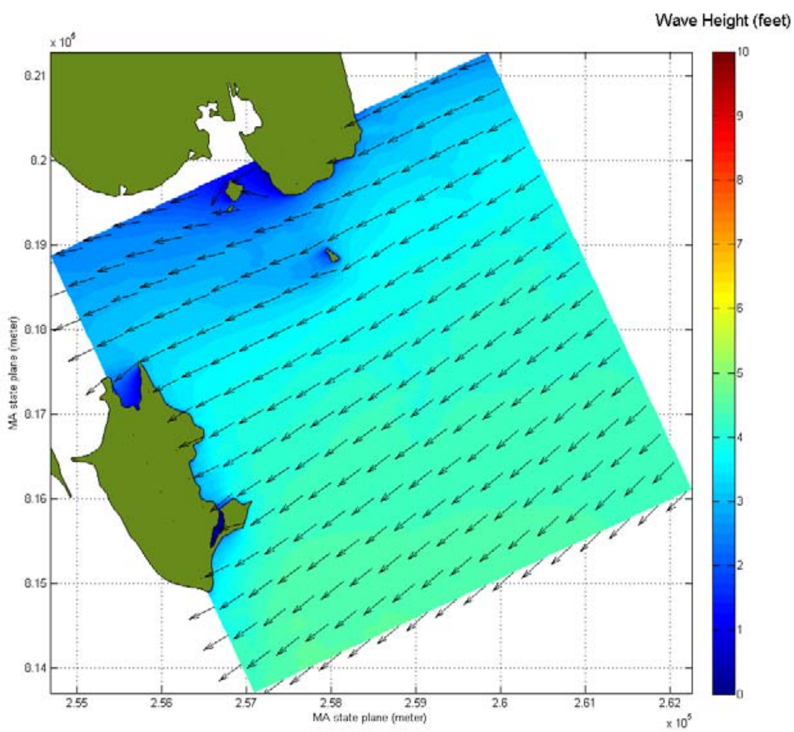

Figure I. Fine grid model results. 2-yr event from the northeast.

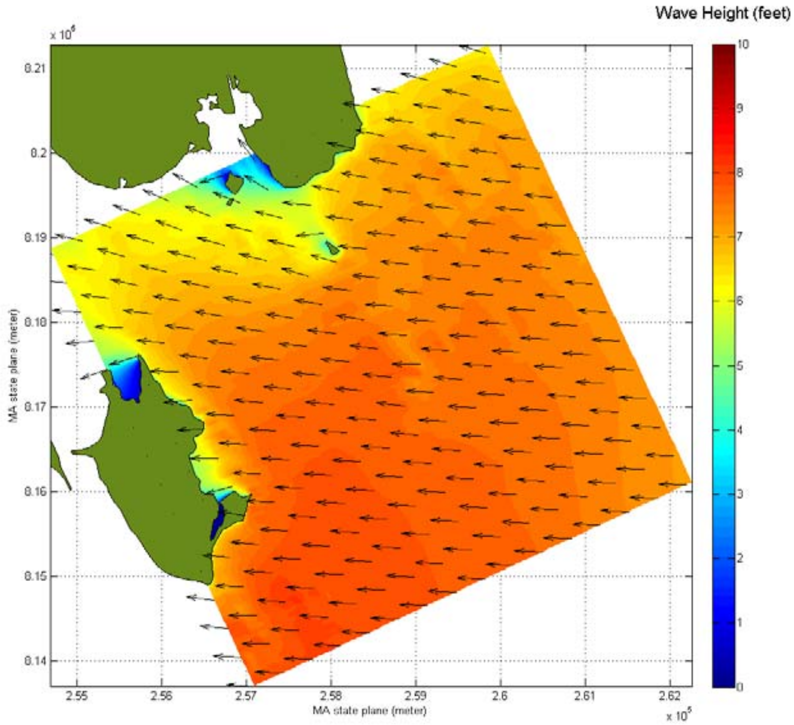

Figure J. Fine grid model results. 25-yr event from the east.

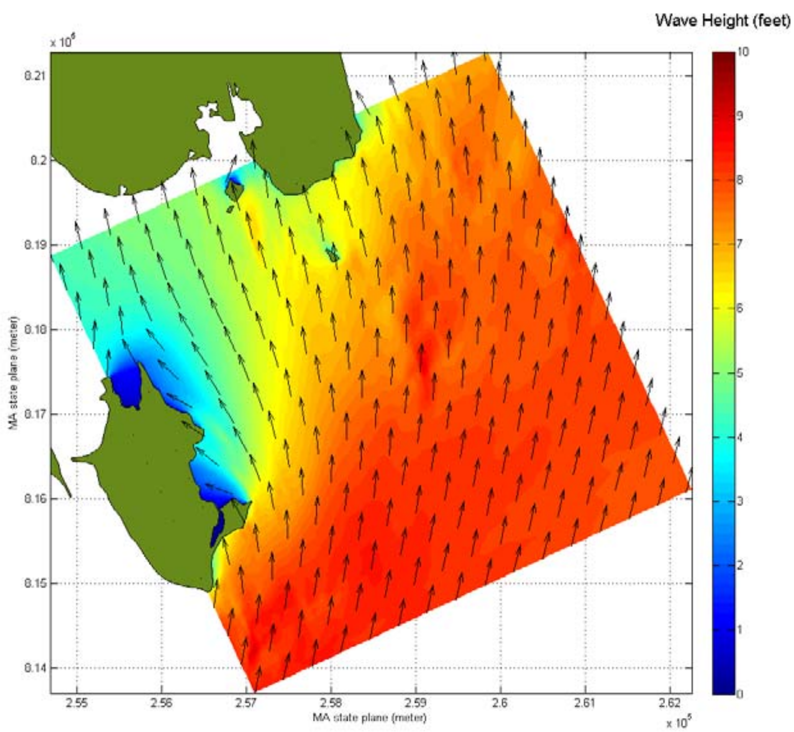

Figure K. Fine grid model results. 25-yr event from the south.

The worst case conditions for the southwest face of Ram Island are the 25-year conditions from due south, which are shown in Figure J. In this scenario, the wave heights incident on the southwest face of Ram Island are 6.1 feet. Although West Island clearly plays an important role in sheltering the land to the north, Ram Island falls just outside this sheltered area, and is subject to nearly the full wave heights observed to the southeast within Buzzards Bay.

Conclusions

The wave modeling provided a useful tool to quantify the influence that wind speed, direction and water levels have on the wave conditions at Ram Island. Table D contains a summary of wave heights observed at the east and southwest face of Ram Island. These values were obtained directly from the fine grid for each of the 3 water levels and 8 directions which were simulated.

Under all water levels, the largest waves reaching east side of Ram Island occur when the winds are incident from the northeast through to the southwest, with the largest waves occurring when winds are from due east. While Ram Island has no sheltering for waves from the east, the height of these waves is limited by the relatively short fetch across Buzzards Bay.

Along the southwest face of Ram Island the worst case scenario is wind and waves from due south. The southwest face also suffers the highest incident wave heights during conditions where the winds are from the northeast through the southwest. Model results show that during events from the southwest, wave heights across Buzzards Bay are slightly higher than during the easterly conditions. West Island provides significant sheltering for land to the north and east, however Ram Island typically falls along the outside edge of this area and is still subject to relatively high wave energy.

Table D - Wave Heights on east and southwest faces of Ram Island

Return Period (years)	***East Side of Ram Island***							
	Wind Direction							
	N	NE	E	SE	S	SW	W	NW
	Wave Height (feet)							
2	2.1	3.1	3.3	3.1	3.0	2.5	2.2	1.7
5	2.6	3.7	4.2	3.9	3.8	3.3	2.8	2.2
25	3.3	4.9	6.1	5.4	5.5	4.8	3.9	3.0
Return Period (years)	***Southwest Side of Ram Island***							
	Wind Direction							
	N	NE	E	SE	S	SW	W	NW
	Wave Height (feet)							
2	1.7	2.2	2.7	3.5	4.0	3.3	2.7	1.9
5	2.3	2.9	3.6	4.2	4.7	3.8	3.0	2.3
25	3.3	4.5	5.5	5.5	6.1	4.8	3.6	2.9

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