Coastal Climate Change Vulnerability Assessment and Adaptation Study

Town Hull, MA

June 30, 2016
Final Report

KLEINFELDER
Bright People. Right Solutions.

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INTRODUCTION

The Town of Hull is highly vulnerable to coastal flooding and is possibly the most vulnerable community in Massachusetts to the longer-term impacts of sea level rise and increasingly extreme storm surge. Hull is a peninsula of “hills” connected by narrow strips of land and low-lying plains. It is surrounded on all sides by coastal and tidally-influenced waters. With its extensive northeast exposure to the ocean, Hull is particularly susceptible to nor’easter storms. Since the Blizzard of 1978, in which Hull saw historic flooding, the National Flood Insurance Program has paid over $15 million to policy holders in town for flood-related property damages. Coastal flooding now causes property damage almost every year in Hull and results in the closure of vulnerable roads several times a year.

Given its exposure to the combined effects of sea level rise and storm surge from extreme storm events, the Town of Hull applied for and was awarded a Coastal Community Resilience grant from Massachusetts Coastal Zone Management under the Coastal Resilience Grants Program for Fiscal Year 2015.

This project had four primary goals:

1. Identify areas of the town that are vulnerable to the combined effects of sea level rise and storm surge from extreme storm events.
2. Assess the vulnerability of municipally-owned public infrastructure and natural resources.
3. Identify adaptation strategies that will help to mitigate the long-term effects of sea level rise and storm surge.
4. Educate the public, city officials and state legislators about those potential impacts.

It is important to note that this vulnerability assessment and adaptation planning study is in no way connected with flood risk studies and mapping efforts periodically conducted by the Federal Emergency Management Agency (FEMA) to produce Flood Insurance Rate Maps (FIRMs) for Hull. The coastal flood maps prepared as part of this study were developed for the purpose of long-term planning using very different methods, scenarios, and data than were used by FEMA to prepare FIRMs for the Town of Hull. Data from this report should not be used in any way as a substitute for FIRMs as the legally-binding basis for determining flood insurance premiums and <u>minimum</u> required elevations for the design and permitting of projects inside the floodplain.

Project Team

The Town of Hull selected the team of Kleinfelder and Woods Hole Group through a Request for Proposal process. Kleinfelder, located in Cambridge, MA, was the prime consultant responsible for client liaison, vulnerability assessment, adaptation planning, and public process. Woods Hole Group, located in Falmouth, MA, was responsible for coastal flood modeling and natural resource impacts. The team’s primary members included:

- Andre Martecchini, PE – Kleinfelder - Project Manager, Public Process
- Nasser Brahim – Kleinfelder - Project Scientist, Vulnerability Assessment, Adaptation Planning
- Kirk Bosma, PE – Woods Hole Group – Flood and Natural Resources Modeling

Kleinfelder worked closely with the Town's Steering Committee, which included the following members:

- Anne Herbst, Conservation Department (Project Manager)
- Robert Fultz, Community Development and Planning Department
- Joe Stigliani, Department of Public Works
- Andrew Thomas, Fire Department
- Panos Tokadjian, Municipal Light Plant
- Diane Saniuk, School Department
- Judy Kuehn, School Department
- Jim Dow, Sewer Plant
- Sheila Connor, Conservation Commission
- Jeanne Paquin, Planning Board
- Rick Mattila, Sewer Commission

Public Outreach

As noted above, one of the primary goals of the project was to raise public awareness of both the escalating flood risks posed by sea level rise and storm surge, and the potential strategies available to adapt to those changes over time. Five Steering Committee meetings were held to review interim findings and to obtain feedback from committee members. A televised presentation was made to the Hull Board of Selectmen on June 9, 2016, which provided the public with an in-depth review of the project's findings. Additional public meetings will be conducted in the future to present the findings of this final report.

Acknowledgements

We wish to acknowledge the contribution of the Massachusetts Department of Transportation under the direction of Steven Miller, Project Manager, and the Federal Highway Administration related to the modeling associated with the Boston Harbor – Flood Risk Model (BH-FRM). Modeling data from this model was utilized in the preparation of this study.

We would also like to thank the Massachusetts Coastal Zone Management for funding this project through a Coastal Community Resilience grant and meeting with the project team to review adaptation recommendations.

COASTAL FLOOD MODELING

The first step of the project was to determine which areas of Hull would likely be exposed to coastal flooding in the medium and longer term future. The Woods Hole Group used the Boston Harbor Flood Risk Model (BH-FRM) to assess coastal flooding probabilities and depths for the present (2013), 2030, and 2070 time horizons.

BH-FRM is the most comprehensive and sophisticated model available for anticipating how climate change will influence future coastal flood risks in Boston Harbor communities. The model is based on mathematical representations of the hydrodynamic processes that affect water levels along the coast, including tides, waves, winds, storm surge, sea level rise, wave set-up, etc. These processes were modeled at a high enough resolution to identify site-specific locations in Hull that are vulnerable and may require adaptation responses.

BH-FRM explicitly and quantitatively incorporates sea level rise and increasingly extreme storm surge events caused by climate change. Woods Hole Group and its partners developed BH-FRM for the Massachusetts Department of Transportation (MassDOT) and the Federal Highway Administration (FHWA) to assess potential flooding vulnerabilities of the Central Artery tunnel system due to sea level rise and extreme storm surge. The model is also being used for climate change planning and design by Massachusetts state agencies, including the Department of Transportation, Department of Conservation and Recreation, and Massachusetts Port Authority, as well as most municipalities in the Boston Harbor area.

Since the BH-FRM model boundaries (Figure 1) include the Town of Hull's coastline and upland topography, this model was ideally suited to assess the vulnerability of Hull's critical municipal infrastructure to coastal flooding under future scenarios of climate change. Using this existing model was beneficial to Hull since much of the upfront work in developing the model was already conducted as part of the MassDOT/FHWA project. Woods Hole Group also carried out additional wave run-up and overtopping analyses specifically for Hull, which were not previously included in the BH-FRM.

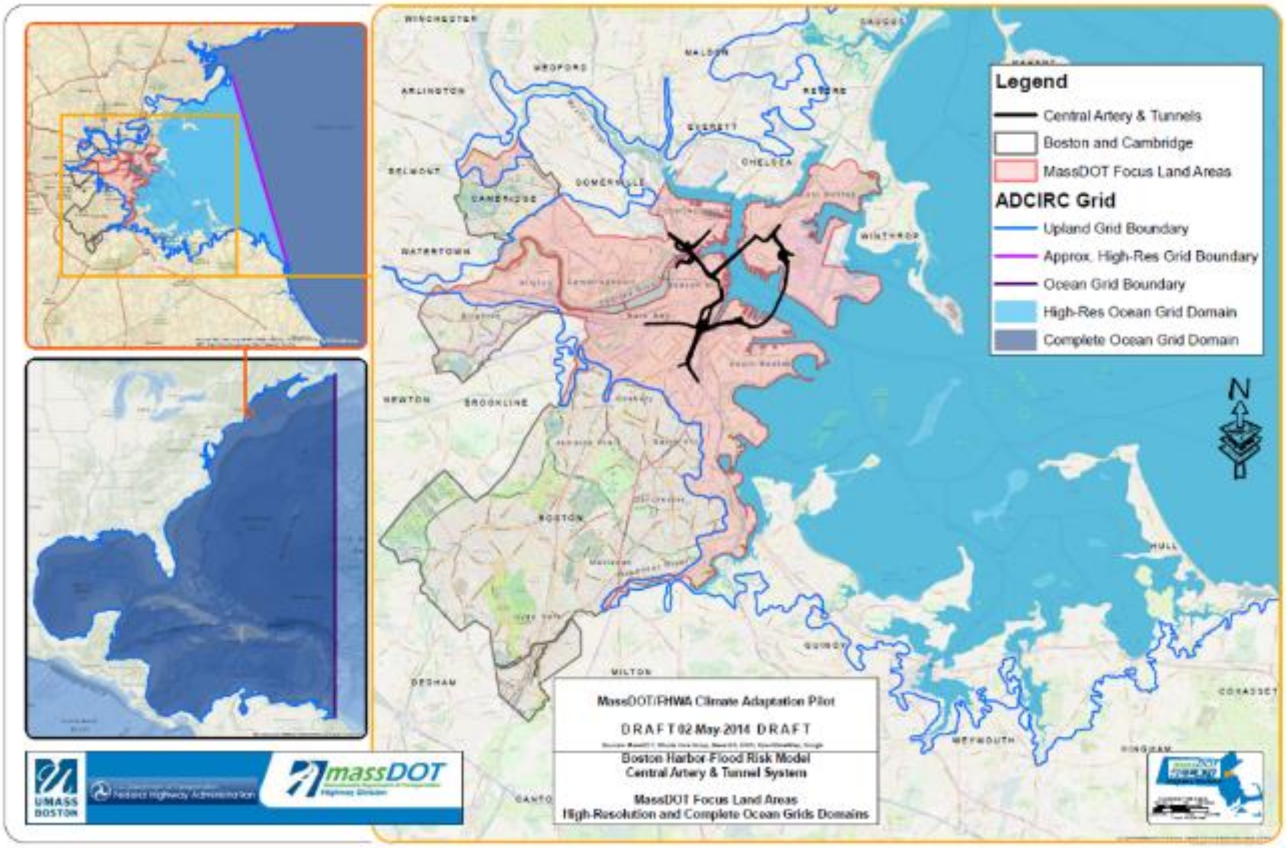


Figure 1. BH-FRM Model Boundaries

Model Attributes

BH-FRM was built on a model grid that is a digital representation of the geometry of the model domain. The model grid breaks the physical environment down into discrete nodes at which model equations can be solved. The grid was developed at three resolutions: regional (deep ocean), local (nearer to shore), and site-specific (coastline and uplands). The resolution of the model grid gets finer – meaning the distance between nodes in the grid get shorter – moving from regional, to local, to site-specific grids.

The grid for Hull and its surroundings is shown in Figure 2, overlaid on an aerial image. A site-specific grid has a resolution of 10 meters or less between nodes, and sometimes as low as 1 meter, to ensure that all critical topographic and bathymetric features that influence flow dynamics along the near shore are captured. It includes areas of open water, along with uplands subject to present and future flooding.

Figure 2. BH-FRM Model Grid for Hull

BH-FRM then uses modeling software to simulate the effect of sea level rise and storm events on water elevations at each node. It uses the ADvanced CIRCulation (ADCIRC) modeling software to predict storm surge flooding and the Simulated WAves Nearshore (SWAN) modeling software to predict wave generation and transformation. BH-FRM tightly couples ADCIRC with SWAN, such that for any given storm event being modeled, they dynamically exchange information on physical processes during each time step of the event. This allows BH-FRM to provide an accurate representation of the resulting water surface elevations, winds, waves, and flooding at each node and at each time step for any given storm event.

Model Calibration and Validation

BH-FRM was calibrated and validated at three levels. First, the model was calibrated to average tidal conditions over the entire model domain, from the Caribbean Islands to Canada to ensure the model was capable of reproducing water levels and coastal hydrodynamics. The magnitude of the bias is equal or less than 0.02 ft. at all locations meaning that the calibration simulation reproduced average water levels within 0.25 inch at all locations.

Second, the model was calibrated to both water surface elevation time series data (measured at NOAA gages) and observed high water marks from the Blizzard of 1978, which had significant impact in the

Hull area. The water surface elevation time series comparison had a bias of less than a 0.25 inch, Root-Mean-Square Error (RMSE) of 3 inches, and a percent error of 2.5%. The model had an 8% relative error to the observed high water mark data, which is quite reasonable considering the uncertainty associated with the high water mark observations. Greater error is expected when comparing model results to observed high water marks due to the uncertainty associated with the high water marks themselves, which are subject to human interpretation and judgment errors (e.g., wet mark on the side a building).

Finally, the model was validated to the No Name Storm of 1991 (the "Perfect Storm"), to observed water surface elevation time series with bias of 0.25 inches and RMSE of 0.75 inches. This storm also had significant impacts in the Hull area, hence it was an appropriate storm for validation in this area as well.

Complete details on the calibration and validation of the model can be found in the MassDOT-FHWA Pilot Project Report: Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options for the Central Artery (2015), which is available from MassDOT. In addition, the model was reviewed by a technical advisory committee made up of experts from the USGS, EPA, NOAA, USACE, and Woods Hole Oceanographic Institute.

Selection of Sea Level Rise Scenarios

National Oceanographic and Atmospheric Administration (NOAA) has been recording tidal observations since 1921 at Tide Gauge No. 8443970 in Boston Harbor (Figure 3). Over this period, sea level in Boston Harbor has risen approximately 10.5 inches (2.79 mm per year). This rate of sea level rise (SLR) is expected to increase in the future due to a volumetric expansion of the oceans coupled with glacial ice melt as a result of global warming caused by greenhouse gas emissions.

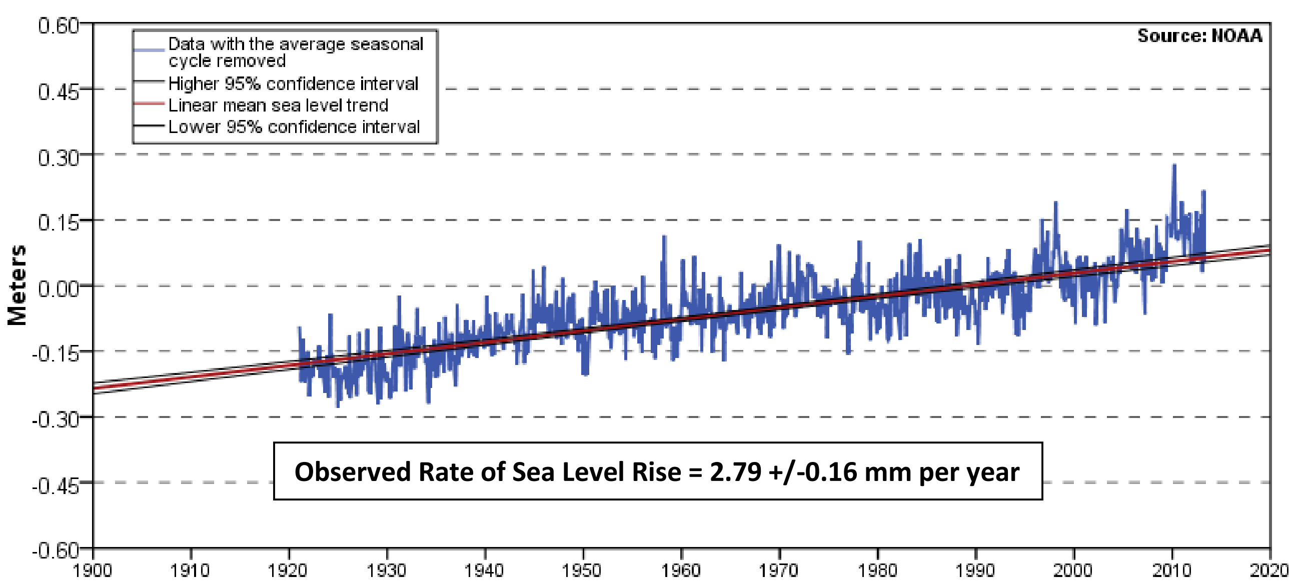


Figure 3. Mean sea level trend at Boston Tide Gauge (#8443970)

For the purposes of this project, sea level rise (SLR) scenarios were selected for two distinct time horizons: 2030 (medium term), and 2070 (longer term). These horizons are aligned with BH-FRM and match up with the climate change planning horizons being used by most municipalities in the region. To estimate the amount of SLR that will occur by 2030 and 2070 in Hull, the project team used the global SLR scenarios produced by NOAA (2012)[1] for the U.S. National Climate Assessment, shown in Figure 4. In addition, a previously established local land subsidence rate of 0.04 inches/year was included.

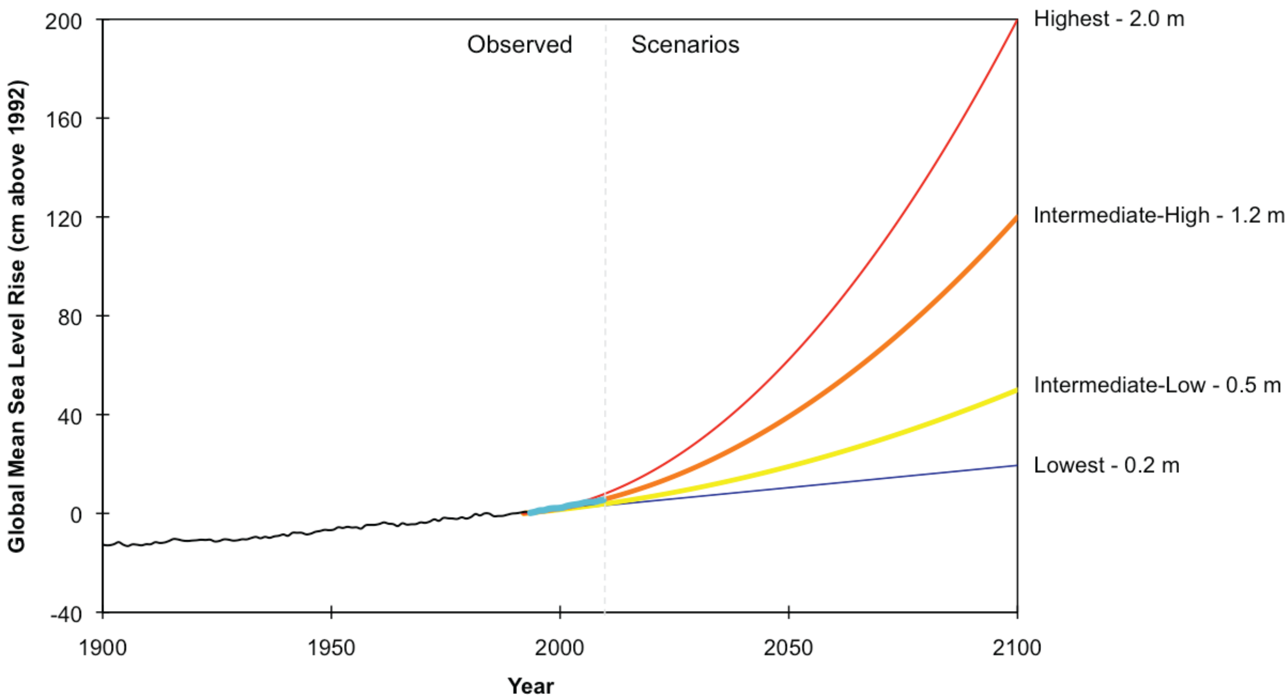


Figure 4. Global mean sea level rise scenarios (Not including local subsidence)

Table 1 presents the total relative SLR projections (global SLR plus local land subsidence) for Hull using the NOAA "Highest", "Intermediate-High" and "Intermediate-Low" scenarios, for the purposes of comparison. Projections are presented for years 2020 through 2100 in 10 year increments for Hull, considering a start year of 2013 (the start year for the SLR projections used in BH-FRM).

[1] *Global Sea Level Rise Scenarios for the United States National Climate Assessment, NOAA Technical Report OAR CPO-1, December 12, 2012*

Table 1. Sea level rise estimates for Hull using the National Climate Assessment SLR scenarios

Scenarios	2020	2030	2040	2050	2060	2070	2080	2090	2100
Global SLR (from 2013) "Highest" (ft.)	0.21	0.61	1.10	1.70	2.40	3.21	4.11	5.12	6.23
Global SLR (from 2013) "Intermediate-High" (ft.)	0.14	0.38	0.68	1.04	1.46	1.93	2.46	3.05	3.69
Global SLR (from 2013) "Intermediate-Low" (ft.)	0.07	0.18	0.32	0.47	0.63	0.82	1.02	1.24	1.48
Land subsidence (ft.) @ 0.04 in./yr	0.02	0.06	0.09	0.12	0.15	0.19	0.22	0.25	0.29
Total Relative SLR - "Highest" (ft.)	0.24	**<u>0.66</u>**	1.19	1.82	2.56	**<u>3.39</u>**	4.33	5.37	6.52
Total Relative SLR – "Intermediate-High" (ft.)	0.16	0.44	0.77	1.16	1.61	2.12	2.68	3.30	3.98
Total Relative SLR – "Intermediate-Low" (ft.)	0.09	0.24	0.40	0.59	0.79	1.01	1.24	1.50	1.77

BH-FRM modeling for Hull incorporated the “Highest” total relative SLR estimates of 0.66 ft. by 2030 and 3.39 ft. by 2070 (Table 1, bold and underlined). That means that storms simulated in BH-FRM for 2030 and 2070 were run with background tide levels that are 0.66 ft. and 3.39 ft. higher than present (2013), respectively.

Selection of the “Highest” scenario may be interpreted as conservative. However, observed SLR rates over the past few decades have been most closely following the “Highest” scenario rates. This selection also allows for representing a range of scenarios that allows decision makers to consider multiple possible future conditions and to develop multiple response options. For example, the “Highest” total relative SLR estimate for 2030 (0.66 ft of SLR) would be equaled under the “Intermediate-High” scenario in the 2030-2040 timeframe, and under the “Intermediate-Low” scenario in the 2050-2060 timeframe.

Storm Events and Storm Climatology

The storm climatology parameters in BH-FRM include wind directions and speeds, radius of maximum winds, pressure fields, and forward track. BH-FRM requires storm input data to run storm surge simulations and generate flooding results. Without input data, BH-FRM cannot determine which areas of Hull will likely be exposed to coastal flooding in the medium and longer term future, as much of the community’s flood risk profile is dependent on storms.

As part of the development of BH-FRM, a large statistically-robust sample of storms, including tropical (hurricanes) and extra-tropical (nor’easters) storms, was developed specifically for Boston Harbor’s existing climatology. This data set was used to assess coastal flooding risks in the present and in 2030. Figure 5 shows a representation of storms included in the model.

Figure 5. Storms Used in BH-FRM for Present and 2030 Simulations

To assess coastal flooding risks in 2070, a different sample of storms reflecting a late 21st century climatology was used. This storm sample includes some very powerful hurricanes, for example, reflecting projections that tropical storms will be more intense on average in the second half of the century assuming that air and ocean temperatures are significantly higher than in the past. This set of storm input data was created by MIT professor Dr. Kerry Emmanuel based on climate projections.

Fully-optimized Monte Carlo simulations were run in BH-FRM using the respective storm sets and SLR projections for present, 2030, and 2070. These simulations importantly included the tide cycle as a dynamic element of the model. In Boston Harbor, the wide tide range means that the same storm surge can result in very different flooding outcomes depending on whether it coincides with high, mid, or low tide. Results of the Monte Carlo simulations were used to generate cumulative probability distribution functions of the storm surge water levels at a high degree of spatial precision. In particular, they provide an accurate and precise assessment of the probability of water levels from combined SLR and storm surge exceeding the elevation of the ground at each node in the model.

The inclusion of nor'easters is one of the unique aspects of the BH-FRM model that is not available in other storm surge models, such as SLOSH. While hurricanes are typically shorter duration events that often last over only one tidal cycle, nor'easters are longer duration events that typically last over multiple tidal cycles spanning multiple days. So the probability of a nor'easter occurring or lasting through a high tide is more likely than a hurricane. Also, the diameter of a nor'easter (also commonly called the "fetch") can typically be 3-4 times that of hurricanes, and therefore they can impact much larger areas as well. Under the present and medium term (2030) scenarios, the probability of flooding due to nor'easters dominates because the annual average frequency of nor'easters (~2.3) is much higher than that of hurricanes (~0.34). In the longer term (2070), the influence of hurricanes becomes more pronounced, reflecting the late 21st century climatology.

Wave Run-Up and Overtopping

While BH-FRM includes many dynamic physical processes described above, one limitation of the model is that it does not, in its 'out-of-the-box' form, include the effects of wave run-up and overtopping of coastal structures. Due to Hull's extensive ocean-facing coastline and the historic prevalence of flooding caused by wave run-up and overtopping of dunes and man-made coastal structures (seawalls, revetments, etc), Woods Hole Group conducted additional wave run-up and overtopping analyses for 17 transects along the coast (Figure 6) to take into account the higher water surfaces near the immediate coastline that can affect flooding behind dunes and man-made coastal structures. Woods Hole Group applied professional judgment in determining how to distribute the flood volumes generated by these processes throughout the receiving upland areas.

Figure 6. Location map of transects used for wave run-up and overtopping analysis

It is also important to note that these analyses were based on existing dune and coastal structure elevations and beach bathymetry. Hull has extensive dune systems providing protection from wave run-up and overtopping. However, these dunes undergo dynamic changes over time. Future dune erosion could result in under-prediction of flooding in the results produced, while future dune enhancement, coastal structure raising, and beach nourishment projects could result in an over-prediction of flooding. With those caveats, including the wave run-up and overtopping analysis provide a more holistic assessment of Hull's coastal flood risks.

Coastal Flooding Maps

The results of BH-FRM simulations for present, 2030, and 2070 were used to generate two types of coastal flooding maps for the Town:

- Percent Probability of Flooding Maps - These maps can be used as a screening tool to identify locations, structures, assets, etc. that are likely to flood. Finer-grain probability and depth data from BH-FRM can then be obtained from nodes in the model that represent the locations of elements that stakeholders identify as critical. Stakeholders can then determine if the level of risk represented in the detailed probability data is acceptable, or if some adaptive response action may be required.

- Depth of Flooding Maps – These maps show the estimated difference between the projected water surface elevation for a given percent probability of flooding during the year of interest and existing ground elevations derived from the 2011 Northeast LiDAR survey. The datum for depth calculations is NAVD88. For this study, two sets of Depth of Flooding Maps were produced:

- Depths at 1% Probability of Exceedance which has approximately a 100 year recurrence interval.
- Depths at 0.2% Probability of Exceedance which has approximately a 500 year recurrence interval.

The following coastal flood maps are included in Appendix A:

- A-1: Present – Percent Probability of Flooding Map
- A-2: 2030 – Percent Probability of Flooding Map
- A-3: 2070 – Percent Probability of Flooding Map
- A-4: Present - Depth of Flooding at 1% Annual Probability (≈100 year recurrence)
- A-5: 2030 - Depth of Flooding at 1% Annual Probability (≈100 year recurrence)
- A-6: 2070 - Depth of Flooding at 1% Annual Probability (≈100 year recurrence)
- A-7: Present - Depth of Flooding at 0.2% Annual Probability (≈500 year recurrence)
- A-8: 2030 - Depth of Flooding at 0.2% Annual Probability (≈500 year recurrence)
- A-9: 2070 - Depth of Flooding at 0.2% Annual Probability (≈500 year recurrence)

Nodal Interpolation to Create Flood Maps

To create smooth water surfaces for flood maps, the BH-FRM interpolates elevations between nodes in the model grid. However, the distances between nodes differ. In some cases, where there are significant changes in elevation over short distances – for example a high bluff rising sharply from the shoreline where the nodes in the high elevation areas are not all at the edge of the topographic feature – this smoothing process can create interpolation errors showing parts of the high elevation areas as though they are at risk of flooding, when in reality they are not. This may affect the accuracy of the flood maps, particularly around the edges of the flood extent in high elevation areas. Figure 7 illustrates an enlarged area at Atlantic Avenue and Summit Avenue.

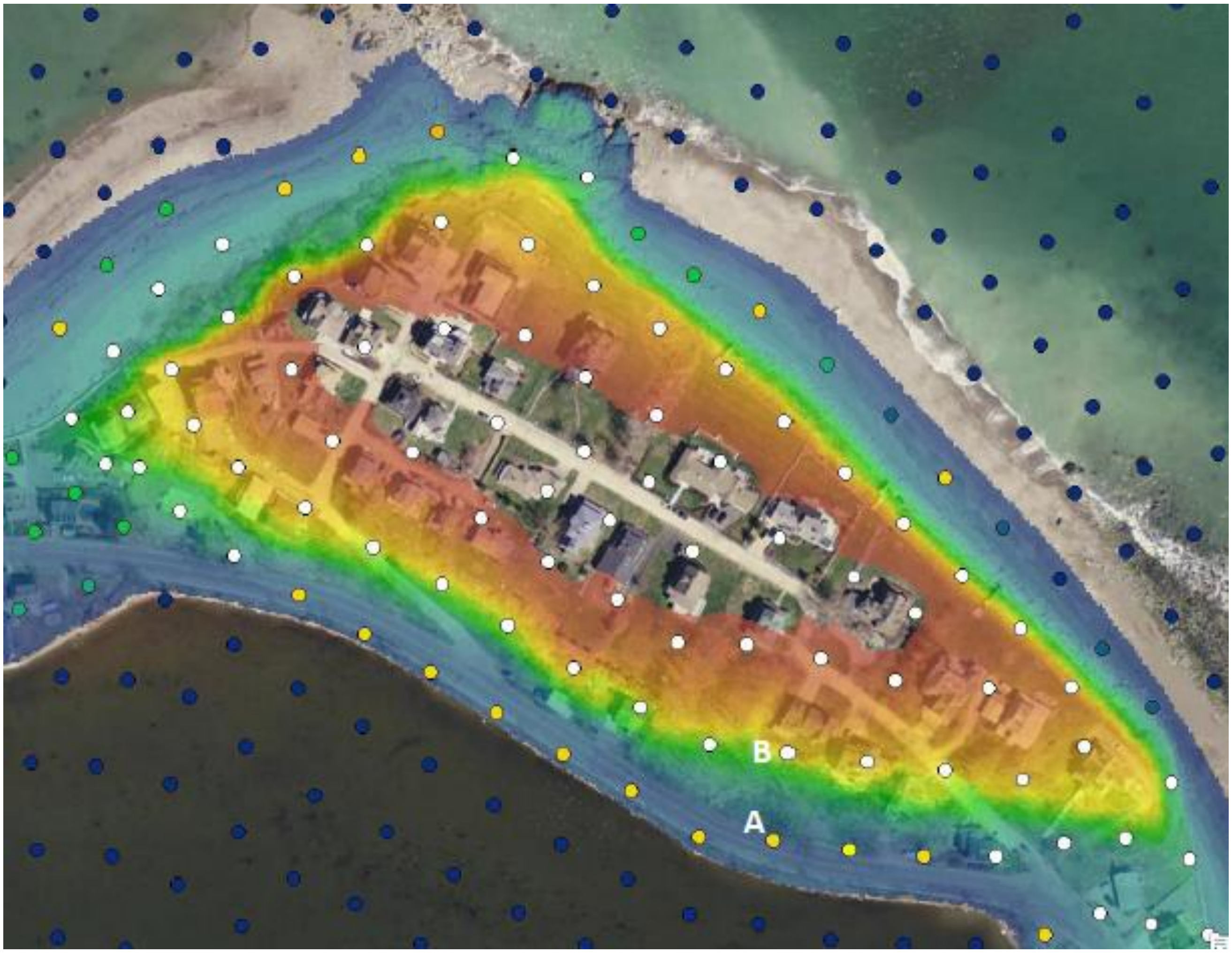


Figure 7. Enlarged area at Atlantic and Summit Avenues showing model nodes

Figure 7 shows a portion of the elevation data (LiDAR) as color contours with blue being a low elevation and red being a higher elevation (this should not be confused with the probability of flooding map distribution, as the color coding here is showing elevation). Areas that are very high (the upper elevation of the headland) are not symbolized and left uncolored. The dots on the map show the location of model nodes, which are color coded based on the probability of flooding in 2013. Nodes that are white represent an insignificant probability of inundation (less than 0.1%). Nodes that are blue represent 100% probability of inundation, with various additional probabilities colored in between. Note that model node spacing in this area is approximately 150 ft., which is relatively coarse.

The results are showing that Atlantic Avenue is expected to be inundated at around a 0.5-1% probability level (dots colored with shades of yellow), but the next landward nodes have a 0% probability of flooding (dots colored with white). For example, see nodes demarcated as A (1%) and B (0%). In order to create a shaded contour map, it is necessary to interpolate between these nodes. This creates a zone between Atlantic Avenue and the next node that is between 1% and 0%, which may not actually be subject to flooding.

It should be noted that the probability maps should not be applied at such a granular level to assess the fate of individual buildings or properties, rather they should be used as a tool to identify areas that may be vulnerable to flooding. Once those areas are identified, detailed information for individual buildings or other infrastructure can then be extracted from the closest model node. This approach has been used on many previous vulnerability assessments, including for MassDOT, and is the approach being used for this project. Nodal data (Probability of Exceedance data) are more accurate on a property scale then interpolated values shown on the maps.

Woods Hole Group reviewed the originally interpreted flood maps and, in some locations, added additional nodes along the edges of high elevation areas. This grid density refinement process improved the accuracy of the flood maps, though some interpolation errors may still remain.

NATURAL RESOURCES

Modeling

Impacts to natural resources including beaches, coves and salt marsh, were assessed on a qualitative basis. Woods Hole Group recently completed work for the Massachusetts Office of Coastal Zone Management (CZM) to model the effects of sea level rise on coastal wetlands and natural resources statewide. The software Sea Level Rise Affecting Marshes Model (SLAMM) was used to assess the impacts to natural resources for that project. The SLAMM results were also linked to results from the Marsh Equilibrium Model (MEM). Final model simulations were recently completed for both sub-site and state-wide simulation for three out-year scenarios and three projected sea level rise curves. The results of this statewide project were incorporated into this study.

Elevation Information

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

For the Hull area, the 2013-14 USGS LiDAR flight was used. In order to reduce processing time within the SLAMM model, areas of higher elevation within each regional panel that are unlikely to be affected by coastal processes, such as sea level rise, were excluded prior to processing. All areas above an elevation of 60 ft. (NAVD88) were clipped from the input files.

Wetland Classification Information

The 2011 wetland layer developed by the National Wetlands Inventory (NWI) was used as the baseline source for the wetlands input file for the SLAMM model.

Utilizing the NWI data had two key benefits over the 1990s MassDEP wetland layer. First, the NWI data not only provided a more recent dataset, but also matches that of the LiDAR datasets more closely. Although different input years were used, most of the LiDAR data used was collected in or around 2011.

The second benefit to utilizing the NWI data is that it streamlined the conversion between source wetland categories and SLAMM model wetland codes. The documentation provided with the SLAMM software contains a key to convert each NWI classification to the wetland classification system used by SLAMM. A summary of this conversion key is present in Table B1 included in Appendix B.

Sea Level Rise Projections

The SLR projections used in the marsh migration modeling are consistent with those used in the BH-FRM modeling to produce the coastal flooding maps for Hull.

Additional Data Input

Additional model input includes, but is not limited to, accretion rates (marsh, beach, etc.), erosion rates, tidal range and attenuation, freshwater parameters, dikes and dams, and impervious surfaces.

There is a limited amount of accretion rate data throughout the state (only select areas have measured accretion data), so the model is run in two ways:

(1) In areas where there are no observed accretion data, the model is run with an accretion rate equivalent to the historic SLR rate, which is a very reasonable assumption given measured accretion rates in the mid-Atlantic and northeast.

(2) In areas where there are observed accretion data, the model is run with the observed data AND with an accretion rate equivalent to the historic SLR rate.

The Hull region has some regional data that is applicable and will have both run types eventually available. The results provided in this report are for the historical SLR rate only. While it is likely that increased sediment may be brought into the region due to storms, these ephemeral increases are not nearly enough to keep up with SLR. Therefore, the influence of any accretion unaccounted for by the current methodology would likely be small.

SLAMM was intentionally run first without the limitation that impervious surfaces (roads, parking lots, etc.) would not be subject to change to see how and where the marshes and other natural resources would migrate, if there was no restriction to their migration. As such, the ecological modeling assumes that existing infrastructure may not remain in place. The mapping results therefore do not reflect certain realities. For example, by 2030, the SLAMM model projects that the residential neighborhood between Warfield Avenue and Newport Road will begin to shift to a transitional scrub-shrub wetland – an obviously unlikely scenario. However, an additional post-processing step was applied to overlay the impervious layer to indicate heavily developed areas that are not expected to naturally transition to wetlands.

For complete details of the natural resources mapping process, see the Statewide Modeling: the Effects of Sea Level Rise on Coastal Wetlands for Massachusetts Coastal Zone Management. (ENV 14 CZM 08 in publication, 2015).

Impacts to Natural Resources

Figures B1 through B3 in Appendix B show the wetland classification areas for 2011, 2030, and 2070 respectively based on the marsh migration modeling. Figure B1 presents the current conditions, as defined by the NWI (with the exception of non-tidal upland swamp). Figure B2 shows the change in wetland classification locations projected to 2030, impacted by SLR. Similarly, Figure B3 shows the change in wetland classification locations projected to 2070 impacted by SLR. Both the results shown in Figures B2 and B3 for 2030 and 2070, respectively, are based on the SLAMM modeling. Existing infrastructure has been overlaid on the SLAMM modeling results, since the model does not take into account limits to migration imposed by existing infrastructure. Close-up versions of these maps for different areas of interest are shown in Figures B4 through B15 in Appendix B.

Primary Areas Where Natural Resources are Evolving in Response to SLR and Potential Adaptation Strategies

Town-Wide

Although the SLAMM results project some wetland expansion and loss of upland area within developed and residential neighborhoods, due to the high density of development and impervious surfaces in Hull, it is unlikely that the majority of these areas will be allowed to transition to wetland. However, these areas will likely experience higher water tables, increased salt water intrusion and higher frequency of flooding. The maps in Appendix B can therefore be used as a planning tool for the Town to identify areas that will need additional protection in the future under sea level rise conditions (no storms). For example, by 2070 (Figure B3), the SLAMM model projects that almost the entire town west of Nantasket Avenue will transition to wetlands.

There are, however, a number of undeveloped or less developed areas within Hull that will likely experience significant changes in land cover and wetland type and may offer opportunities for natural resource management and/or expansion due to the changing climate. These include the areas around:

- Weir River Estuary Park,
- Pemberton (north of Main Street), and
- Hampton Circle

Weir River Estuary Park Region

In 2011 and 2030, the wetlands in the Weir River Estuary Park region are primarily irregularly flooded marsh (salt marsh); however, by 2070 these regions have not only transitioned almost entirely to regularly flooded marsh, with some marsh loss along the water's edge to tidal flat, but also expanded in area to include some transitional scrub-shrub areas around the periphery (Figure B4 to B6). This indicates that the advancing tide levels propagate past George Washington Boulevard Bridge and regularly inundate low-lying areas along the north shore of the Weir River Estuary in Hull.

No immediate adaptations are required for this area in terms of natural resources because this is a largely natural, undeveloped area, and can be allowed to advance naturally, as it transitions from irregularly flooded marsh (high marsh) to regularly flooded marsh (low marsh). However, over the longer term, one recommended adaptation measure for this region would be to implement thin layer deposition projects to maintain and enhance the diversity of the salt marsh in terms of having some mix of high and low marsh and to reduce the amount of marsh lost to tidal flat conversion. This adaptation would involve the placement of clean, compatible sediment in thin layers on the existing salt marsh to assist the elevations in keeping up with the rising tidal elevations.

Pemberton

In 2011 and 2030, the wetland north of Main Street is primarily irregularly flooded marsh (high marsh) and is relatively small, however, by 2070 that wetland area has the potential to transition to regularly flooded marsh (low marsh) with some sections of tidal flat (Figure B10 to B12) and expand into Dust Bowl field and areas west of it. This depends on whether new sources of flow to the wetland area established (the marsh is currently fed by a small pipe with a flap valve that is not included in the SLAMM model) and existing impermeable surfaces are removed or reduced west of Ocean Avenue. Flooding from the bay over Main Street and into the area west of Ocean Avenue is projected to occur at least annually, but very likely more frequently in 2070 if no action is taken to raise Main Street or redesign existing seawalls along the bay.

Additionally, in 2011 and 2030, there is an area of rocky intertidal habitat southeast of Spinnaker Island, however, by 2070 that area is entirely open water due to the increased tidal elevations.

Potential adaptations in this area include:

- Since there appears to be limited ability of the existing marsh area north of Main Street to migrate (due to the surrounding roadways), site specific marsh enhancement projects would be required to assist in the enhancement, protection, and growth of the perimeter salt marsh areas. Additionally, because the center of the existing marsh area is projected to transition to tidal flat by 2070, a recommended potential adaptation for this wetland may consist of thin layer deposition projects to maintain and enhance the elevation of the salt marsh in the face of sea level rise. This adaptation would involve the placement of clean, compatible sediment in thin layers on the existing salt marsh to assist the elevations in keeping up with the rising tidal elevations.

- For the rocky intertidal area southeast of Spinnaker Island, although this resource is expected to be lost by 2070 due to rising water levels, no adaptations are recommended for this area.

Hampton Circle Area

In 2011 and 2030, the open area between Marginal Road and Moreland Avenue is upland. However, by 2070 that area is projected to transition to a regularly flooded marsh (low marsh) (Figure B13 to B15). The existing wetlands along the shoreline from Hampton Circle to Bay Street on both sides of the peninsula are expected to transition from predominantly irregularly flooded marsh to regularly flooded marsh, as well as to expand in area.

In the broader context, this means that Hampton Hill would become largely or entirely inaccessible by roadway. If such a scenario is to be avoided, the Town and/or residents of Hampton Hill may need to build a new bridge in the current footprint of Moreland Avenue or Marginal Road.

The recommended adaptation measures, as related to natural resources in the Hampton Circle area, consist mainly of proactively planning for wetland creation and expansion in this area. As the area between Marginal Road and Moreland Avenue is projected to be predominantly marsh by 2070, the Town may want to remove or limit infrastructure development, and/or complete a wetland restoration project here. This would involve measures to create a tidal opening, allowing water to enter this center area, to establish a marsh in between existing infrastructure, and to elevate houses and other structures on stilts or piles (or implement other forms of floodproofing), in an effort to actively integrate marshes into region. The planning of such measures would need to include significant public involvement and be combined with planning for how access will be provided to Hampton Hills once the Marginal Road and Moreland Avenue are no longer viable.

INFRASTRUCTURE VULNERABILITY ASSESSMENT

Scope of Infrastructure Vulnerability Assessment

A vulnerability assessment was performed on critical municipally-owned infrastructure subject to flooding. Municipally-owned infrastructure includes pump stations, roads, bridges, piers, beach dunes, and other critical facilities such as schools, police stations, fire stations, etc. owned and operated by the Town of Hull. Critical infrastructure information was obtained from the Hull Hazard Mitigation Plan and information provided by Town Departments. All elevational information was obtained from LiDAR – no survey was carried out for this project.

A risk-based vulnerability assessment was performed for each of the municipally-owned assets impacted by flooding. These are built assets and do not include natural resources. The impacts of flooding were assessed for each asset deemed to be susceptible to flooding during any one of the time periods being investigated. The following is a description of the vulnerability assessment methodology for infrastructure.

Using Risk to Understand the Vulnerability of Infrastructure Susceptible to Flooding

Risk is defined here as the probability of an asset flooding times the consequence of that asset failing. Put into mathematical terms:

Risk (R) = Probability of Flooding (P) x Consequence of Failure (C)

or

R = P x C

Each node in BH-FRM has unique Probability of Exceedance data associated with it, which gives the probabilities of exceeding various water surface elevations at that node.

Using risk to assess the vulnerability of infrastructure allows one to take into account both how likely a damaging flood event is, and also, what the consequence of that damaging flood is to the community. Relative risk rankings are an excellent way for helping to prioritize scarce capital funds.

Risk Assessment - A Five Step Process

The risk assessment process, described below, was implemented using the following five basic steps:

1. Determine Critical Assets Subject to Flooding
2. Determine Critical Elevations
3. Obtain Probability of Exceedance Data
4. Determine Consequence of Failure Score
5. Calculate Risk Scores and Rankings

1. Determine Critical Assets Subject to Flooding

All identified municipally-owned infrastructure were located as an overlay in the GIS project map. The Percent Probability of Flooding map for 2070 was then used to screen out assets that showed no probability of flooding in 2070. Assets that showed no probability of flooding were excluded from further analysis. Municipally-owned infrastructure assets have been identified in Tables 2 through 7 as being vulnerable to flooding in the indicated time period between the present time and 2070:

Table 2. Emergency Facilities Vulnerable to Flooding

Time Horizon	Facility	Location
Present	Dust Bowl Heliport	Main St At Ocean Ave
	Hull Memorial Middle School - Emergency Operations Center and Warming Center	81 Central Ave
	Mariners Park Heliport	3 Fitzpatrick Way
	DPW Salt Shed	5 Nantasket Ave
2030	A Street Fire Station	671 Nantasket Ave
	DPW Barn	5 Nantasket Ave
	Kenberma Playground Heliport	Nantasket Ave and Nantasket Rd
	L Street Playground Heliport	L St and Nantasket Ave
2070	Roller Hockey Park Heliport	GW Blvd

Table 3. Senior Center and School Facilities Vulnerable to Flooding

Time Horizon	Facility	Location
Present	Anne Scully Senior Center	197 Samoset Ave
	Hull Memorial Middle School	81 Central Ave
2070	Hull High School	180 Main St

Table 4. Energy, Stormwater, and Wastewater Facilities Vulnerable to Flooding

Time Horizon	Facility	Location
Present	Storm Water Pump Station	D St & Cadish Ave
	Municipal Light Department	15 Edgewater Road
	Hull Sewer Plant	1111 Nantasket Ave
	Waste Water Pump Station 1	157 Atlantic Ave
	Waste Water Pump Station 6	765 Nantasket Ave
2030	Waste Water Pump Station 4	13 Marginal Road
	Waste Water Pump Station 9	165 Main St
	Draper Ave Storm Water Pump Station	220 Newport Rd
	Waste Water Pump Station 5	70 Draper Ave

Time Horizon	Facility	Location
2070	Hull Wind 1	1 Wind Mill Point
	Waste Water Pump Station 3	13 Rockland Cir

Table 5. Major Bridges and Roadways Vulnerable to Flooding

Time Horizon	Facility	Location
Present	Atlantic Ave	Summit Ave to Richards Rd
	Main St	South Main St to Windmill Point
	Spring St	Nantasket Ave to Main St
	George Washington Blvd	Rockland Cir to Nantasket Ave
	Nantasket Ave	C St to H St
	Nantasket Ave	V St to Fitzpatrick Way
	George Washington Blvd	Gosnold St to Rockland Cir
2030	West Corner Bridge	Nantasket Ave at Town Line
	Nantasket Ave	State Park Rd to GW Blvd
2070	MLK Bridge	Fitzpatrick Way

Table 6. Water Dependent Facilities Vulnerable to Flooding

Time Horizon	Facility	Location
Present	Nantasket Pier	48 GW Blvd
	A Street Pier	A St & Cadish Ave
	Town Pier	5 Fitzpatrick Way
	Pemberton Pier	171 Main St

Table 7. Coastal Barriers Vulnerable to Flooding

Time Horizon	Facility	Location
Present	Barrier Dunes*	Phipps St to Malta St
	Barrier Dunes*	Alphabet Streets
	Barrier Dunes*	Lewis St
2070	Newport Road Dike	Newport Rd

*To accurately evaluate these dune systems would require a cross-shore sediment transport model effort to evaluate the fate of the dunes during various storm events. Without modeling the cross-shore dune erosion, it is difficult to predict the fate of the dunes. It is expected that these dunes may erode, possibly substantially, during a storm event, be overtopped, and breached. For the purposes of this study, time horizons and probabilities were assigned based on an estimate of when they would become “wet”, not when the stillwater level (without wave run-up) exceeds the dune crest elevation.

2. Determine Critical Elevations

Critical elevations (NAVD88 datum) were then determined for each asset subject to flooding in 2070 or sooner. Critical elevations are defined as that elevation at which flood water will cause the asset to cease to function as intended. For example, the critical elevation may be the first floor of a building. In another case, the critical elevation could be a basement window sill elevation, above which water can enter the basement and damage critical mechanical equipment located in the basement. In another case, the critical elevation could be the bottom of a critical electrical transformer or electrical panel, above which flood water would damage the equipment and shut down the facility.

For buildings, pump stations and similar facilities, critical elevations are determined in several ways:

- Information provided by Town staff,
- Estimated from on-site observations (no surveys were performed for this project),
- Estimated from LiDAR survey and aerial photography.

Critical elevations for roads and bridges were determined using LiDAR survey data. The low points of a roadway section subject to flooding were used as the critical elevation. Critical elevations for bridges were set as the lowest approach road elevations at the ends of the bridge.

Barrier dune critical elevations were determined based on LiDAR, taking the average elevation along the dune crest at three representative dune locations identified by the Town. Locations are described in the tables and figures in this report.

Critical elevations for coastal stabilization structures were determined using LiDAR data or, where available, survey elevations included in the Massachusetts CZM's "*South Shore Coastal Infrastructure Inventory and Assessment Demonstration Project: Town of Hull*" (February, 2007).

3. Obtain Probability of Exceedance Data

Probability of Exceedance data for the present, 2030, and 2070 time horizons for each critical infrastructure asset were obtained directly from the BH-FRM model. Data were obtained from the closest model node to the asset.

A representative example of Probability of Exceedance data from the A Street Fire Station is shown in Table 8. For this facility, the critical elevation is 10.3 NAVD88. This data shows some of the following information:

- For the present time frame, the Fire Station does not show any probability of flooding (<0.1%).
- In the 2030 time frame, there is a 0.5% chance that flood water will meet the critical elevation of 10.3 ft.
- In the 2070 time frame, the probability of exceeding the critical elevation increases significantly to 30%, and the depth of water at the 1% probability level (100 year recurrence interval) is 2.7 ft.

Table 8. Probability of Exceedance Data for Hull A Street Fire Station (671 Nantasket Ave)

	Present		2030		2070	
Annual Probability (%)	Flood Elevation (ft. NAVD88)	Depth above Critical Elevation (ft.)	Flood Elevation (ft. NAVD88)	Depth above Critical Elevation (ft.)	Flood Elevation (ft. NAVD88)	Depth above Critical Elevation (ft.)
0.1	dry	dry	10.9	0.6	14.1	3.8
0.2	dry	dry	10.5	0.2	14.0	3.7
0.5	dry	dry	10.3	0.0	13.5	3.2
1	dry	dry	10.2	-0.1	13.0	2.7
2	dry	dry	dry	dry	12.6	2.3
5	dry	dry	dry	dry	12.1	1.8
10	dry	dry	dry	dry	11.5	1.2
20	dry	dry	dry	dry	11.0	0.7
25	dry	dry	dry	dry	10.8	0.5
30	dry	dry	dry	dry	10.7	0.4
50	dry	dry	dry	dry	10.2	-0.1
100	dry	dry	dry	dry	dry	dry

This example illustrates how the risk assessment process can be used to evaluate how coastal flooding impacts for a single facility are likely to escalate over time due to climate change. At present there is very little chance that the A Street Fire Station will be flooded, but by 2070, it could flood once every three years on average.

4. Determine Consequence of Failure Score

The consequence of failure for each infrastructure asset subject to flooding was then rated on a scale of 0 through 4 (from low to high consequence) for six different potential impacts in accordance with the guide shown in Table 9.

Table 9. Consequence Scoring Categories and Scales

Rating	Area of Service Loss	Duration of Service Loss	Cost of Damage	Impact on Public Safety & Emergency Services	Impact on Important Economic Activities	Impact on Public Health & Environment
4	Whole town/city	> 30 days	> $5m	Very high	Very high	Very high
3	Multiple neighborhoods	14 - 30 days	$1m - $5m	High	High	High
2	Neighborhood	7 - 14 days	$100k - $1m	Moderate	Moderate	Moderate
1	Locality	1 - 7 days	$10k - $100k	Low	Low	Low
0	Property	< 1 day	< $10k	None	None	None

Each impact is rated separately, and then a composite Consequence of Flooding score is calculated by summing the individual scores, dividing by 24 (the highest total possible), and normalizing to 100 using the following equation:

$$\textbf{Composite Consequence of Failure Score} = \frac{\sum \textbf{all six ratings}}{\textbf{24}} \textbf{ x 100}$$

Composite consequence scores can be as low as 0 and as high as 100. The higher the rating, the more consequential is the flooding of the asset. Table 10 shows a representative example of the Consequence of Flooding rating for the A Street Fire Station, with a total rating of 58 (rounded) out of a possible 100. Narrative is provided in the table, illustrating the rationale for the ratings under each impact. Consequence scores for all assets at risk of flooding are reported in Appendix C (Table C1).

Table 10 – Consequence of Flooding Scoring Example for A Street Fire Station

Scoring Category	Rating	Rationale
Area of Service Loss	3	A Street Fire Station serves as the main Fire Department for the highly populated central part of Hull and includes covered parking for at least three of the Town's five apparatus. The area impacted by service loss due to flooding of the station is multiple neighborhoods.
Duration of Service Loss	1	While the Fire Station structure, equipment, and contents could take longer to restore from flood damages, it is assumed that the emergency services provided from the Fire Station would be quickly relocated to and provided from another Town-owned facility and that all movable equipment would be moved to dry ground before a storm.
Cost of Damage	2	It is assumed that the apparatus would be relocated prior to flooding. The costs of damages to the building structure, other equipment, and contents at the Fire Station could be upwards of $100,000, but unlikely to exceed $1,000,000. *Note that these are order-of-magnitude estimates made without a detailed appraisal and shall not be used for insurance purposes.
Impacts to Public Safety Services	4	Flooding of this essential facility would have a very high impact on the Town's capabilities for the duration of service loss, and to a lower extent thereafter, to provide public safety services (e.g., firefighting, emergency medical services, hazardous materials response).
Impacts to Economic Activities	2	The Fire Department plays a role in supporting business preparedness, response, and recovery. Flooding of the Fire Station could have a moderate impact on businesses by reducing the Fire Department's capabilities to respond to incidents, inspect or approve post-flood safety measures, and address public safety concerns that might inhibit economic activity.
Impacts to Public Health & Environment	3	The Fire Station is an occupied building. Occupants may be exposed to health hazards after flooding including contamination and mold. Fire Department is responsible for providing first-response to hazardous materials incidents. Flooding often results in hazardous material releases to public areas and the environment, and fast response is critical to containing the negative impacts of such incidents. Reduced response capability due to flooding of the Fire Station, in addition to potential releases of hazardous materials stored in the station's garage, make the consequences for public health and the environment potentially high.
Consequence Score	**63**	**A Street Fire Station is among the top ten highest consequence assets that are vulnerable to flooding.**

5. Calculate Risk Scores and Rankings

A risk score was then calculated for each infrastructure asset subject to flooding in a given time horizon using the following equation:

$$R_{tn} = P_{tn} \times C_{tn}$$

Where:

R_{tn} = Risk Score at a given time horizon
P_{tn} = Probability of Exceedance at a given time horizon
C_{tn} = Consequence of Failure rating at a given time horizon
tn = Time horizon n (present, 2030, or 2070)

Assets were then ranked according to their risk scores for each time horizon. Finally, composite risk scores and rankings were developed taking into account the risk scores from all time horizons using the following equation:

$$R_{comp} = (R_{present} \times W_{present}) + (R_{2030} \times W_{2030}) + (R_{2070} \times W_{2070})$$

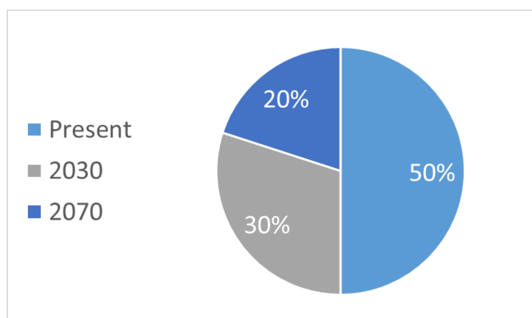
Where:

R_{comp} = Composite risk score for all time horizons
$R_{Present}$ = Risk score for present day time horizon
R_{2030} = Risk score for 2030 time horizon
R_{2070} = Risk score for 2070 time horizon
$W_{Present}$, W_{2030} W_{2070} = Weighting factors for each respective time horizon

A weighting factor is used to give more emphasis to assets vulnerable to flooding in the nearer time horizons. For example, a facility which is susceptible to flooding today and more flooding in the future, should probably get more priority than a facility that is only vulnerable to flooding starting in 2070. The weighting factors can be adjusted, but for the purposes of this study, the Steering Committee decided to use the following weighting based on the consultant's recommendation:

- $W_{Present}$ = 50% (or 0.50)
- W_{2030} = 30% (or 0.30)
- W_{2070} = 20% (or 0.20)

100%



An Excel spreadsheet was developed which incorporated the Probability of Exceedance data, Consequence of Failure scores, and the Risk formulas to automate the ranking process. An example of the Risk Scoring for A Street Fire Station is shown in Table 11. Risk scores for all assets at risk of flooding are reported in Table 12.

Table 11. Risk Scoring Example Matrix for A Street Fire Station

Time Horizon	Probability of Exceedance (%)	Consequence Score	Risk Score	Weight	Composite Risk Score
Present	0	58	0	0.5	359
2030	0.5	58	29	0.3	
2070	30	58	1750	0.2	

Note that the Consequence of Failure scores remain constant for an asset over its lifetime, and that only the Probabilities of Flooding change over time. The only instance where the Consequence of Failure score would change is if some known changes can be anticipated in the future, such as construction of a redundant facility, which would make failure of the asset in question less consequential. For the purposes of this study, we have not anticipated any future changes that would change the Consequence of Failure scores.

Vulnerability Assessment Results

All critical municipal assets in Hull that are vulnerable to flooding are listed in Table 12 along with their Consequence Scores, Probability of Flooding in each time horizon, and Risk Scores for each time horizon and composite. Assets are ranked from highest to lowest Consequence Score.

Table 12. Vulnerable Municipal Assets' Consequence Scores, Probabilities of Flooding, and Risk Scores
(Colors indicate which risk score quartile the asset is in for the given time horizon. Red = High, Orange = Moderate-High, Yellow = Moderate-Low, Green = Low. In addition, Pink = High risk score with very low consequence)

Asset Name/Number	Consequence Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score
Hull Sewer Plant	92	0.1	9	1	92	50	4583	949
Barrier Dunes (Alphabet Streets)	88	20	1750	25	2188	100	8750	3281
Barrier Dunes (Lewis St)	88	10	875	25	2188	100	8750	2844
Barrier Dunes (Phipps St to Malta St)	88	5	438	10	875	100	8750	2231
Hull Memorial Middle School & Emergency Ops Center	79	1	79	2	158	100	7917	1670
Hull High School	71	0	0	0	0	10	708	142
A Street Fire Station	63	0	0	0.5	31	30	1875	384
Municipal Light Dep't	58	0.5	29	5	292	100	5833	1269
DPW Barn	58	0	0	0.2	12	30	1750	354
Spring Street	54	10	542	30	1625	100	5417	1842
Main Street (S Main St to Windmill Point)	54	10	542	25	1354	100	5417	1760
Nantasket Ave (V St to Fitzpatrick Way)	54	1	54	20	1083	100	5417	1435
George Washington Blvd (Rockland Cir to Nantasket Ave)	54	2	108	10	542	50	2708	758
Nantasket Ave (C St to H St)	54	1	54	5	271	50	2708	650
DPW Salt Shack	54	0.2	11	5	271	50	2708	628
Anne Scully Senior Center	54	1	54	2	108	50	2708	601
Waste Water Pump Station 6	54	0.1	5	2	108	50	2708	577
George Washington Blvd (Gosnold St to Rockland Cir)	54	0.2	11	2	108	30	1625	363
West Corner Bridge	54	0	0	0.2	11	30	1625	328
Nantasket Ave (State Park Rd to GW Blvd)	54	5	271	10	542	50	2708	840
Pemberton Pier	54	0	0	0	0	20	1083	217
Newport Road Dike	54	0	0	0	0	0.2	11	2
Waste Water Pump Station 9	50	0	10	0.1	5	30	1500	302
Waste Water Pump Station 5	50	0	0	0.1	5	50	2500	502

Waste Water Pump Station 1	50	0.1	5	10	500	25	1250	403
Waste Water Pump Station 3	50	0	0	0	0	25	1250	250
Atlantic Ave (Summit Ave to Richards Rd)	46	50	2292	100	4583	100	4583	3438
Storm Water Pump Station (D St & Cadish Ave)	46	2	92	5	229	100	4583	1031
Waste Water Pump Station 4	46	0	0	0.2	9	30	1375	278
MLK Bridge	46	0	0	0	0	10	458	92
Draper Ave Storm Water Pump Station	46	0	0	0	0	10	458	92
A Street Pier	29	5	146	20	583	100	2917	831
Nantasket Pier	29	10	292	30	875	50	1458	700
Town Pier (Public)	29	5	146	20	583	50	1458	540
Dust Bowl Heliport	21	25	521	30	625	100	2083	865
Mariners Park Heliport	21	0.5	10	5	104	50	1042	245
L Street Playground Heliport	21	0.2	4	1	21	50	1042	217
Kenberma Playground Heliport	21	0	0	0.1	2	50	1042	209
Roller Hockey Park Heliport	21	0	0	0	0	30	625	125
Hull Wind 1	21	0	0	0	0	10	208	42

ADAPTATION STRATEGIES

General

Types of Adaptation Strategies

There are generally three types of adaptation strategies that may be applicable, individually or in combination, to adapt to the risks of flooding from sea level rise and storm surge:

- Protection,
- Accommodation, and
- Retreat.

These three types of strategies are conceptually illustrated in Figure 8, comparing existing conditions in a typical cross-section of Town with three alternative future conditions where the respective adaptation strategies are implemented. Each strategy is explained below, along with examples.

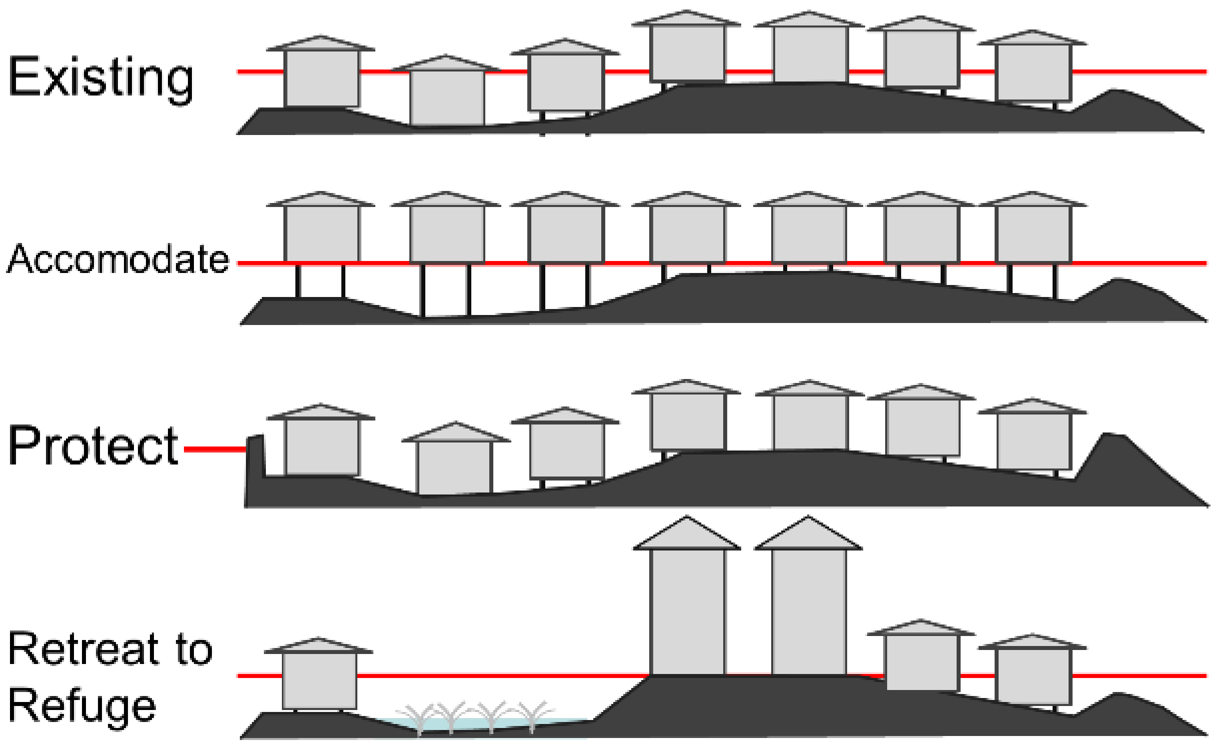


Figure 8. Conceptual Illustrations of Accommodate, Protect, and Retreat Strategies

Protection

Protection strategies try to prevent unsafe conditions and physical damage from occurring by creating a barrier between flood water and vulnerable areas, infrastructure, and buildings. To be truly effective over the longer term, existing protective structures may need to be raised incrementally, in response to sea level rise, and strengthened to withstand the forces of increasingly powerful storms. New structures may also be needed to protect areas that have not historically flooded.

Sea walls, beach dunes, dikes, bulkheads, levees, revetments, flood gates, temporary flood protection barriers, dry floodproofing, and hurricane barriers are all examples of protection strategies that aim to prevent flood water from reaching sensitive areas.

Accommodation

Accommodation strategies accept that vulnerable areas, infrastructure, and buildings will flood, but aim to minimize and control physical damage and unsafe conditions. Accommodation strategies may include physical, operational, or regulatory measures (Figure 9).

Type of Measure	Examples		
Physical	Construct an artificial floodway to convey flood water away from roadways and homes to a natural area or flood-tolerant green space that can store the water with limited damage.	Raise new and existing structures, for example on stilts or piles, above flood elevations with additional freeboard to provide a safety factor.	Implement wet floodproofing measures such as raising occupied spaces and utilities above flood elevations, building with flood damage resistant materials, or using flood-resilient structural design.
Operational	Improve flood evacuation and emergency planning by updating scenarios and plans, training first responders, or providing education and resources to residents and businesses in high flood risk areas.		
Regulatory	Strengthen building codes and zoning to require or encourage projects in high flood risk areas to implement increased setbacks, physical accommodation measures, onsite flood storage, or protection or enhancement of existing natural systems (e.g., dunes, wetlands).		

Figure 9. Examples of Accommodation Strategies

Retreat

Retreat strategies recognize the fact that in some areas it may be too costly, technically not feasible, or politically unrealistic to prevent damage from rising sea levels and storm surge, and that the best strategy is to remove vulnerable infrastructure, buildings, or populations from high risk flood zones. These areas can then be transformed back to more natural states to provide protective, recreational, or other functions that are compatible with occasional or regular flooding. Retreat strategies require significant planning to relocate infrastructure and buildings or resettle populations in areas outside of high risk flood zones.

Examples of retreat strategies include property buyouts, relocation of roads and infrastructure, implementation of new zoning or other regulations that limit new construction, reconstruction, or expansion of structures in high risk flood areas, and policies and programs that steer development towards areas that are safe from flood risks.

Recommended Base Flood Elevations

Prior to developing adaptation strategies, it is important to select a base flood elevation that will be the level to which infrastructure is adapted to.

For the purposes of this study, base flood elevations do not include "freeboard" – height often added above the expected flood level for additional safety. The *design flood elevation* should include freeboard and will vary from site-to-site, reflecting local conditions, criticality of the facility in question, and the owner's tolerance for risk. In addition, designs of any adaption measures must also take into account any code-required minimum base-elevations such as shown on FEMA Flood Insurance Rate Maps. The base flood elevations discussed in this report do not in any way supersede the minimum base flood elevations legally established by the Massachusetts State Building Code or other applicable codes for the design of buildings and infrastructure. The base flood elevations used in this report are presented for the purpose of establishing a reference elevation by which to evaluate various strategies to address flooding impacts from sea level rise and storm surge. During the preliminary design stage of a project, site-level investigations, such as wave run-up and overtopping analyses and code reviews, should be completed where applicable (e.g., seawalls and dunes) to determine actual design flood elevations.

Figure 10 below shows representative coastal base flood elevations for Hull at different probabilities of exceedance in the 2030 and 2070 time horizons. For the purposes of this study, we have based recommended adaptation options on a base flood elevation equivalent to the 1% probability of exceedance flood levels in 2030 and 2070 (approximate 100 year recurrence interval). Site-specific flood elevations vary and are documented in the data submitted to the Town with the Task 2 Memorandum. The 1% probability of exceedance sets a reasonably conservative base flood elevation on which to base minimum standards for critical assets and large floodplains.

The typical difference between the 1% and 0.2% flood elevations is approximately 0.5 ft. in 2030 and 1.1 ft. in 2070.

Exceedance Probability (%)	2030 Water Surface Elevation (ft-NAVD88)	2070 Water Surface Elevation (ft-NAVD88)
0.1	10.8	14.1
0.2	10.5	14.0
0.5	10.1	13.6
1	10.0	12.9
2	9.9	12.6
5	9.6	12.1
10	9.0	11.5
20	8.5	11.0
25	8.1	10.8
30	8.0	10.7
50	dry	10.2
100	dry	9.1

Recommended Base Flood Elevations

Figure 10. Water Levels at Different Probabilities of Exceedance for 2030 and 2070

Selecting a more conservative base flood elevation, such as the 0.2% probability elevation (500-year recurrence interval), may be prudent if the criticality of the area or asset to be protected is very high, but it has some impacts on the feasibility and cost of adaptation strategies to modify what exists today in vulnerable areas. If, for example, the Town proposed to raise an existing seawall, the cost of construction would be higher if it raised it to the 0.2% flood elevation than to the 1% flood elevation. It might also present design challenges, depending on the site.

Adaptation at Different Scales

Asset Level

For specific critical municipal infrastructure assets and buildings, it may be necessary or preferable to implement strategies at the asset level to adapt to flooding. Asset level strategies are particularly needed for assets located in high flood risk areas for which regional strategies have been rejected for technical, political, or financial reasons. It is also necessary for assets that are outside of the scope of regional flood protection strategies. Asset level adaptation is also preferable for very critical assets that cannot afford to wait until regional solutions are implemented.

This report provides conceptual, asset level adaptation strategies for many critical municipally-owned assets at risk of flooding, along with order-of-magnitude cost estimates. The recommended strategies have been vetted with the Town’s Steering Committee, as well as with Massachusetts Coastal Zone Management staff members.

Regional

Regional adaptation strategies aim to reduce flood risks across a geographical area that may contain multiple critical municipally-owned assets as well as privately-owned assets including buildings, roadways, and other infrastructure. Some of the large areas at risk of coastal flooding in Hull are at risk because of “flood pathways”, which are low-lying strips of land that permit coastal flood waters to flow further inland into other low-lying areas where there is existing development (areas that are usually dry). Solutions to close these flood pathways, or otherwise address them, are referred to in this report as regional strategies. In other cases, regional strategies may be related to improving the protective value of existing natural protections (e.g., dunes, beach) or man-made coastal structures along an entire stretch of coastline.

Regional strategies can be costly to implement. However, the benefits of regional strategies are that they can be relatively cost-effective and straightforward to implement, and provide significant reduction in flood risk for a large number of beneficiaries through a single project, compared to a site-by-site approach of many independent projects. Implementation of regional strategies to address flood risks in the 2070 time horizon, when most of the Town will face significant risks, may face higher technical, political, and financial challenges.

Regional strategies can require significant efforts to develop and evaluate alternatives. This level of effort is beyond the scope of this project. However, in the following sections, each region’s sources of flood risk (flood pathways, etc.) and critical infrastructure at risk are identified for future use in developing regional strategies.

High Risk Areas and Asset Level Adaptation Strategies

This section of the report describes the areas of Town with critical Town-owned assets at a high risk of coastal flooding. For each high risk area, the critical municipal assets within it are listed and the potential pathways, sources, and depths of coastal flooding are described with a focus on the longer term (2070). With this information, the Town can begin developing alternative adaptation strategies tailored to each region.

The following seven high risk areas of Hull are outlined and numbered in yellow in Figure 11:

1. Pemberton
2. Stony Beach
3. Waveland – West of Nantasket Avenue
4. North Nantasket Beach
5. Kenberma – West of Nantasket Avenue
6. Nantasket Beach and George Washington Boulevard
7. Atlantic Avenue

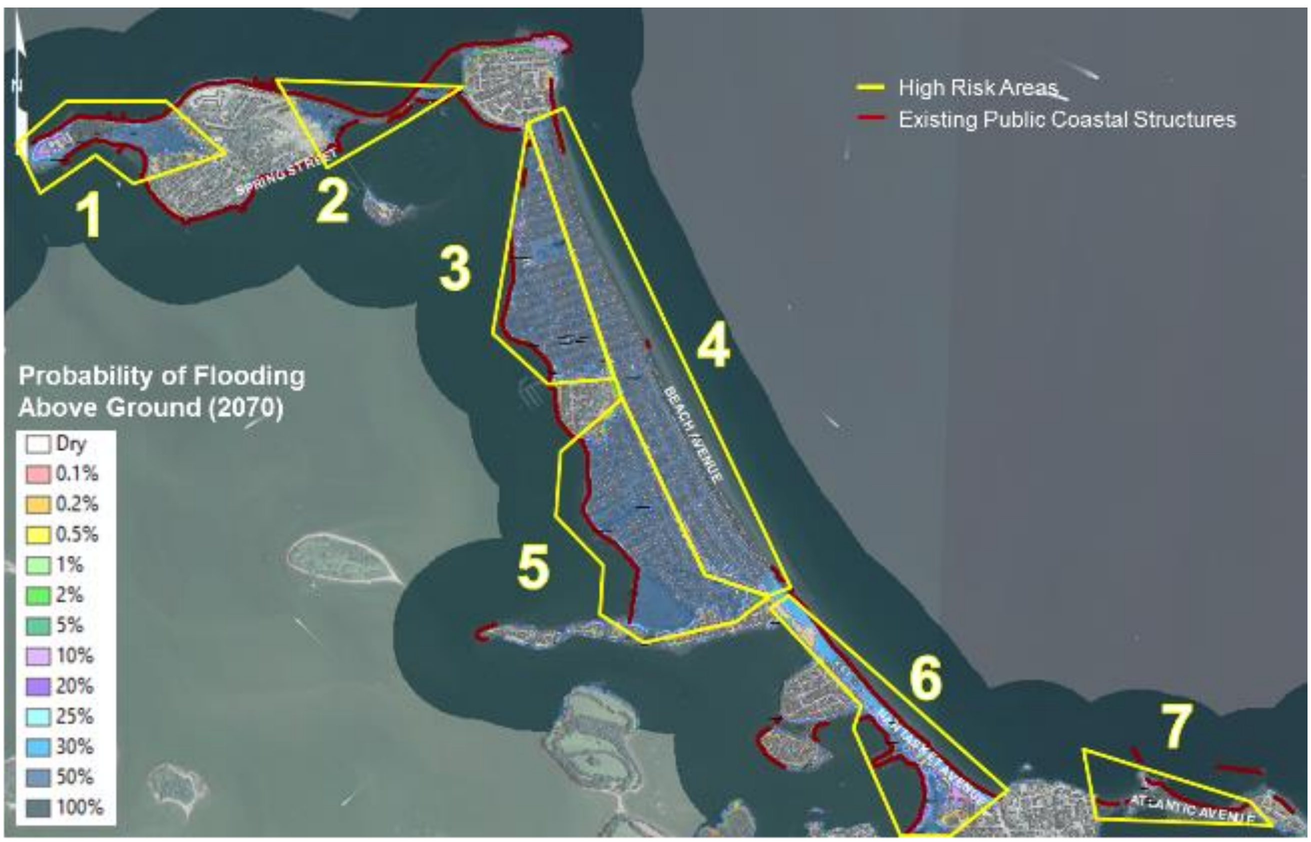


Figure 11. Seven High Risk Areas in Hull

There are a number of municipally-owned infrastructure assets and facilities that are vulnerable to flooding today and more so by 2030 and 2070. Given that regional adaption strategies for the high risk areas may take many years to develop and implement, if they can be implemented at all, asset level recommendations are presented that can be implemented in the near, medium, and longer term future.

In the following sections, adaptation options are recommended for assets in each high risk area, with additional guidance for decision makers and designers. Order-of-magnitude cost estimates, in 2016 dollars are provided, where possible, for long-term planning purposes. These costs in no way are meant to represent actual estimates of total project costs as no surveying, subsurface exploration, engineering design, permitting and escalation of costs was performed as part of this project, all of which are necessary to establish true project costs required to design and construct a project.

Adaptation strategies recommended for vulnerable municipal assets are summarized in Table C2 in Appendix C, along with risk information that is important for decision-making.

High Risk Area 1: Pemberton

Description of the Area Vulnerable to Flooding

The Pemberton area is at the northernmost tip of the Hull mainland. It hosts several critical municipal infrastructure assets, most notably Hull High School, as well as non-municipal public facilities. Aside from these and a few maritime businesses, the area is primarily residential. The area also includes an existing high marsh ecosystem which is isolated from normal tidal exchange by roadways, flood control infrastructure, and surrounding residential development.

In 2030, the low-lying parts of this area are anticipated to have a 25% to 30% (1-in-4 to 1-in-3) annual probability of flooding. By 2070, this area is anticipated to flood every year or every other year on average. In that time frame, the area also has a 1% annual probability of flooding over 7.0 ft. in depth at some buildings.

Sources of Flooding

The Pemberton area is subject to flooding from storm surge on both the ocean and bay side (see the red arrows in Figure 12).

Wave run-up and overtopping are the main issues historically experienced on the ocean side. The top elevation of the existing seawall on the ocean side is 13.0 ft. NAVD88 and the top elevation of the revetment is 14.0 ft. NAVD88 which are both higher than the 2070 1% flood elevation of 12.8 ft. NAVD88. However, revetments do not prevent overland flooding through the spaces between the revetment stones.

Overland flooding through low-lying flood pathways and over low seawalls on the bay side are serious medium and long term concerns. The top elevations of seawalls on the bay side range from around 8.0 ft. to 10.5 ft. NAVD88. Once water passes over Main Street from the bay, extensive low-lying residential neighborhoods areas are subject to flooding.

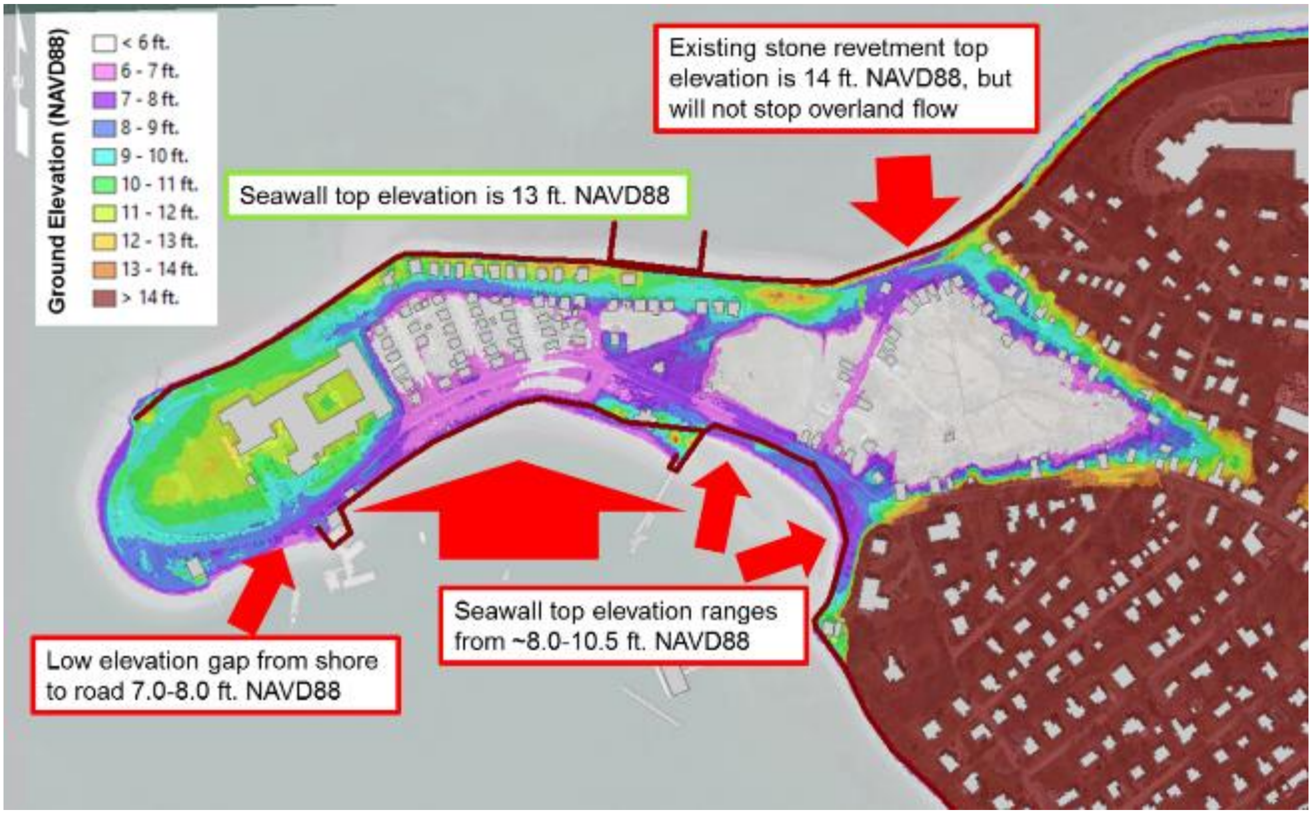


Figure 12. Sources of Flooding for High Risk Area 1: Pemberton

Critical Assets at Risk

There are numerous municipally-owned critical assets within this area that are vulnerable to flooding, including:

Hull High School	Pemberton Pier (MBTA Commuter Ferry, Ambulance service to islands)
Hull Wind 1	Waste Water Pump Station 9
Dust Bowl Heliport	Seawalls and Revetments

The roads vulnerable to flooding in this area, include:

Main Street	Channel Street
Helen Street	Arthur Street
Mildred Street	Town Way
Ocean Avenue	Spring Street
Bay View Street	Adduci Way
S Main Street	

Although not municipally-owned assets, the MBTA Commuter Ferry Floating Dock, US Coast Guard facility, and Federal Aviation Administration (FAA) facility in this area may also be vulnerable to flooding. The FAA facility is being removed this year.

The area includes an estimated 112 buildings (excluding the Hull High School and Pemberton Pier buildings), with a total footprint area of 111,406 square ft., that are potentially vulnerable to flooding.

Main Street

Main Street is the single access route to Hull High School and the MBTA Commuter Ferry from Telegraph Hill and Hull Village.

The entire road from South Main Street to Wind Mill Point is below the 2070 1% annual probability flood elevation (12.8 ft. NAVD88) and the 2030 1% annual probability flood elevation (9.5 ft. NAVD88). The lowest point of the road is at 6.0 ft. NAVD88 at the intersection with Mildred Street. This low area has an annual probability of flooding of 10% (1-in-10 chance) at present, 25% (1-in-4 chance) in 2030, and 100% (every year) in 2070.

Seawalls on the bay side of the road have a top elevation ranging from 8.0-10.5 ft. NAVD88. However, the seawall ends at Pemberton Pier and returns to a ground elevation of 7.0-8.0 ft. NAVD88. Redesigning and raising these coastal structures, and regrading or constructing a berm to eliminate the gap from Pemberton Pier to Windmill Point, would provide additional protection to the roadway, Hull High School, Waste Water Pump Station 9, and private residences. However, permitting of such improvements may be a challenge, as would financing the improvements.

An alternative strategy to addressing the road's vulnerabilities is to improve evacuation planning for the surrounding neighborhood, to reduce the public safety impacts of the road being inaccessible during flooding, and to develop a debris management plan for reestablishing roadway access following a flood. This strategy requires no capital costs.

Another strategy would be to raise low-lying segments of the road. There are only two private properties with driveways on Main Street that would be impacted. However, adjacent parking lots and connections to feeder roads would need to be regrading to provide a safe transition.

The order-of-magnitude cost of raising the road to 10.0 ft. NAVD88 (~0.2% annual probability of flooding in 2030) would be approximately $4 million. This does not include impacts to private properties, or adjustments needed to transition to adjacent parking lots.

Hull High School

The approximate first floor elevation of Hull High School is 11.5 ft. NAVD88, and the 2030 and 2070 1% flood elevations are 9.5 ft. and 12.8 ft. NAVD88, respectively. Some doorways that water could enter the building through are at a lower elevation than the first floor, such as the one shown in Figure 13. In addition, weep holes in the building's brick façade may allow water to seep into the building and cause damage or mold, especially if flooding is prolonged. These weep holes are typically located close to ground level, just above the top of the concrete foundation wall. Because the ground along the east wing of the school is about 2.0 ft. lower in elevation than the rest of the High School grounds, this part of the school is more vulnerable to seepage issues. These flood risks are approximately illustrated in Figure 13, alongside a conceptual illustration of the recommended adaptation strategy to protect Hull High School.

The recommended adaptation strategy is to construct a decorative flood wall (e.g., concrete with brick or stone veneer) around the building perimeter, with openings across the parking lot and at each entrance to the building (1,050 linear ft.). Sections of the wall would vary in height according to the site topography, ranging from 2.5 ft. to 5.0 ft, in order to meet the 2070 1% flood elevation. Demountable flood panels, of the same height as the adjoining flood walls, would be purchased and installed across the wall openings, as shown in Figure 13 (265 linear ft.). The building may require additional floodproofing measures such as conduit sealing, backflow protection, and portable pump systems to be protected from other sources of flooding.

<u>Estimated order-of-magnitude cost (longer term):</u> $650,000

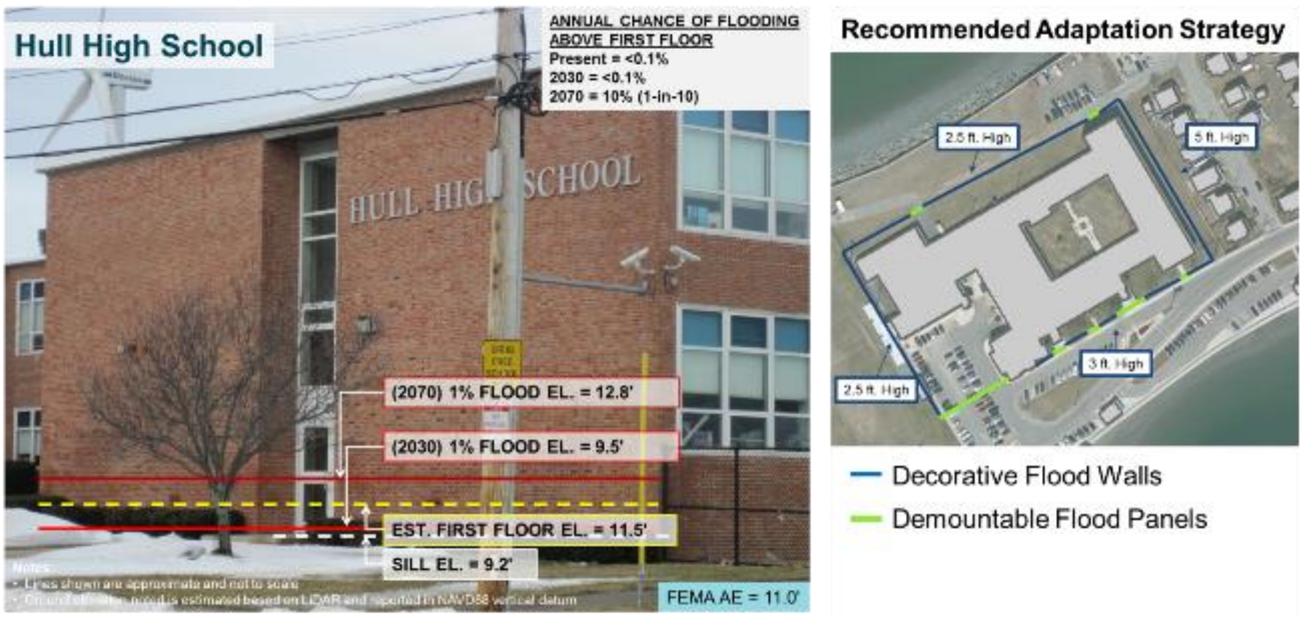


Figure 13. Hull High School Flood Risks and Adaptation Strategies

Hull Wind 1

The approximate ground elevation at the electrical cabinets powering Hull Wind 1 is 11.8 ft. NAVD88, and the 2070 1% flood elevation is 12.8 ft. NAVD88. The entrance to the base of the tower where controls are located appears to be elevated above 12.8 ft. NAVD88. However, interior conduits with electrical and telecommunications cabling may be affected by flooding. These flood risks are approximately illustrated in Figure 14, alongside a conceptual illustration of the alternative adaptation strategies to protect Hull Wind 1 from coastal flooding.

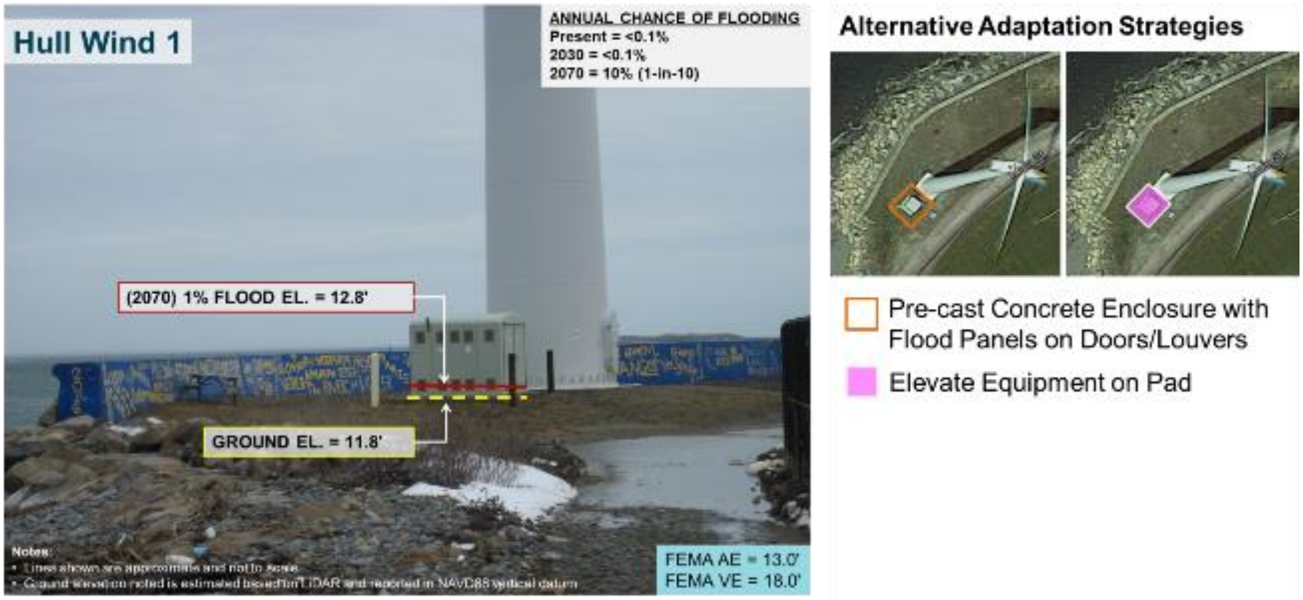


Figure 14. Hull Wind 1 Flood Risks and Adaptation Strategies

In both alternatives, conduits in the base of the tower with openings below the 2070 1% flood elevation should be sealed to prevent leakage, and any critical controls below this elevation should be elevated. It is assumed that controls are already elevated.

The adaptation alternative on the left is to construct a pre-cast concrete enclosure over the existing cabinets. This enclosure would be designed to be watertight and withstand flood forces up to the 2070 1% flood elevation. If the enclosure door sill is below the design flood elevation, a demountable flood panel would need to be installed across the door opening. Louver sills should be elevated above the design flood elevation, but if that is not feasible, demountable flood panels would also need to be installed across the louver openings. Conduits should be sealed to prevent leakage into the enclosure.

Estimated order-of-magnitude cost: $ 75,000

The adaptation alternative on the right is to elevate the existing electrical cabinets at least 1.0 ft. above grade so that the base of the cabinets is above the 2070 1% flood elevation.

Estimated order-of-magnitude cost: $150,000

Given the typical lifetime of electrical equipment, it is likely that major repairs or equipment replacement would be carried out between 2030 and 2070. It may therefore make sense to incorporate adaptation measures at such time as these maintenance activities take place. Hull’s access to electricity is not dependent on the functioning of Hull Wind 1, so its temporary loss of function due to flood damages may be an acceptable risk when compared with the cost of implementing adaptation measures.

Pemberton Pier

Pemberton Pier is a fixed pier structure with several floating docks, including the MBTA Commuter Ferry floating dock. It is also used for ambulance service to the islands.

Fixed pier structures are subject to damage from vertical and horizontal forces caused by surge and waves as well as debris impacts. Typical storm damages for fixed docks include uplifting of deck planks and, in more powerful storms, misalignment or structural damage to pilings.

Minor storm damages to the fixed pier in the near-to-medium term (present to 2030) should simply be repaired, as needed. If major damage occurs, such as structural damage to pilings, the Town should take the opportunity to raise the pier top elevation by as much as is allowable given the types of vessels the pier serves. The deck elevation of the fixed pier is estimated to be 11.0 ft. NAVD88. At a minimum, the new top elevation should aim to compensate for the projected impacts of sea level rise on high tide elevation within the redesigned pier's design life. Sea level rise estimates are shown in Table 1. Over the longer term (2070) the pier's deck height will need to be raised to a higher elevation or face a 20% annual probability of stillwater flooding, which is substantially lower than wave crest heights.

Floating docks are at risk of rising above the heights of the pilings they are collared to and becoming dislodged. Free-floating docks act as waterborne debris and can not only be severely damaged, they can also damage other structures. The MBTA Commuter Ferry floating dock has come within 3 ft. of the top of pilings (top elevation of 16.0 ft. NAVD88) in past storms, according to the Hull Harbormaster (Figure 15). These wooden pilings should be vertically extended to minimize the risk of an extended disruption to commuter ferry service, which many Hull residents depend on, following a major storm.

<u>Estimated order-of-magnitude cost (extending pilings):</u> $150,000

Figure 15. MBTA Commuter Ferry Floating Dock at Pemberton Pier

Waste Water Pump Station 9

Waste Water Pump Station 9 is located just adjacent to Pemberton Pier in the parking lot area behind a low seawall. The pump station structure is elevated approximately 3.5 ft. above ground on a raised foundation (floor elevation is ~10.5 ft. NAVD88). The enclosure has a doorway and louvers through which flood waters could enter and flood the pump station, damaging critical equipment.

Projected flood elevations indicate that the pump station is unlikely to flood by 2030 (only 0.1% annual probability or 1-in-1,000 chance). However, by 2070, it is projected to have a 30% annual probability of flooding, with depths over 2.0 ft. from the 1% annual probability flood elevation. These flood risks are approximately illustrated in Figure 16.

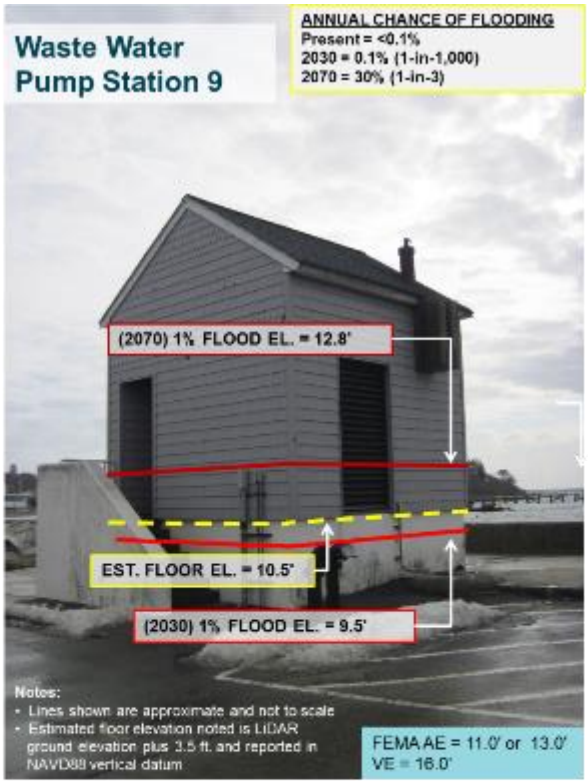


Figure 16. Waste Water Pump Station 9 Flood Risks

Alternative longer term adaptation strategies for Waste Water Pump Station 9 include elevating or dry floodproofing the pump station building (Figure 17).

In the first alternative, on the left, the pump station would be elevated by approximately 2.5 ft. so that the first floor elevation is above the projected 1% annual probability flood elevation in 2070. Due to the pump station's location in the velocity zone, the new foundation must be carefully designed by a structural engineer to withstand wave forces. This alternative realistically would be undertaken as part of a regularly scheduled replacement/upgrade project.

<u>Estimated order-of-magnitude cost (elevation):</u> $250,000 to $400,000

In the second alternative, the building envelope would be replaced with a waterproof pre-cast concrete enclosure. Then openings in the enclosure, such as the doorway and any required louvers would be fitted with demountable flood panels up to the design flood elevation. Structural anchoring of the enclosure to the foundation must also be designed to withstand wave forces.

<u>Estimated order-of-magnitude cost (dry floodproofing):</u> $200,000 to 300,000

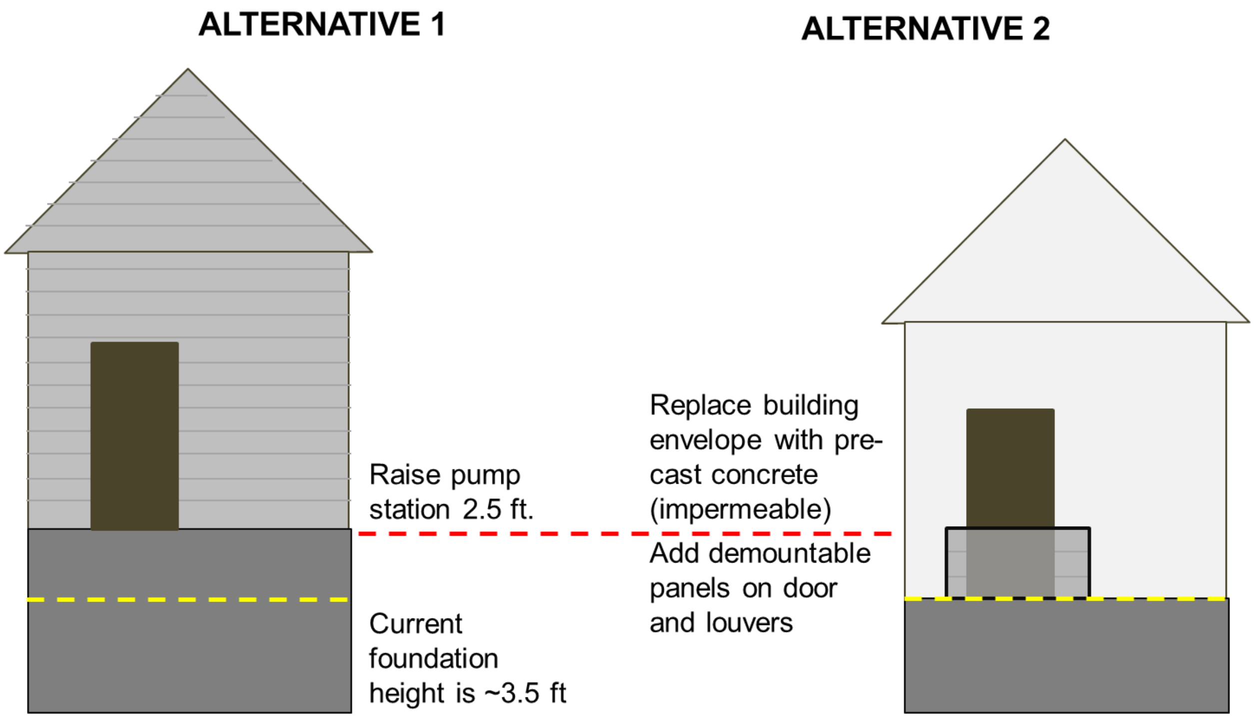


Figure 17. Elevating equipment and dry floodproofing measures

High Risk Area 2: Stony Beach

Description of the Area Vulnerable to Flooding

The Stony Beach high risk area begins at Duck Lane and Spring Street, at the east end of Hull Village and Telegraph Hill, and extends along Nantasket Avenue and Fitzpatrick Way past Mariners Park and the Town Pier. The defining feature of this area is the Hull Sewer Plant. Beyond that, the area hosts a small wetland, residential buildings, and the causeway to Spinnaker Island.

In 2030, this area is anticipated to have a 25% (1-in-4) annual probability of flooding. By 2070, this area is anticipated to flood every year or every other year on average. In that time frame, the area also has a 1% annual probability of flooding over 4.0 ft. in depth at some buildings.

Sources of Flooding

The Stony Beach area is subject to flooding from storm surge on both the ocean and bay side (see the red arrows in Figure 18).

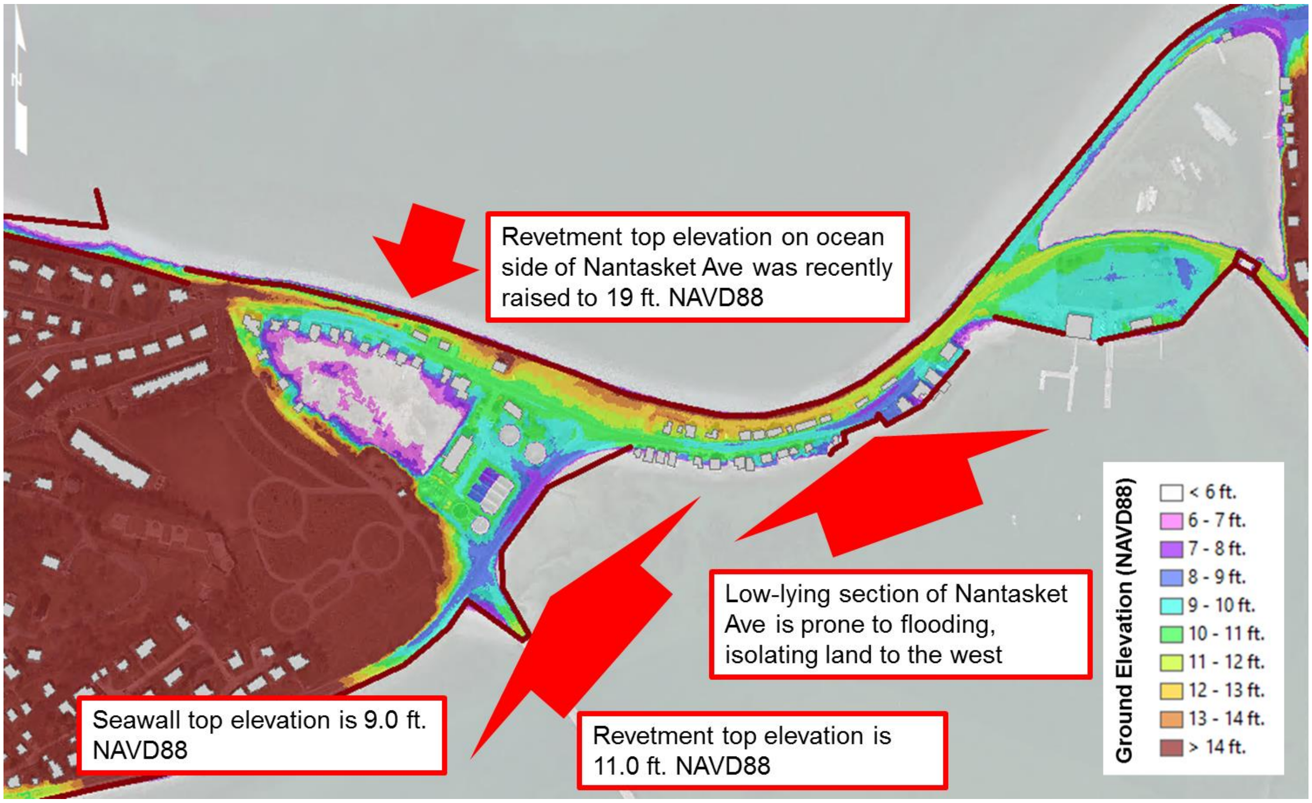


Figure 18 – Sources of Flooding for High Risk Area 2: Stony Beach

Wave run-up and overtopping are the main issues historically experienced on the ocean side. Such flooding has occurred several times in the past significant flood damage to the Sewer Plant. A flap valve was installed at the end of the pipe that provides a hydraulic connection from the bay to the wetland, eliminating that source of flooding. The top elevation of the recently-repaired stone revetment on the ocean side is 17.0 ft. NAVD88 which is higher than the 2070 1% flood elevation of 12.8 ft. NAVD88. However, revetments do not prevent overland flooding through the spaces between the revetment stones.

Overland flooding across Spring Street from the bay will become a serious concern in the medium to longer term, both for the Hull Sewer Plant and the residential properties that line the edge of the adjacent wetland. Coastal protection along Spring Street includes a 429 ft. long seawall, south of the Spinnaker Island Causeway, and a 1,105 ft. long revetment. The top elevation of seawall is only 9.0 ft. NAVD88 and the revetment's top elevation is 11.0 ft. NAVD88. Again, revetments do not prevent overland flooding through the spaces between the revetment stones.

In addition, there is a low-lying section of Nantasket Avenue (less than 9.0 ft. NAVD88 in elevation) that floods on a recurring basis, turning the communities of Hull Village, Telegraph Hill, and Pemberton into an island. Some residential buildings on its bay side have their first floors at or below the roadway grade and are very exposed to waves from the bay.

Critical Assets at Risk

There are numerous municipally-owned critical assets within this area that are vulnerable to flooding, including:

Hull Sewer Plant	Town Pier
Mariners Park Heliport	Seawalls and Revetments
James Avenue Pier	

The roads vulnerable to flooding in this area, include:

Nantasket Avenue	Spring Street
Fitzpatrick Way	Duck Lane

The area includes an estimated 44 buildings (excluding the Hull Sewer Plant buildings), with total footprints of 50,865 square ft., that are potentially vulnerable to flooding.

Spring Street

Spring Street is one of two roads that provide access to and from the neighborhoods of Telegraph Hill, Hull Village, and Pemberton, including to Hull High School and the MBTA Commuter Ferry.

Approximately 1,600 linear ft. out of the 2,600 linear ft. of Spring Street between Nantasket Avenue and Main Street are below the 2070 1% annual probability flood elevation (12.8 ft. NAVD88). The lowest area within this segment, located directly between Hull Sewer Plant and the bay, has an elevation just above 8.0 ft. NAVD88 and has an annual probability of flooding of 10% (1-in-10 chance) at present, 30% (~1-in-3 chance) in 2030, and 100% (every year) in 2070. Another area near the intersection with Main Street will be at risk of flooding by 2030.

Between the low-lying areas of the road and the bay there is a 1,105 linear foot revetment with a top elevation of 11.0 ft. NAVD88, and a 429 linear foot seawall with a top elevation of 10.0 ft. NAVD88. Redesigning and raising these coastal structures may provide additional protection to the roadway and Hull Sewer Plant. However, permitting of such improvements may be a challenge, as would financing the improvements.

One adaptation strategy to explore would be to raise low-lying segments of the road. Raising Spring Street along its border with the Hull Cemetery and Hull Sewer Plant would not be technically or politically difficult, due to the lack of private property impacts.

The order-of-magnitude cost of raising this area to 11.0 ft. NAVD88 (~0.2% annual probability of flooding in 2030) would be approximately $1-2 million.

Nantasket Avenue / Fitzpatrick Way

In order for raising Spring Street to be an effective strategy for reducing road inaccessibility due to flooding, low-lying segments would also need to be raised on Nantasket Avenue, from Spring Street to Fitzpatrick Way, and the entirety of Fitzpatrick Way. Nantasket Avenue has numerous abutting private residences which would be impacted by a road raising project, unless they were elevated first.

The order-of-magnitude cost of raising these over 3,000 linear ft. of road to 11.0 ft. NAVD88 (~0.2% annual probability of flooding in 2030) would be approximately $5-6 million. This does not include impacts to private property.

Hull Sewer Plant

Hull Sewer Plant is located at the intersection of Nantasket Avenue and Spring Street. The Sewer Plant had the highest Consequence score of any vulnerable municipal infrastructure asset in Hull. It provides sewer treatment service to the entire Town. According to the modeling carried out for this study, the main building has a 1% annual probability of flood waters exceeding its first floor elevation in 2030 and a 50% chance in 2070. Figure 19 shows the flood risk based on this study for the Hull Sewer Plant.

Figure 19. Hull Sewer Plant Flood Risks and Adaptation Strategies

The facility was damaged by coastal flooding in the Blizzard of 1978 and no-name storm of 1991 ("the Perfect Storm"), when flooding was high enough to flood the entire main building and flow into the tanks distributed around the Sewer Plant grounds. After the main building was flooding in 1978, it was retrofitted with various floodproofing measures, including removable and permanent flood barriers to prevent water entry through vulnerable openings such as doorways along the building's exterior. Removable flood panels installed across overhead doorways can be seen in Figure 19. Like most dry floodproofing systems, it is not designed to prevent flooding above a certain point after which the building structure could fail due to overwhelming hydrostatic forces. If water exceeds roughly 3.5 ft. in depth against the building, water will flow over the barriers and into the building, equalizing the pressure inside and out.

The Town recently repaired and elevated the revetment along Stony Beach, on the ocean side of Nantasket Avenue. This improvement was included in the modeling carried out for this study. The results indicate that the probability and projected depths of flooding at the Sewer Plant have been significantly mitigated by this project, especially in the near to medium term.

Due to critical components of the Sewer Plant, including buildings, tanks, pumps, controls, and utilities, being spread throughout the facility grounds, the least complicated strategy is to protect the entire site with a perimeter flood wall. This strategy would have the added benefit of protecting the main building from flooding greater than the 3.5 ft. limitation of its current floodproofing system. The existing perimeter chain link fence (approximately 1,400 linear ft.) should be replaced with a concrete or sheet-pile perimeter flood wall, with movable barriers at the two main road entrances to the plant. The Town would need to decide on the appropriate height of the wall. Given the long-lived and highly critical nature of the Sewer Plant, the top elevation should be no lower than the 0.2% annual probability flood elevation for 2070 (13.9 ft. NAVD88) which would mean the wall would need to be at least 5 ft. tall. Freeboard above that elevation should be considered, based on the additional incremental cost, uncertainties with the future projections, and the Town's appetite for risk. The building may require additional floodproofing measures such as conduit sealing, backflow protection, and portable pump systems to be protected from other sources of flooding.

The Town's consultants previously estimated the <u>order-of-magnitude cost (long term)</u> of constructing such a flood wall to be approximately $3 million.

An incremental version of this strategy would be to design the sheet pile wall with a lower above ground height and sufficient below ground depth to support an eventual above ground height of 5.0 ft. or greater (i.e., overbuild the foundation so that it can handle a future extension). In the future, sheet pile attachments could be designed and installed to extend the above ground flood wall height to meet a higher design flood elevation.

If such an expense is not financially feasible in the medium term, the Town should consider carrying out a maintenance overhaul of the main building's existing flood protection system. The effectiveness of floodproofing systems depends on the water-tightness of various gaskets and seals which break down over time and become subject to leakage and failure. The Town should carry out a thorough inspection of the existing system and repair and replace parts that have surpassed their design life or gone missing.

<u>High Risk Area 3: Waveland – West of Nantasket Ave</u>

<u>Description of the Area Vulnerable to Flooding</u>

The Waveland area, west of Nantasket Avenue, stretches from A Street to Fitzpatrick Way on the bay side of Hull. It includes a large number of residences along with numerous critical municipal infrastructure assets and the Town's largest recreational park. The area is topographically shaped like a basin, with Cadish Avenue and Nantasket Avenue forming the outer rim.

In 2030, this area is anticipated to have a 5% to 20% (1-in-20 to 1-in-5) annual probability of flooding. By 2070, this entire area is anticipated to flood every other year on average. In the 2070 time frame, the area also has a 1% annual probability of flooding over 5.0 ft. in depth at some buildings.

<u>Sources of Flooding</u>

During the Blizzard of 1978, flooding from the ocean side crossed over Nantasket Avenue, between A Street and X Street, and caused flooding in the Waveland are. However, the main source of future flooding in this area is likely from the bay side of Hull. There are several low-lying flood pathways along the bay which, given sea level rise and increasing storm surge, can allow flooding to penetrate the bay side coastline and reach interior areas of Waveland (see red arrows in Figure 20).

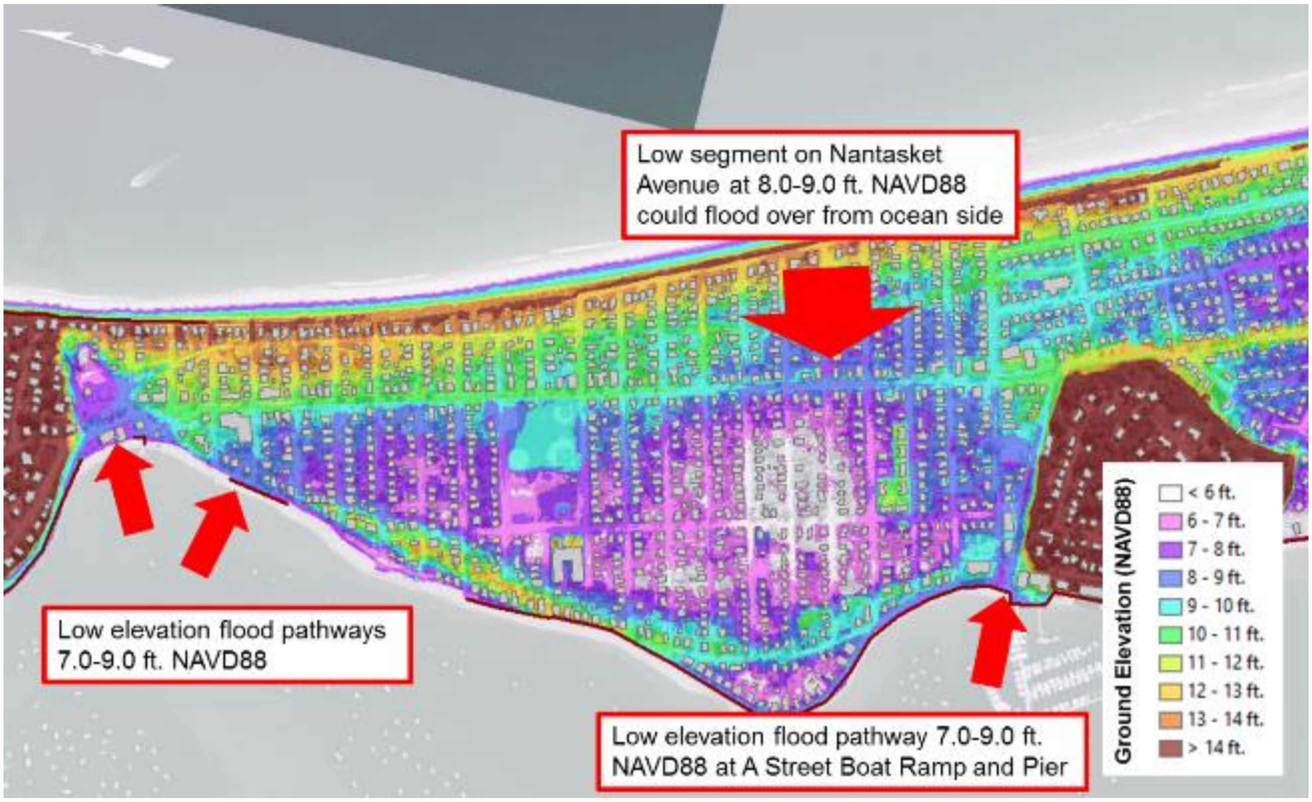


Figure 20. Sources of Flooding for High Risk Area 3: Waveland – West of Nantasket Ave

The northernmost flood pathway is at the junction of Nantasket Avenue and Fitzpatrick Way, where the land elevation drops considerably to around 8.0-9.0 ft. NAVD88. Aside from the loss of accessibility to Fitzpatrick Way that this would result in, if flood elevations remained below 10.0 ft. NAVD88, only a small area with several commercial properties and no critical municipal infrastructure would be affected.

The widest and possibly most critical flood pathway is along Cadish Avenue from S Street to U Street. The elevation in this area is 8.0-9.0 ft. NAVD88 and leads directly to interior areas that are lower in elevation. Through this flood pathway, overland flow would enter and fill the low-lying basin that covers most of Waveland. There is a 340 linear ft. seawall of unknown top elevation across part of this pathway, but it does not cover the entire pathway and would therefore be ineffective.

Another flood pathway leading to the same basin-filling outcome is at the A Street Boat Ramp and Pier. Again, if water on the bay side reached 8.0-9.0 ft. NAVD88, it would flow through A Street and fill the low-lying interior areas of Waveland. This flood pathway is much narrower than the other two.

Finally, flood could also originate from the ocean side of Nantasket Avenue, as it did during the Blizzard of 1978. Land on that side is generally more elevated than on the bay side. However, there are lower-lying areas and the ocean side is more exposed to flooding from wave run-up and overtopping, as well as dune erosion. If the ocean side of Nantasket Avenue flooded to an elevation at or above 8.0-9.0 ft. NAVD88, it could pass over a low segment of Nantasket Avenue between C Street and H Street and fill the Waveland basin.

Addressing these flood pathways will provide a significant improvement in flood protection over existing conditions, but would not eliminate the risk of flooding under very extreme scenarios in 2030 (1% or lower probability) or even moderate scenarios in 2070.

Critical Assets at Risk

There are several municipally-owned critical assets within this area that are vulnerable to flooding, including:

A Street Fire Station	Memorial Middle School (also the Emergency Operations Center and a Warming Center)
Waste Water Pump Station 6	D Street Stormwater Pumping Station
A Street Pier	L Street Playground Heliport
Seawalls and Revetments	

The roads vulnerable to flooding in this area, include:

Nantasket Avenue	Central Avenue
Cadish Avenue	Sunset Avenue
A Street	B Street
C Street	D Street
East Street	F Street
G Street	H Street
I Street	J Street
K Street	L Street
M Street	N Street
O Street	P Street
Q Street	R Street
S Street	T Street
U Street	V Street

The Waveland high risk area includes an estimated 673 buildings (13% of all in Hull), with total footprints of 875,435 square ft., that are potentially vulnerable to flooding.

Memorial Middle School

It is the consultant's opinion that the recommended adaptation strategies for the Memorial Middle School should be implemented as a high priority for the Town. There is a relatively high probability that the building's lower level will experience damaging flooding by 2030, and the consequences in terms of damage and remediation costs, public health concerns, the impact on school operations, and the loss of emergency operations center functions, make the consequences of allowing it to flood unacceptably high.

The present (2013), 2030, and 2070 1% flood elevations at the Memorial Middle School are 8.7 ft., 10.0 ft., and 13.0 ft. NAVD88, respectively. The critical elevations above which flooding would enter the Memorial Middle School lower level range from 7.5 ft. NAVD88 and 8.5 ft. NAVD88. These are the approximately ground elevations at lower level doorways on the west side of the building along L Street and in the parking area between the north and south wings. Water could also enter the lower level entrance at the front of the school if flooding on Central Avenue exceeded an elevation of 8.5 ft. NAVD88. This means that the school is presently at risk of flooding (albeit to a limited depth), and that the likelihood and possible depths of flooding that it could experience will increase over the medium and longer term. Figure 21 shows the ground elevation at the doorway on the corner of M Street and L Street, alongside a conceptual illustration of the incremental adaptation strategies recommended to protect the Middle School.

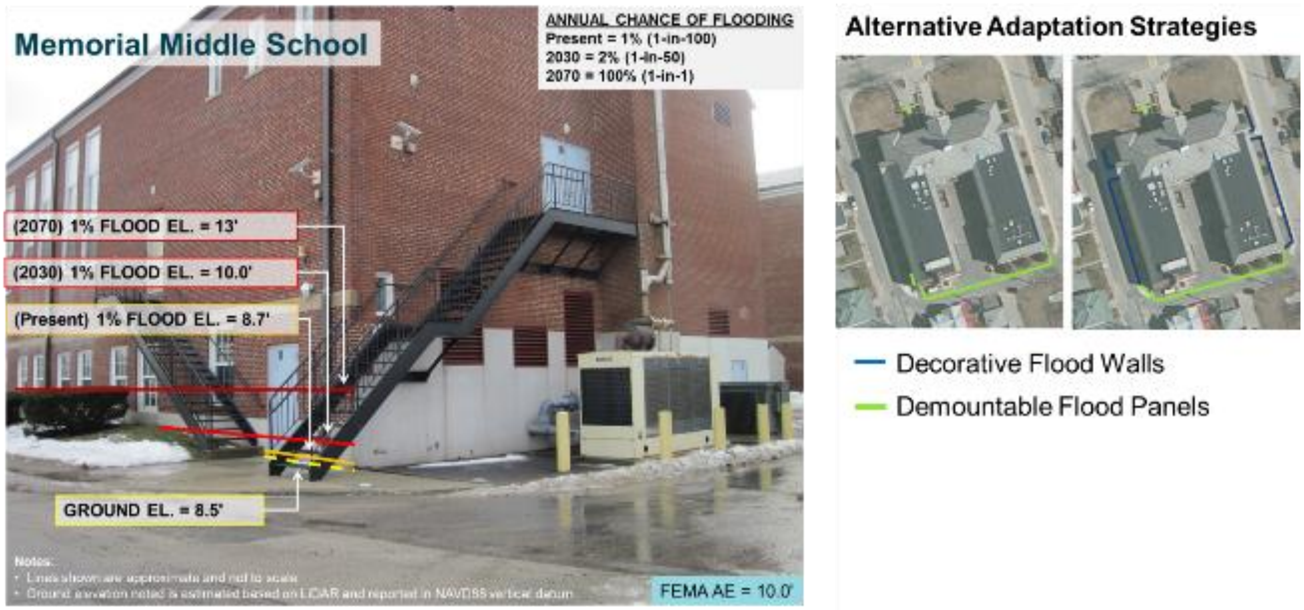


Figure 21. Memorial Middle School Flood Risks and Adaptation Strategies

The adaptation alternative on the left is presented as a medium term solution to protect the school from flooding under the 2030 1% flood elevation. It consists of purchasing demountable flood panels and installing them across low-lying doorways and other possible entryways for water. One long span would extend across the entire west side of the building and connect to the building on both ends (195 linear ft.). In the front of the building, flood panels would extend across the top of the stairs that lead down to the lower level entrance, and attach to the retaining walls on either side of the stairs (12 linear ft.). For both installations, the panels need not be higher than 3.0 ft., because, if flood elevations exceed this height, water will enter the lower level through windows along the north and south sides of the building. That is unlikely in the medium term according to the study's findings. One applicable type of demountable flood panel system (Aquafence) comes standard with a 4.0 ft. height and can be extended an additional 2.0 ft. in height with attachments sold separately. This would be required for the entire system to be re-used as part of the longer term solution.

<u>Estimated order-of-magnitude cost (medium term):</u> $184,000

The adaptation alternative on the right is presented as a longer term solution to protect the school from flooding under the 2070 1% flood elevation. A decorative flood wall (e.g., concrete with brick veneer), approximately 5.0 ft. in height, would be constructed at the current edge-of-sidewalk along the north and south sides of the buildings. There would be breaks in the wall with connections back to the building at the stairs to the second floor entrances (360 linear ft.). Demountable flood panels (5.0-6.0 ft. high) would be purchased and installed across the west side of the building (208 linear ft.) and across the top of the stairs to the lower level entrance at the front of the building on Central Avenue (12 linear ft.).

The top of the foundation along the rest of the front of the building appears to be at 13.0 ft. NAVD88, and is therefore assumed to not require any additional flood protection.

Estimated order-of-magnitude cost (longer term): $442,000 (note that this is cumulative to the above, not additive)

A Street Fire Station

The Town has prioritized the A Street Fire Station for floodproofing improvements in its annual updates to the FEMA-required Hazard Mitigation Plan. In 2008, the boiler was elevated to protect it from damage in case the building floods, and the Fire Department has applied for grants to install hurricane doors.

The approximate ground elevation at the A Street Fire Station apparatus bays is 10.3 ft. NAVD88, and the 2030 and 2070 1% flood elevations are 10.2 ft. and 13.0 ft. NAVD88, respectively. These flood risks are approximately illustrated in Figure 22, alongside a conceptual illustration of the recommended adaptation strategy to protect the Fire Station.

The recommended adaptation strategy is to construct a 3.5 ft. high decorative flood wall along the south and west sides of the building and along the grassy are at the northeast corner of the building (260 linear ft.). As an option, the grassy area could be built up as a 2.0 ft. high raised planter for employees and pedestrians to sit on. Demountable flood panels to temporarily close off the north and east sides of the building, between the flood walls, in advance of a storm should be purchased and installed (140 linear ft.). The building may require additional floodproofing measures such as conduit sealing, backflow protection, and portable pump systems to be protected from other sources of flooding.

Estimated order-of-magnitude cost (without optional planter): $200,000

Estimated order-of-magnitude cost (with optional planter): $400,000

Figure 22. A Street Fire Station Flood Risks and Adaptation Strategy

The Fire Department already implements plans to relocate critical vehicles from A Street Fire Station to another location on higher ground. Even with the recommended adaptation strategy shown in Figure 22 in place, it may still be a good idea to temporarily relocate critical vehicles to higher ground prior to a forecasted flood event, as that would ensure the vehicles are accessible for use during and immediately after a flood. If the vehicles are parked inside the protected building, they would not be accessible for use until after flooding had receded to a safe level for the flood panels to be taken down so that vehicles could be driven off site.

Nantasket Avenue

Nantasket Avenue is the spine of Hull's road transportation system. It is the main route for accessing most neighborhoods, businesses, and public services. It is also the main evacuation route and emergency response route for thousands of people. It should be at a higher elevation relative to the landscape, to prevent flooding and facilitate rapid drainage thereafter. However, there are some low segments (road elevation of 8.0-9.0 ft. NAVD88), such as at the intersection with Fitzpatrick Way and between C Street and H Street, that will become unreliable in the face of increasing flood risks from climate change. During the Blizzard of 1978, flooding from the ocean side crossed Nantasket Avenue from A Street to X Street.

All reasonable efforts should be made by the Town to incrementally increase the elevation of Nantasket Avenue as part of future road rehabilitation and reconstruction projects. The priority is to raise relatively low-lying segments and intersections with roads that lead directly to Nantasket Avenue from the ocean or bay, as these can act as conduits for flooding. Any incremental raising that is possible is an improvement and reduction in flood risk over current conditions. In the medium term, the goal for the Nantasket Avenue segments in this area should be to reach an elevation of 10.0-11.0 ft. NAVD88 (1% or lower annual probability of flooding in 2030), which is similar to the elevation of the rest of Nantasket Avenue in this area. The potential impacts to driveways, parking lots, and front doors do not appear to be technically challenging to address in general.

<u>Estimated order-of-magnitude cost:</u> $2-4 million

D Street Stormwater Pump Station

The D Street Stormwater Pump Station is located on the ocean side of Cadish Avenue across from the intersection with D Street. The pump station is critical for draining stormwater from low-lying areas in the Waveland area between A Street and G Street. Due to its low elevation (7.9 ft. NAVD88) and its highly exposed location in the wave action zone, D Street Stormwater Pump Station has the highest (at present and in 2070) or second highest (in 2030) probability of flooding of all critical municipal buildings. As such, the pump station should be considered among the higher priorities for adaptation.

The pump station has a 2% (1-in-50), 5% (1-in-20), and 100% annual probability of flooding at present, in 2030, and in 2070, respectively. Flood risks from the 1% annual probability flood are approximately illustrated in Figure 23.

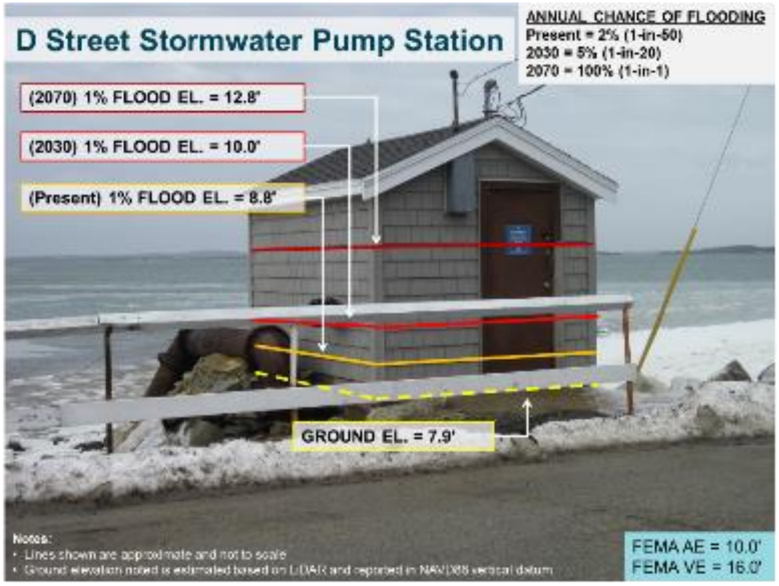


Figure 23. D Street Storm Water Pump Station Flood Risks

The Town has already begun exploring options to replace this pump station and upgrade the capacity of upstream pipes that are known to be undersized. In further developing conceptual designs, the Town should investigate the feasibility of relocating the pump station away from the wave action zone. Piped infrastructure was not mapped or assessed as part of this project, and therefore alternative locations have not been evaluated for feasibility. One nearby location with potentially sufficient public right-of-way to site a new pump station, thereby avoiding property acquisition costs, is at the intersection of Cadish Avenue and Sunset Avenue. However, relocation to this site may result impact water views from nearby private properties.

With or without relocation, the pump station should be elevated by 3.0-5.0 ft. so that the annual probability of flooding during its lifetime is no greater than 1%. Other waste water and stormwater pump stations in Hull have been elevated to similar heights (e.g., Waste Water Pump Station 9, Draper Avenue Stormwater Pump Station), so this is a familiar adaptation measure for the Town to implement. Structural design of the elevated foundation should account for wave forces.

The new pump station should also have an elevated emergency generator to ensure that it is powered during and after a major flood, when widespread power outages could occur.

Extreme precipitation is also projected to increase in Massachusetts by 2030 and 2070 as a result of climate change, so the new pump station should be designed with additional capacity.

Due to the uncertainties of the possible project scopes, it is impossible to develop a reasonably accurate cost estimate at this time. It is recommended that the Town develop more precise cost estimates as the basis for budgeting and developing grant applications.

Waste Water Pump Station 6

Waste Water Pump Station 6 is located on the west side of Nantasket Avenue, directly across from M Street and within the boundaries of the L Street Field/Playground. An image of the pump station building is included below (Figure 24), along with the flood risks identified based on this study.

Figure 24. Waste Water Pump Station 6 Flood Risks and Adaptation Strategy

The Town should consider implementing an incremental adaptation strategy for the pump station.

In the near to medium term, a 2.0 ft. high grassy berm could be constructed around three sides of the pump station, leaving enough clearance between the berm and the building to allow for access around all sides of the building. Permanent posts would be installed at the two terminal ends of the berm and temporary flood panels would be installed between them in advance of a major flood, creating a perimeter flood protection system. One challenge for this strategy is that there may be existing trees within close proximity to the pump station that may be in conflict with the berm. Field measurements were not taken to verify this issue. An added benefit of using a berm at this location is that it could be used by children as a play feature of the park. The building may require additional floodproofing measures such as conduit sealing, backflow protection, and portable pump systems to be protected from other sources of flooding.

<u>Estimated order-of-magnitude cost (near to medium term):</u> $55,000

Then, over the longer term, a 4.0 ft. high concrete flood wall could be constructed along the inside edge of the berm, again leaving clearance to access the building. The fill from the berm could be re-used to slope the ground up to the top of the flood wall on three sides. The same temporary flood panels could be used to close the fourth side of the perimeter barrier off in advance of a flood (Figure 25).

<u>Estimated order-of-magnitude cost (longer term):</u> $102,000 (note that this is cumulative to the above)

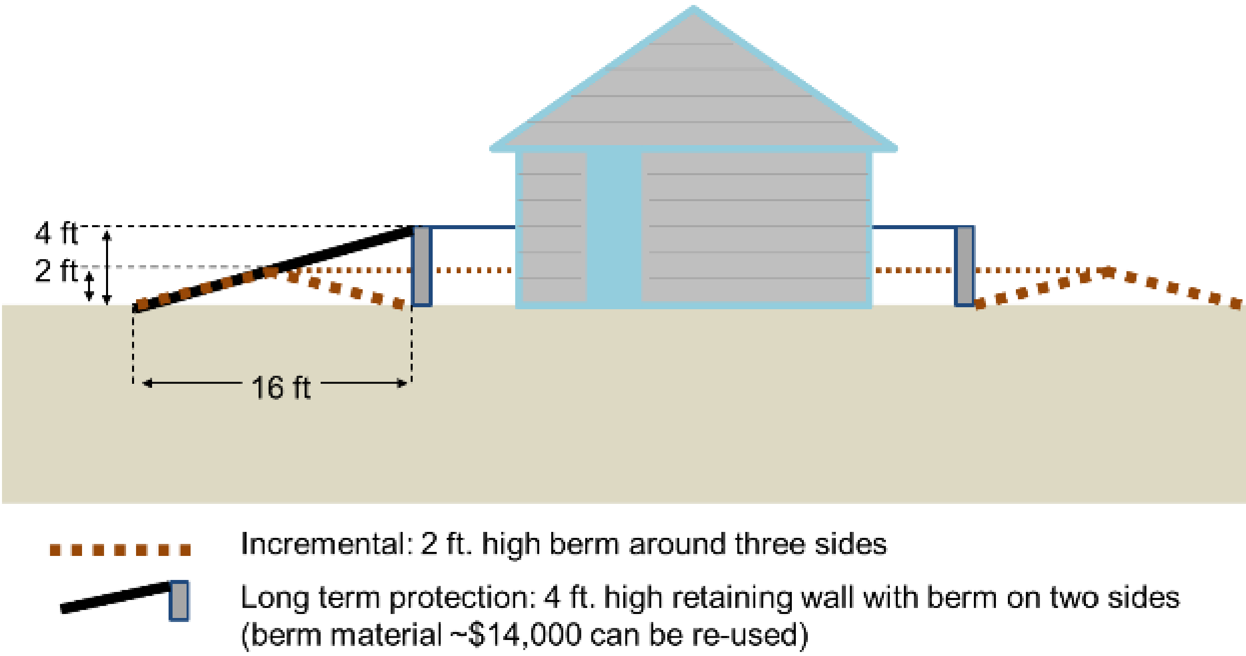


Figure 25. Perimeter Berms and Flood Wall Strategies

High Risk Area 4: North Nantasket Beach

Description of the Area Vulnerable to Flooding

The North Nantasket Beach area includes all land east of Nantasket Avenue between Phipps Street and Y Street. This is by far the largest of all the high risk areas identified in this study. The area is ocean-facing and contains most of the Town's beach and barrier dune resources. The area is mostly residential and has three business zones distributed along Nantasket Avenue. An estimated 24% of all private buildings in Hull are located within this area.

In 2030, most of the North Nantasket Beach area is projected to have a 2-5% annual probability of flooding (1-in-50 to 1-in-20 chance), with the exception of areas in the vicinity of Beach Avenue which have a 10-25% annual probability of flooding (1-in-10 to 1-in-4 chance).

By 2070, this entire area is projected to flood every other year on average, or every year in the case of areas along Beach Avenue. There is significant variability in land elevations throughout this large area, and as a result, 1% annual probability flood depths in 2070 may be as low as 1.5 ft. and as high as 5.0 ft. at some buildings.

Sources of Flooding

The North Nantasket Beach area is subject to flooding from sea level rise and storm surge on both the ocean and bay side (see the red arrows in Figure 26).

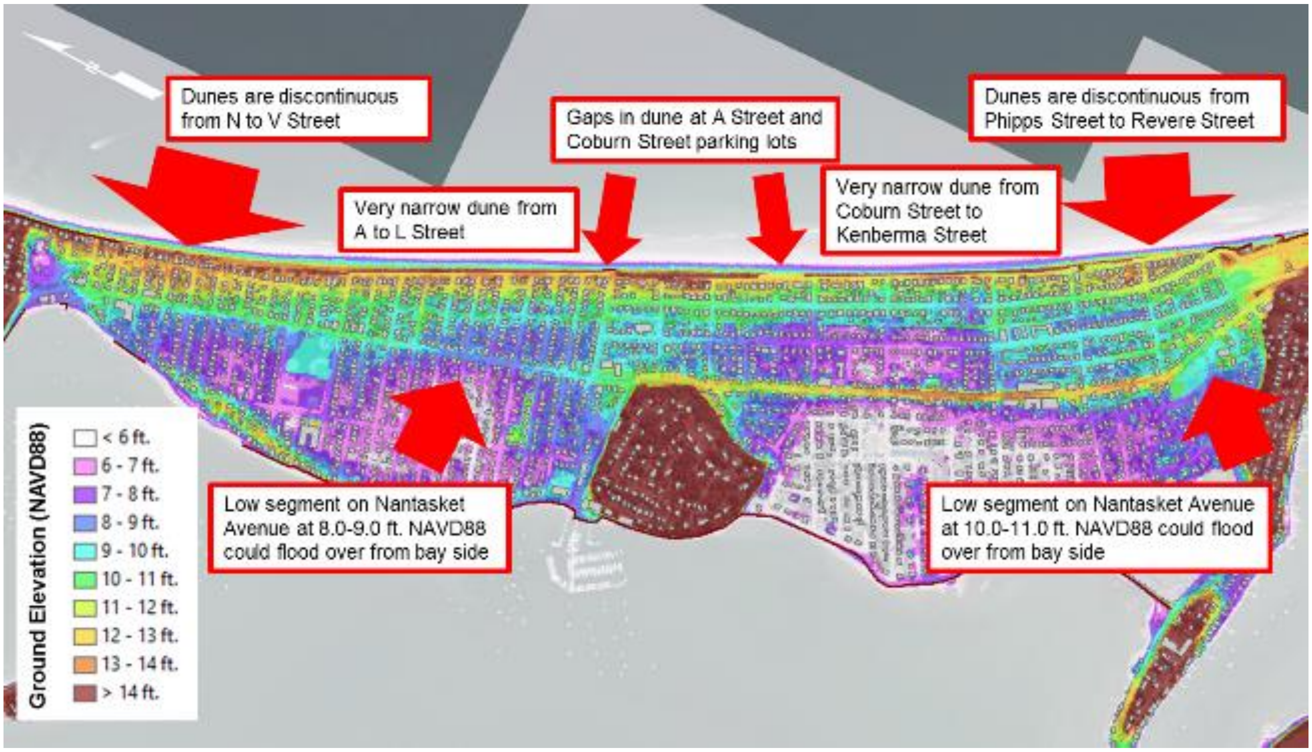


Figure 26. Sources of Flooding for High Risk Area 4: North Nantasket Beach

Wave run-up and overtopping of dunes are the main flooding issues historically experienced on the ocean side. The extensive ocean-facing coastline is subject to significant wave action during nor'easters and other coastal storms. Waves can erode, overtop, and flow through gaps in the relatively low and narrow barrier dune system. Figure 26 identifies narrow segments of dunes, large gaps in the dune system, and dune segments that are discontinuous (i.e., have numerous smaller gaps due to erosion, degradation, vandalism, or geology). Once flooding passes over the higher elevation coastline (12.0-13.0 ft. NAVD88) it can pond in lower elevation areas (<9.0 ft. NAVD88) further inland where it may be slow to drain. This longer duration flooding can be more disruptive and damaging to buildings and infrastructure.

In addition, there is a low-lying section of Nantasket Avenue (8.0-9.0 ft. NAVD88 in elevation) between C Street and H Street that flooding from the bay side could flow over and into low-lying areas of the North Nantasket Beach area (and vice versa). The annual probability of flooding over this segment is 1% (1-in-100 chance) at present, 5% (1-in-20 chance) in 2030, and 50% (1-in-2) in 2070, irrespective of whether it originates from the bay, or ocean (as it did in 1978). These probabilities don not reflect the fact that there are gaps in the dune system and that dunes will erode in a storm, as described below in the section on Barrier Dunes.

<u>Critical Assets at Risk</u>

There are a few municipally-owned critical assets within this area that are vulnerable to flooding, including:

Anne Scully Senior Center	Barrier Dunes
North Nantasket Beach	

The roads vulnerable to flooding in this area, include:

Nantasket Avenue	Beach Avenue
Samoset Avenue	Manomet Avenue
Weston Street	Phipps Street
Malta Street	Revere Street
Kenberma Street	Alden Street
Warren Street	Coburn Street
Irwin Street	Brewster Street
Adams Street	Lewis Street
A Street	B Street
C Street	D Street
E Street	F Street
G Street	H Street
J Street	K Street
L Street	M Street
N Street	O Street
P Street	Q Street
R Street	S Street
T Street	U Street
V Street	W Street
X Street	Y Street

The North Nantasket Beach high risk area includes an estimated 1,194 buildings (24% of all in Hull), with total footprints of 1,633,828 square ft., that are potentially vulnerable to flooding.

Anne Scully Senior Center

The approximate ground elevation at the Senior Center front entrance is 9.1 ft. NAVD88, and the 2030 and 2070 1% flood elevations are 10.5 ft. and 13.0 ft. NAVD88, respectively. These flood risks are approximately illustrated in Figure 27.

The adaptation recommendation for this facility is to retreat from it. Services currently provided at the Senior Center could be moved to another Town-owned facility that is on higher ground, thereby avoiding the future risks of flooding and the costs of adaptation.

Physical protection measures for the Senior Center are either infeasible or difficult to permit. Installing flood panels on openings would be ineffective due to the porosity of the building's wooden exterior. Building flood walls around the facility may not be considered appropriate from a permitting perspective due to the potential flood flow channelization impacts that it may cause on adjacent properties and the lack of a highly critical function such as public safety. The building could be elevated, but it would be costly, require temporarily closing the center, and be a challenge to redesign accessibility features such as wheelchair ramps in the limited space available on the property.

Figure 27. Anne Scully Senior Center Flood Risks

At present, the Senior Center should develop an emergency relocation plan for vehicles that are typically parked at the property. The plan should address which vehicles should be moved, where and when they should be moved, and by whom. With the alternative adaptation strategy shown in Figure 27 in place, there would be no space within the protected area to park vehicles.

North Nantasket Beach

Sea level rise is projected to significantly narrow the width of North Nantasket Beach under normal tidal conditions by 2070. Table 13 compares the existing width of the beach at specific road intersections to those projected in 2070, based on the natural resources modeling conducted for this project.

Table 13. Loss of Beach Width on North Nantasket Beach from Sea Level Rise

Road Intersection	Beach Width (ft.)		Loss of Beach Width by 2070	
	Present	2070	ft.	%
Malta Street	525	390	135	26
A Street	520	400	120	23
T Street	340	230	110	32

Large scale beach nourishment on North Nantasket Beach could prevent the loss of beach width and potentially significantly reduce flooding risks for neighborhoods, businesses, and public facilities and infrastructure between the beach and Nantasket Avenue. Beach nourishment, when properly designed, can reduce wave heights and forces as well as mitigate storm surge development. It would also protect the beach as an important recreational and tourism resource. According to MA Coastal Zone Management, this pocket beach is relatively stable in terms of sediment loss and therefore could be a more sustainable financial investment.

In the near to medium term, it is recommended that the Town carry out a coastal processes study to determine how to accomplish beach nourishment, which will help to support design, permitting, and construction. The estimated order-of-magnitude cost of such a study is $150,000 to $200,000.

Based on estimated beach nourishment costs based on the US Army Corps of Engineers Coastal Storm Damage Reduction Report, Draft Feasibility Report and Environmental Assessment for the Nantasket Beach DCR Reservation, the order-of-magnitude cost of extending similar levels of protection to the entire 2 miles of North Nantasket Beach could approximately $25 million.

Barrier Dunes

In addition, the protection that the existing barrier dunes along North Nantasket Beach provide to residential and commercial buildings, Nantasket Avenue, and municipal facilities such as the Senior Center and A Street Fire Station, from storm surge and waves is projected to be diminished over time (Table 14).

Table 14. Barrier Dune Segments Vulnerability to Flooding in Present, 2030, and 2070

Barrier Dune Segment Locations	Average Crest Elevation (ft. NAVD88)	Annual Probability of Flooding (%)		
		Present	2030	2070
Phipps Street to Malta Street	12.5	20	25	100
Lewis Street	15.0	5	10	100
Alphabet Streets	14.7	10	25	100

To accurately evaluate these dune systems would require a cross-shore sediment transport model effort to evaluate the fate of the dunes during various storm events. Without modeling the cross-shore dune erosion, it is difficult to predict the fate of the dunes. It is expected that these dunes may erode, possibly substantially, during a large storm event, be overtopped, and breached. For the purposes of this study, time horizons and probabilities were assigned based on an estimate of when they would become "wet", not when the stillwater level (without wave run-up) will exceed the dune crest elevation.

The Town should conduct a study to investigate this issue further and identify priority areas for restoration or enhancement. For example, degraded and discontinuous segments of dune at both the northern and southern end of the beach could be targeted. One limitation to the dune restoration and enhancement strategy is that narrow dune segments and large gaps identified in the LiDAR are constrained by existing infrastructure on their landward side (i.e., Beach Avenue, housing, and parking areas) and limited beach width on their ocean side. However, if large-scale beach nourishment were to be implemented, dunes could be expanded towards the ocean and built up to higher crest elevations. This would further enhance the protection of flood prone areas landward of the dunes.

Another recommendation is to fill, vegetate and stabilize any unpermitted openings in the dunes. There are a number of openings which become paths for waves to pass through the dunes, eroding the openings wider. The Town has undertaken a project to close unpermitted openings.

High Risk Area 5: Kenberma – West of Nantasket Ave

Description of the Area Vulnerable to Flooding

The Kenberma high flood risk area is bounded by Nantasket Avenue to the east, Nantasket Road/Mountford Road to the south, and Newport Road to the west and north. The area includes a small business district along the southern stretch of Nantasket Avenue, but is otherwise residential and open space. There is a large irregularly flooded marsh (high marsh) that is restricted from tidal exchange by the Newport Road dike.

This area has a very low chance (0.1% annual probability) of flooding in 2030 according to the modeling conducted for this study. It is important to note that the model does not simulate flooding through the tide gate in the Newport Road Dike. The flood risk increases dramatically by 2070, when the area is anticipated to flood every other year on average. In 2070, the area also has a 1% annual probability of flooding over 7.0 ft. in depth at some buildings.

Sources of Flooding

The Kenberma area, west of Nantasket Avenue, from Nantasket Road/Mountford Road to Newport Road is subject to flooding from storm surge on both the ocean and bay side (see the red arrows in Figure 28).

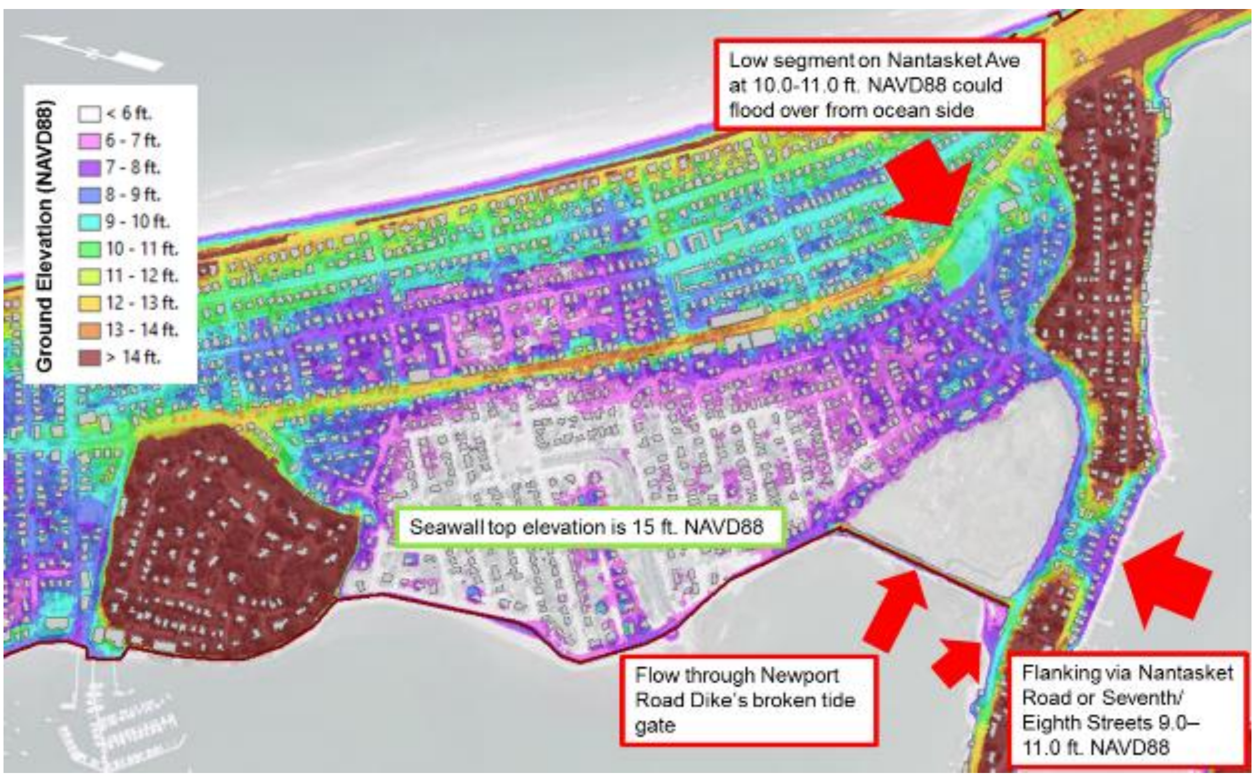


Figure 28. Sources of Flooding for High Risk Area 5: Kenberma – West of Nantasket Avenue

The Kenberma area is provided significant protection from flooding on its bay side by an extensive 3,160 foot seawall along Newport Road, which connects to the Newport Road Dike. The seawall's top elevation is 15.0 ft. NAVD88, and the Newport Road Dike is slightly lower and more variable in elevation

(13.5-13.9 ft. NAVD88). The seawall top elevation is higher than the projected flood elevations for this area in 2030 and 2070, and the dike provides protection up to the 0.5% (1-in-200 chance) annual probability flood in 2070.

However, there are three weak points in this flood protection system that make it likely, over the longer term (2070), that the Kenberma area will flood. The Newport Road Dike has a broken tide gate in the center of the dike. Water can pass through the opening in the dike and contribute to flooding the area, although the extent of its impact was not simulated in this model and needs to be further studied. The dike can also be “flanked”, meaning that flood waters could go around it flowing through low-lying flood pathways. Two such pathways exist. If flood water elevations at the southern end of the dike reached above 10.0 ft. NAVD88, water would flow onto Nantasket Road and around the dike. At the same elevation range, water would also pass between Seventh Street and Eighth Street from the south and into the Kenberma area. These elevations have a 50% annual probability of being exceeded by flood waters in 2070.

In addition to flooding from the bay side, it is possible that flooding from the ocean side could flow over Nantasket Avenue into the Kenberma area. A relatively low segment along Nantasket Avenue is in the elevation range of 10.0-11.0 ft. NAVD88. These elevations have up to a 50% annual probability of being exceeded by flood waters in 2070. The rest of Nantasket Avenue in this area is within the 11.0-14.0 ft. NAVD88 elevation range and has up to a 20% annual probability of flooding in 2070.

Critical Assets at Risk

There are several municipally-owned critical assets within this area that are vulnerable to flooding, including:

Draper Avenue Stormwater Pump Station	Kenberma Playground Heliport
Newport Road Dike (Private)	

The roads vulnerable to flooding in this area, include:

Nantasket Avenue	Newport Road
Kingsley Road	Brockton Circle
Dover Street	Front Street
Stafford Road	Fair Street
Westminster Road	Mountford Road
Nantasket Road	Coburn Street
Brookline Avenue	Lynn Avenue
Touraine Avenue	Packard Avenue
Vernon Avenue	Draper Avenue
Kenberma Street	Bates Street
Guild Street	Russell Street
Revere Street	Belmont Street
Waltham Street	Sumner Street

The Kenberma high risk area includes an estimated 604 buildings (12% of all in Hull), with total footprints of 775,422 square ft., that are potentially vulnerable to flooding.

Nantasket Avenue

Nantasket Avenue serves as a critical transportation route, including for emergencies, economic activity, and general mobility. Nantasket Avenue is generally at a high elevation in this area. However, there is a low segment (10.0-11.0 ft. NAVD88) between Malta Street and Nantasket Road that faces a 50% annual probability of flooding in the longer term (2070). In the medium term (2030) this segment only has a 0.1% annual probability of flooding. Therefore, this is not a near term priority.

When opportunities arise, the Town should incrementally increase the elevation of this low segment as part of future road rehabilitation and reconstruction projects. Raising this segment should not be technically or politically challenging. Most of the western right-of-way abuts Kenberma Park, which would not be impacted by a higher roadway. The goal for this segment should be to reach an elevation of 13.0 ft. NAVD88, which is similar to the elevation of the rest of Nantasket Avenue in this area and is approximately equal to the 1% annual probability flood elevation in 2070.

<u>Estimated order-of-magnitude cost:</u> $950,000

Draper Avenue Stormwater Pump Station

Draper Avenue Stormwater Pump Station is located in a very low-lying area, adjacent to a drainage ditch. However, the pump station itself has already been significantly elevated above grade (~4.5 ft.) to an elevation of approximately 11.4 ft. NAVD88. It is not projected to flood in the present or medium term (2030). In 2070, it is projected to have a 10% annual probability of flooding (1-in-10 chance).

It is recommended that no action be taken until the medium-to-longer term when the pump station is reaching the end of its design life. Extreme precipitation is also projected to increase in Massachusetts over same time horizons, so the pump station will likely need to be upgraded with increased capacity. When it is replaced, the pump station should be elevated in accordance with the latest flood risk projections for its design life.

Newport Road Dike

Newport Road Dike has a top elevation that ranges from 13.5 ft. NAVD88 near its southern end to 13.9 ft. NAVD88 at its northern end. According to the flood modeling conducted for this study, it is highly improbable that flood waters will exceed the top of the dike at present or in 2030, and there is only a 0.2% annual probability (1-in-500 chance) of the dike top elevation being exceeded in 2070.

However, as described above, the Newport Road Dike is not fully functional as a flood control structure due to the broken tide gate located at its center. This condition may not be adequately captured by the flood modeling conducted for this study, meaning that the large, densely populated, and low-lying Kenberma area may be at greater risk of flooding sooner than projected. The Town should develop plans to restore the flood control function previously provided by the tide gate.

High Risk Area 6: Nantasket Beach / George Washington Boulevard

Description of the Area Vulnerable to Flooding

The Nantasket Beach / George Washington Boulevard high risk flood area includes the Nantasket Avenue corridor from State Park Road to Phipps Street and all of George Washington Boulevard. It includes the DCR Nantasket Beach Reservation (a major tourist attraction and recreational resource) and the largest business and commercial corridor in Hull. The Reservation saw over 200,000 visitors in the summer of 2015 (DCR Public Meeting presentation, 2016).

The locations within this area with the highest probabilities of flooding include George Washington Boulevard at Nantasket Pier (10-20% in 2030 and 50% in 2070) and between Gosnold Street and Rockland Circle (2% in 2030 and 30% in 2070), and on Nantasket Avenue between Wharf Avenue and George Washington Boulevard (10% in 2030 and 50% in 2070). In 2070, almost the entire area is at some risk of flooding.

Sources of Flooding

The Nantasket Beach / George Washington Boulevard area is subject to flooding from storm surge on both the ocean and bay side (see the red arrows in Figure 29) and further described below in the sections on Nantasket Avenue and George Washington Boulevard to avoid repetition.

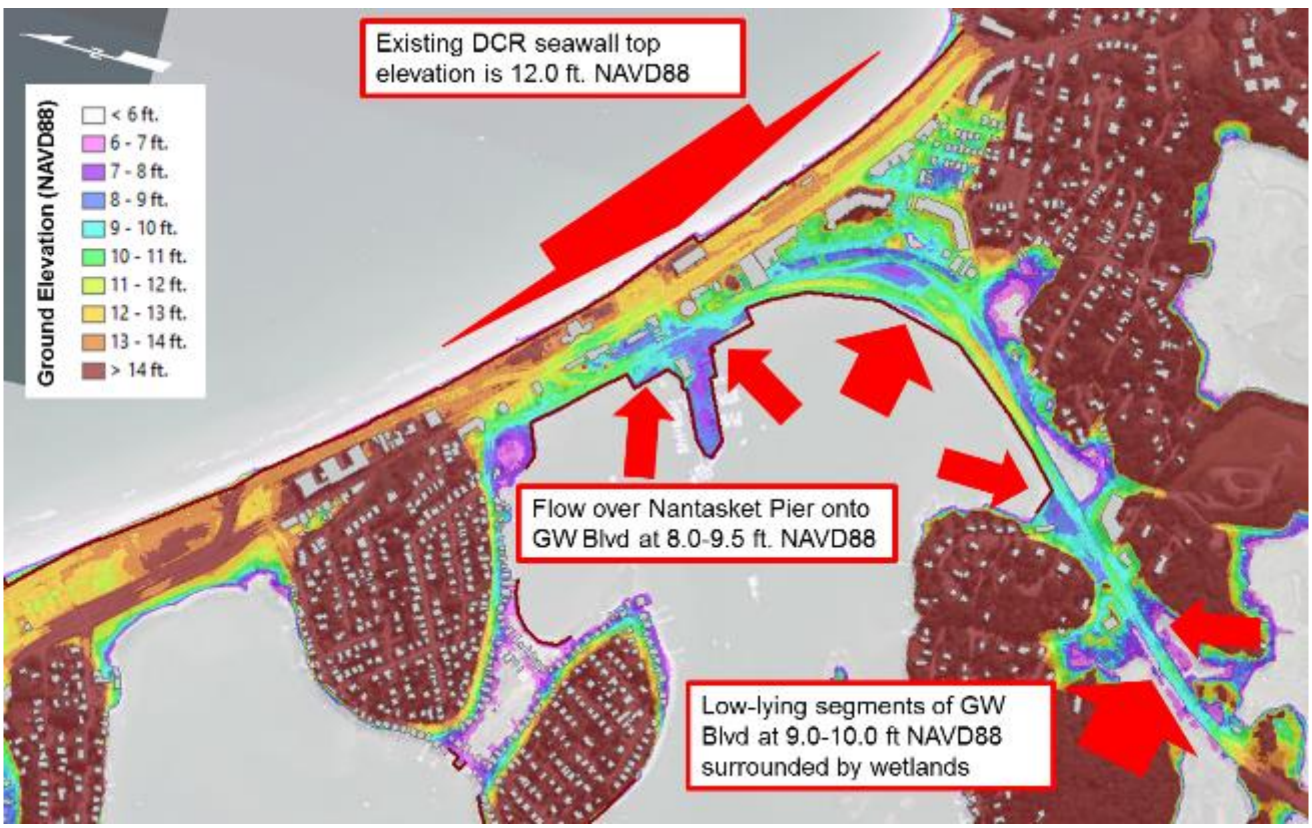


Figure 29. Sources of Flooding for High Risk Area 6: Nantasket Beach / George Washington Boulevard

Critical Assets at Risk

There are a few municipally-owned critical assets within this area, including:

Municipal Light Department	Nantasket Pier
Roller Hockey Park Heliport	Seawalls and Revetments

The roads vulnerable to flooding in this area, include:

George Washington Boulevard (MassDOT)	Barnstable Road
Rockaway Avenue	Rockland Circle
Park Avenue	Berkley Road
Atherton Road	Nantasket Avenue
Wharf Avenue	Hull Shore Drive (DCR)
Bay Street	Moreland Avenue
Hampton Circle	Marginal Road

Although not municipally-owned assets, various DCR facilities in this area may also be vulnerable to flooding from sea level rise and storm surge.

The Nantasket Beach / George Washington Boulevard high risk area includes an estimated 172 buildings, with total footprints of 355,259 square ft., that are potentially vulnerable to flooding.

Nantasket Avenue

As mentioned above, Nantasket Avenue serves as a critical transportation route, including for emergencies, economic activity, and general mobility. This segment is particularly important as the economic thoroughfare of the Nantasket Beach recreation, business, and commercial corridor. It also contains the connection between Nantasket Avenue and George Washington Boulevard for emergency evacuation and response/relief operations.

Nantasket Avenue is mostly elevated above 12.0 ft. NAVD88 in this area, and above 14.0 ft. NAVD88 north of Bay Street. However, there are two lower elevation segments (9.0-11.0 ft. NAVD88) between Wharf Avenue and George Washington Boulevard, and between Park Avenue and State Park Road. The source of flooding is from the ocean side due to wave overtopping of the Nantasket Beach seawalls. This is an existing issue, but it is expected to worsen over time. Overtopping of DCR seawalls at Nantasket Beach Reservation can flow over Nantasket Avenue, towards the bay, and into lower areas along George Washington Boulevard. Water from overtopping will also intermittently flow over Nantasket Avenue to the lower elevation areas to the southwest (i.e., Park Avenue, Berkley Road, Atherton Road). The annual probabilities of these segments experiencing at least intermittent flooding from overtopping are 10% in 2030 and 50% in 2070.

One option for the Town to consider is to elevate low-lying segments of Nantasket Avenue. This may not be possible in all areas due to the impacts it would have on access to abutting properties, especially buildings that open directly to the Nantasket Avenue sidewalk. Other Town options are limited because flooding of this segment of Nantasket Avenue depends primarily on what DCR does in terms of its seawalls and beach nourishment. Incremental elevation, where feasible, could be implemented by the Town as part of future road rehabilitation and reconstruction projects. The medium-term goal for these segments should be to reach an elevation of 12.0 ft. NAVD88, which is similar to the elevation of the rest of Nantasket Avenue in this area.

Order-of-magnitude costs (medium term) of raising the road to 12.0 ft. NAVD88 would be approximately $1-2 million. This does not include impacts to private properties.

George Washington Boulevard

George Washington Boulevard is one of only three roadways leading in and out of Hull (others being Nantasket Avenue and Atlantic Avenue), and the only one of those with two lanes of two-way traffic. It provides a critical economic and emergency connection with the mainland's regional roadway network via Hingham. In terms of the economy, George Washington Boulevard is especially important during tourist season for handling the large volume of vehicle traffic entering and leaving Nantasket Beach Reservation. Borland Bridge, which connects the Hull and Hingham portions of George Washington Boulevard is also higher in elevation than the West Corner Bridge and Atlantic Avenue. These factors make it especially important for emergency evacuations related to flooding and for flood response/relief operations. It is owned by MassDOT and the only non-municipal asset included in this assessment.

George Washington Boulevard is at risk of flooding from waves overtopping the DCR seawalls and flowing over Nantasket Avenue. In the medium and longer term, it is also at risk of flooding from the bay and Weir River Estuary. The lowest elevation segments are at Nantasket Pier (8.0-9.5 ft. NAVD88) and between Gosnold Street and Rockland Circle (9.0-10.0 ft. in some areas). George Washington Boulevard is not only at risk of flooding Hull, but also in Hingham (low elevation is approximately 11.0 ft. NAVD88 just south of the Court House). This points to the need for some regional coordination between Hull, Hingham, and MassDOT to address the resiliency of this important economic and emergency corridor over the longer term.

Raising low-lying segments between Gosnold Street and Rockland Circle, and possibly even up to Nantasket Pier, would have very limited impacts on abutting private properties, as there are few with direct access to the road. However, such improvements must be designed in such a way that they do not negatively impact the Weir River Area of Critical Environmental Concern and should, where possible, aim to further the goals of the *Weir River Estuary Park Land Protection Plan* (e.g., expand public access and low impact recreational opportunities, protect and restore natural resources and biological diversity). Since the road is owned by MassDOT, the Town will need to work through its MassDOT coordination processes to get the improvements considered in longer term capital plans.

Order-of-magnitude costs (longer term) of raising the road, from Gosnold Street to Nantasket Avenue, to 13.0 ft. NAVD88 (~1% annual probability of flooding in 2070) would be approximately $8-10 million. This does not include impacts to private properties, wetland mitigation, or natural resource enhancements.

Municipal Light Department

The Municipal Light Department property, located on Edgewater Road, contains several buildings (some free-standing, some attached to the main building) and outdoor equipment storage areas that all have different elevations and flood risks, as shown in Figure 30.

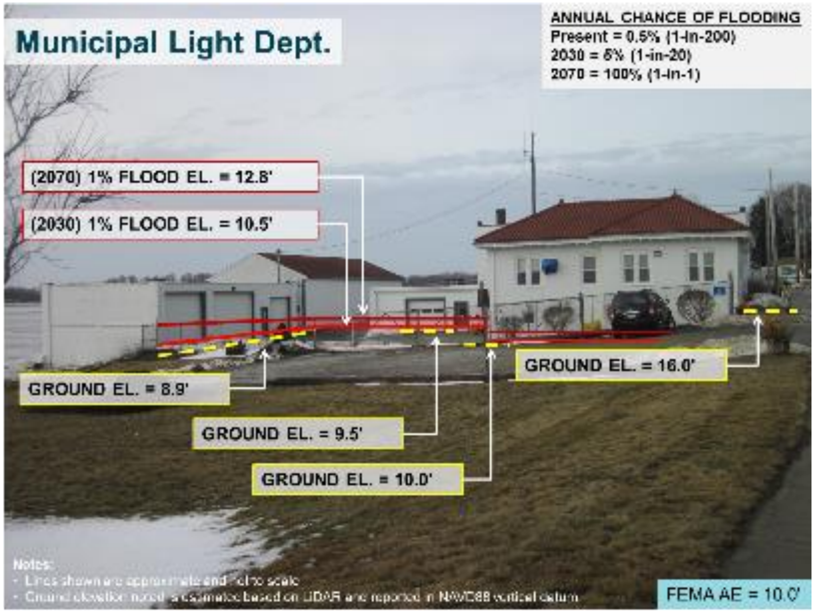


Figure 30. Municipal Light Department Flood Risks

The 2030 and 2070 1% flood elevations are 10.5 ft. and 12.8 ft. NAVD88, respectively. The two buildings situated along the shore have approximate floor elevations of 8.9 ft. NAVD88 and are at the highest risk of flooding. These buildings contain mostly tools and supplies, such as cabling. The building that is positioned perpendicular to those two buildings and is attached to the main building, has a ground elevation of 9.5 ft. NAVD88, and the main building has a lower level elevation of approximately 10.0 ft. NAVD88. Critical utility feeds enter the main building at the lower level and therefore may be vulnerable to flooding. The second floor of the main building, which contains all critical systems equipment as well as office space, is elevated above 16.0 ft. NAVD88 and is not at risk of flooding by 2070. The main building's emergency generator is at a similar elevation as the second floor and also not likely to flood by 2070. Outdoor equipment storage spaces closest to the shore are most likely to flood. According to the Municipal Light Department, the equipment stored in these areas are not very critical and do not contain PCBs or other hazardous materials. The Department has plans to reorganize outdoor storage areas to maximize use of higher elevation areas close to Edgewater Road.

Alternative adaptation strategies are possible for the Municipal Light Department property, at relatively low cost. Conceptual illustrations of these strategies are presented in Figure 31.

Figure 31. Municipal Light Department Adaptation Strategies

The option shown on the left of Figure 31 is the lowest cost option, providing minimal levels of protection that accommodate flooding. They also require the highest operational level of effort. In this strategy, Municipal Light Department staff would temporarily relocate all equipment and supplies located in the buildings and outdoor storage areas shown in blue when a flood is forecasted. Equipment and supplies could be moved to higher ground on the site located adjacent to the street. An alternative for the storage buildings would be to install shelving so that contents could be elevated in place rather than relocated prior to a flood. This would raise the cost of this option but lower the level of operational effort.

The lower level of the main building would be wet floodproofed (~1,650 square ft. of floor space). Flood damage resistant materials would be used for interior floors, walls, and interior furnishings. Utilities on the first floor would either be elevated or designed so that they can be easily isolated and replaced following a flood to prevent total or extended loss of critical utilities required for the rest of the building to function. This strategy would still result in some flood damages and operational disruptions, but those impacts would be limited.

<u>Estimated order-of-magnitude cost (wet floodproofing):</u> $50,000

The option shown on the right of Figure 31 would provide a higher level of protection at a higher cost and even lower level of operational effort. Equipment located in the outdoor storage areas shown in blue would still need to be temporarily relocated or elevated. All building areas at risk of flooding would be dry floodproofed using demountable flood panels to close off the six (6) personnel doors and five (5) overhead doors through which flooding would otherwise enter (78 linear ft.). The buildings may require additional floodproofing measures such as conduit sealing, backflow protection, and portable pump systems to be protected from other sources of flooding.

<u>Estimated order-of-magnitude cost (dry floodproofing):</u> $100,000

High Risk Area 7: Atlantic Avenue

Description of the Area Vulnerable to Flooding

The Atlantic Avenue high risk area begins at Summit Avenue and extends along Atlantic Avenue and most of Gun Rock Avenue to Richards Road. It is a very narrow strip of land, with a few higher elevation areas (e.g., Green Hill). It is bounded by the ocean to the north, and Straits Pond to the south.

Sources of flooding are shown in Figure 32 (see red arrows and boxes) and further described below in the section on Atlantic Avenue to avoid repetition.

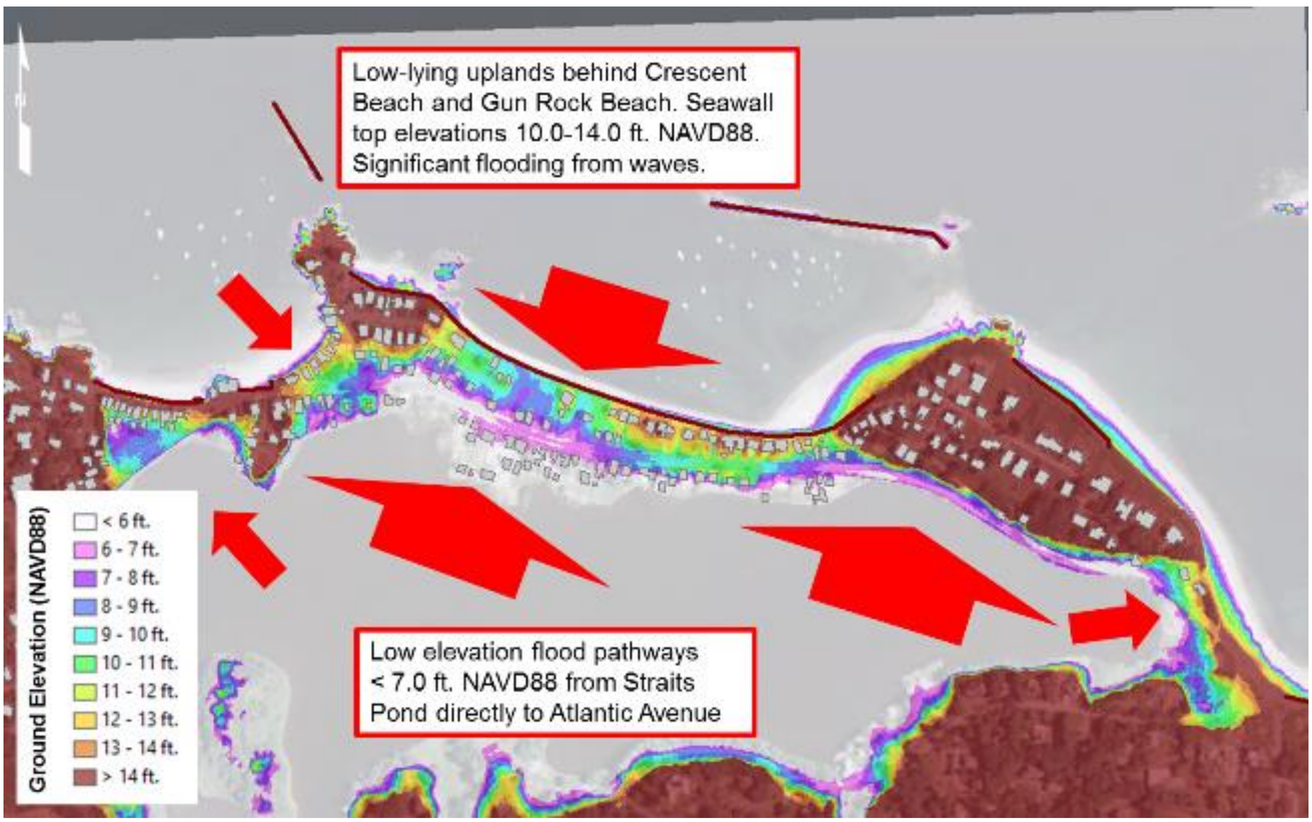


Figure 32. Sources of Flooding for High Risk Area 7: Atlantic Avenue

Critical Assets at Risk

There are few municipally-owned critical assets within this area.

Seawalls, Revetments, and Breakwaters

Some of the important roads vulnerable to flooding in this area, include:

Atlantic Avenue	Gun Rock Avenue

The Atlantic Avenue high risk area includes an estimated 152 buildings, with total footprints of 169,445 square ft., that are potentially vulnerable to flooding.

Atlantic Avenue

Atlantic Avenue is one of only three roads in and out of Hull. It serves as an important connection to the mainland's regional roadway network via Cohasset, including for emergency evacuations. It is also the major road in Hull that is most vulnerable to flooding, particularly between Summit Avenue and Richards Road.

Atlantic Avenue's vulnerability stems from the low elevation of the roadway and its surroundings and its proximity to both Straits Pond and the ocean. Out of the approximately 4,400 linear ft. of road, between Summit Avenue and Richards Road, over 2,300 linear ft. are below 7.0 ft. NAVD88 in elevation. These segments have a present day annual probability of flooding of 30-50% (i.e., flooding is projected to happen once every two or three years on average) and 100% annual probability of flooding in 2030 and 2070 to depths of up to 3.7 ft. and 4.7 ft., respectively.

Historically, the most common source of flooding on Atlantic Avenue is wave run-up and overtopping from the ocean side, particularly at Crescent Beach and Gun Rock Beach, which have relatively low-lying uplands compared to the wave heights they are exposed to. However, the Town is in the process of raising and re-designing the seawall and revetment along Crescent Beach, which should reduce the risk of flooding on Atlantic Avenue from the ocean side in the near to medium term.

Another source of flooding is Straits Pond. There is a direct connection via low-lying edges of the pond (<6.0 ft. NAVD88) to the lowest elevation segments of Atlantic Avenue. The elevation of Straits Pond is currently managed using a self-regulating tide gate at the West Corner Bridge. The pond can be lowered by 2.0 ft. to reduce the risks of flooding. However, if a storm is long enough, or big enough, it is possible the Town will not be able to lower the pond, or keep it lowered enough to prevent flooding. In addition, the risk of the tide gate being flanked or overtopped will increase over time.

There are a few adaptation options for Atlantic Avenue:

1. The Town could simply continue the current practice of temporarily closing the road in anticipation of flooding and carrying out debris removal and repairs as needed after flooding has passed.
2. To further reduce the probability of flooding from the ocean side, the Town could continue to invest in maintaining or ideally incrementally enhancing the existing system of revetments and seawalls at Gun Rock Beach and Crescent Beach.
3. To address the flood risks from Straits Pond, the West Corner Bridge and its approaches could be elevated. However, this is a financially, technically, and politically challenging option, given the scope of work and likely impacts on access to adjacent private properties (i.e., conflicts with door sills and transitions to driveways). It would also require Hingham to implement commensurate measures on its side of the bridge. The bridge was also completely rebuilt in 2010.
4. Segments of Atlantic Avenue could be raised, perhaps incrementally, to reduce the frequency of future road flooding and closures. This option is more feasible for Atlantic Avenue than for other roads with a similar density of development. Residents in this area are already accustomed to flooding and could therefore be more supportive of efforts to address the issue, including raising the road. Residential buildings in this area have already begun to be elevated on pilings, which reduces the impact of raising the road on transitioning to driveways and conflicts with door sills. Given more time and increasing flood risks, more buildings along Atlantic Avenue will likely be raised, allowing low-lying segments to be incrementally raised. In

the near term, the Town could include raising of priority segments in their upcoming Transportation Improvement Program proposal to reconstruct parts of Atlantic Avenue.

The cumulative order-of-magnitude cost of raising all low-lying segments of the road to 12.0 ft. NAVD88 (1% annual probability of flooding in 2030) would be approximately $6-7 million. This does not include impacts to private properties.

Other Critical Assets

Not all vulnerable municipal critical assets are located in the seven main flood risk areas. In addition, some assets, such as heliports, or are easier to address as a group in terms of adaptation strategies. The following sections include such assets.

Department of Public Works Barn and Salt Shed

The approximate finished floor elevation of the Department of Public Works (DPW) Barn is 10.2 ft. NAVD88, and the 2030 and 2070 1% flood elevations are 10.0 ft. and 12.8 ft. NAVD88, respectively. These flood risks are approximately illustrated in Figure 33, alongside a conceptual illustration of the recommended adaptation strategies to protect the DPW Barn.

The recommended adaptation strategy provides protection only for the DPW Barn. The concept is to construct 5.0 ft. high concrete or sheet pile flood walls on both sides of the Barn building (410 linear ft.). Demountable flood panels should be purchased and installed between the flood walls across the front and rear sides of the building to temporarily close off in advance of a storm (240 linear ft.). In order for the panels to be installed on the rear side of the building, the ground will need to be leveled and surfaced with asphalt or concrete so that there is a level surface for the panels to create a water-tight seal against (at least 1,000 square ft.). Space would be provided between the flood wall and the building on the south side to allow critical vehicles and equipment to be stored in safety. An incremental version of this strategy would be to design a sheet pile wall with an above ground height of 2.5 ft. and sufficient below ground depth to support an eventual 5.0 ft. high wall (i.e., overbuild the foundation so that it can handle a future extension). In the future, sheet pile attachments could be designed and installed to extend the above-ground flood wall height by 2.5 ft. to meet the 2070 1% flood elevation.

In addition, the Barn building may require floodproofing measures such as conduit sealing, backflow protection, and portable pump systems to be protected from other sources of flooding.

Estimate order-of-magnitude cost (concrete): $300,000 to $500,000

Estimated order-of-magnitude cost (sheet pile): $500,000 to $750,000

Figure 33. DPW Barn and Salt Shed Flood Risks and Adaptation Strategies

An alternative version of the above strategy would have extended the flood wall system to also protect the DPW Salt Shed. However this strategy was ruled out based on cost. The most reasonable strategy is for the Town to wait until the shed is being replaced, and then design the new shed so that it is elevated to the appropriate level for its design life. An important operational strategy that could be implemented in the meantime, in advance of a major flood, would be to temporarily relocate some or all of the salt supplies to the interior of the DPW Barn (assuming it has been protected). This could be accomplished, for example, by placing a tarp on the floor of the Barn and using a front end loader to move the salt supplies from the shed to the tarp.

The DPW already moves some critical vehicles from the Barn, pre-deploying them to high ground near areas with frequent flooding issues. This strategy helps prevent equipment damage in case the Barn site floods. However, other equipment may need to be temporarily relocated in the future, as the risk of the Barn site flooding increases. It may be prudent for the DPW to develop an emergency relocation plan for critical vehicles and equipment that are typically stored at the property. The plan should address which should be moved, where and when they should be moved, and by whom. Vehicles and equipment stored inside the protected area provided by the recommended adaptation strategy would not be accessible for use until after flooding recedes to a safe level for the flood panels to be taken down so that vehicles could be driven off site.

Heliports

There are several heliports noted throughout this report that are vulnerable to flooding. These heliports may remain flooded immediately following a coastal flood and therefore be unusable to carry out emergency airlifts. Heliports are listed in Table 15 along with their respective annual probabilities of flooding in the near, medium, and longer term.

Table 15. Heliports Vulnerable to Flooding in Present, 2030, and 2070

Heliport Name	Location	Average Ground Elevation (ft. NAVD88)	Annual Probability of Flooding (%)		
			Present	2030	2070
Dust Bowl	Main St at Ocean Ave	5.0	25	30	100
Mariners Park	3 Fitzpatrick Way	9.7	0.5	5	50
L Street Playground	L St and Nantasket Ave	9.5	0.2	1	50
Kenberma Playground	Nantasket Ave and Nantasket Rd	9.7	0	0.1	50
Roller Hockey Park	GW Blvd	9.3	0	0	30

The Hull Fire Department and Police Department, in coordination with regional emergency management partners, should pre-identify appropriate contingency locations for heliports that are vulnerable to flooding in the near and medium term. Contingency locations should be on high ground not subject to flooding and be within the vicinity of the areas served by the affected heliports. If suitable locations are not available for some areas, a plan to use rescue vehicles adapted for flooding conditions and/or boats that can dock at nearby piers should be developed.

Recommendations for Potential Changes to Policies/Regulations

The Town of Hull is a recognized leader in adopting proactive local policies and regulations that encourage adaptation to flooding from sea level rise and extreme storms. Some of the key policies and regulations adopted by the Town include:

- The freeboard incentive that rebates $500 in Building Department fees for homes that elevate 2.0 ft. higher than required.
- Creation of a special permit process for existing homes to exceed local building height limitations by elevating for flood protection.
- Changes to site plan review requiring consideration of sea level rise.
- Creation of the Nanatasket Beach Overlay District with objectives, authorities, design standards, and incentives to ensure that development in this district is adapted and resilient to flooding from sea level rise and extreme storms.
- Achieving the highest Class among MA municipalities in the National Flood Insurance Program's Community Rating System, resulting in lower insurance premiums.
- Obtaining federal and state grant support for various public and private flood protection projects.

Kleinfelder conducted a review of the Town of Hull's existing policies and regulations to see how they might be modified to further advance the Town's goal of adapting to coastal climate change impacts. The following are recommendations for potential changes to these policies and regulations.

Potential Changes to the Zoning By-Law of the Town of Hull

Section 1 – Purpose

- Consider modifying Article 1-1 by adding a new subsection g as follows:

  g. Hazards from coastal flooding caused by sea level rise and storm surge.

Section 22 – Meaning of Words

- Consider adding a definition of Long-Term Sea Level Rise as follows:

  Long-Term Sea Level Rise: The future increase in Mean Sea Level above the current Mean Sea Level in the Town of Hull (defined as Elevation XXXX NAVD88 datum) as determined using the "Highest" curve from the U.S. National Climate Assessment (Global Sea Level Rise Scenarios for the United States National Climate Assessment, NOAA Technical Report OAR CPO-1, December 12, 2012) for a 50 year time horizon.

Section 34 – Business and Mixed Use Residential Districts

- Consider modifying Article 34-1A.1A.3 by adding new subsections k and l as follows:

  k. Boundaries of the Floodplain District, if applicable, as described in Section 37 – Floodplain District.

l. **A written statement describing the effects of long-term sea level rise for developments located in the Floodplain District, with a discussion on how the proposed project mitigates the effects of long-term sea level rise over a 50-year period, what temporary and permanent measures are proposed to control potential flooding, and any adverse effects these measures may have on adjacent properties.**

- Consider modifying Article 34-1A.1A.9 by adding a new subsection l as follows:

  l. **The project does not adversely affect adjacent properties or public infrastructure due to the effects of coastal flooding from long-term sea level rise and storm surge, and that the project adequately addresses the impacts of coastal flooding due to long-term sea level rise and storm surge.**

Section 39B – Nantasket Beach Overlay District (NBOD)

- Consider extending regulations in Section 39B related to sea level rise, flooding, and adaptation (e.g., 1.5-1.7, 2.4, 7.2.2-7.2.3, 8.1, 8.2.2, 11.2.4.3, and especially 12) to all commercial and business districts located in Special Flood Hazard Areas.

Section 40 – Site Plan Review

- Consider modifying Article 40-3.B.1 by adding a new subsection e as follows:

  e. **Location of any floodplain boundaries as defined in Section 37 – Floodplain District**.

- Consider modifying Article 40-3.E.1 by adding a new subsection f as follows:

  f. **Conditions to minimize the effects of coastal flooding due to long-term sea level rise and storm surge.**

Potential Changes to the Town of Hull Rules and Regulations Governing the Subdivision of Land

Section 2, General, A. Definitions:

- Consider adding a definition for Long-Term Sea Level Rise as follows:

  Long-Term Sea Level Rise: The future increase in Mean Sea Level above the current Mean Sea Level in the Town of Hull (defined as Elevation XXXX NAVD88 datum) as determined using the "Highest" curve from the U.S. National Climate Assessment (Global Sea Level Rise Scenarios for the United States National Climate Assessment, NOAA Technical Report OAR CPO-1, December 12, 2012) for a 50 year time horizon.

Section 3, Submission and Approval of Plans

- Consider modifying Section 3, Article C.2 by adding a new subsection (s) as follows:

  (s) **Provide a written statement describing the effects of long-term sea level rise for developments located in the Floodplain District, with a discussion on how the**

proposed project mitigates the effects of long-term sea level rise over a 50-year period, what temporary and permanent measures are proposed to control potential flooding, and any adverse effects these measures may have on adjacent properties.

- Consider requiring that all above-ground points of connection to underground utilities located in subdivisions within the Floodplain District, including power distribution, street lighting, and communications systems (including telephone and Cable TV), be constructed in waterproof enclosures or elevated above the base flood elevation taking into account additional freeboard requirements from the long-term effects of sea level rise, and that all critical elements of such utilities, including transformers, switches and other equipment, be elevated above the base flood elevation, or otherwise protected, taking account additional freeboard requirements from the long-term effects of sea level rise.
- Consider requiring that all sewer connections to residential or commercial properties located in the Floodplain District require backflow prevention technology or shut-off valves that will prevent water from entering a building during a flood.
- Consider requiring that all critical water and sewer facilities (e.g., pump stations) located in subdivisions included in the Coastal Flooding Overlay District be elevated above the base flood elevation, or otherwise protected, taking account additional freeboard requirements from the long-term effects of sea level rise.
- Consider adding language in the Subdivision Regulations and other applicable regulations, to encourage preservation of land bordering salt marsh and other coastal resources to allow for natural growth and evolution of natural resources resulting from long-term sea level rise.

Land/Resource Acquisition

- Consider acquiring land adjacent to coastal resource areas to accommodate changing conditions of natural resource areas such as salt marsh, especially those areas identified in this study as areas of potential resource change and/or migration. The natural resource information provided in this study can be used to identify priority areas for acquisition through easements, fee interest or purchase of development rights to accommodate project effects of sea level rise.
- Investigate the possibility of implementing a rolling easements program in which the Town can purchase an easement from a property owner today in exchange for a promise to surrender the property to the Town once it is substantially damaged by a flood event. This program would be part of a “retreat” policy to be implemented in areas subject to severe and repeated flooding. Rolling easements are a potential way to provide cash to a property owner today with the understanding that when the property is substantially damaged, it will not be rebuilt and will be turned over to the Town. Based on information provided in the latest Town of Hull Hazard Mitigation Plan Update dated January 2012, there are 235 total “repetitive loss” properties in Hull, each having had at least two or more flood claims of $1,000 or more in any given 10-year period since 1978. These properties might be ideal candidates for such a program as they have already experience repeated flood damage in the past. It is likely that these properties will experience more claims in the future unless they have been elevated or otherwise protected from flooding. Four of these properties have experienced five or more claims related to flooding.

Potential Policies for Public Projects

- Develop policies for public projects that incorporate the anticipated effects of long-term sea level rise and promote more sustainable practices throughout the community.
    - Require that all Town-funded projects take into account predicted impacts of long-term sea level rise.
    - Update the Town's Hazard Mitigation Plan in the context of this study and amend as appropriate. Include a documentation requirement/goal to build data on the impacts of coastal storms to inform implementation of future adaptation measures.
    - Develop a regular (perhaps bi-annual) inventory/report of actions taken by the community to improve resilience to climate change and sea level rise.

Coastal Flood Operations Plan

- Consider developing a formal Coastal Flood Operations Plan to prepare for and minimize flood damage due to coastal flooding as a result of extreme weather events. Although the Town of Hull exercises emergency operations plan due to flooding on average at least once a year, formalizing the plan will help to institutionalize flood prevention actions that need to be performed before, during and after a major storm.
    - The plan should utilize actual maximum predicted water elevations for a storm and should clearly define what the sources of the data are and who makes the decision to implement the plan.
    - The plan should clearly define actions to be taken based on the maximum predicted water elevations, parties responsible to perform the actions and timelines required to implement the actions. Actions should include pre-storm mobilization, monitoring during the storm, and post-storm response and recovery (including debris management).
    - The plan should identify training, storage, and maintenance needs for any specific equipment such as temporary flood barriers.
    - Each facility being protected should have facility-specific instructions located on-site for easy access during pre-storm mobilization.

  The plan should be incorporated into the Town's overall emergency response planning documents.

Tide Gauge

Consider installing an automated tide gauge at Pemberton Pier to monitor actual sea level rise locally. This information will be very valuable for longer-term planning as a database of tidal data is collected.

MODELING LIMITATIONS

General

The science of climate change and translating climate risks into design criteria are new and evolving practices, involving many uncertainties. Therefore, the projections made in this report only reflect the professional judgment of the Project Team applying a standard of care consistent with the practice of other professionals undertaking similar work. For these reasons, the recommendations and projections made within this report provide guidelines for investment decisions based on the knowledge to date. The flood level predictions made in this report are based on some of the most recent developments in the science of climate change but are not guaranteed predictions of future events. It is recommended that these results be updated over time as science, data and modeling techniques advance.

The scope of this contract did not include a full review of building and facility drawings, material testing, survey or structural analysis of the building's ability to withstand the projected hydrostatic forces due to flooding. The findings include certain assumptions based on reasonable engineering judgment as to the ability of buildings and facilities to resist the projected hydrostatic forces due to flooding. These assumptions will require additional verification and customization during the design phase of individual projects.

Flood Maps

The flood maps and probabilistic data presented in this report are derived from output of the Boston Harbor Flood Risk Model (BH-FRM) for sea level rise and coastal storm simulations as described in the report MassDOT-FHWA Pilot Project Report: Climate Change and Extreme Weather Vulnerability and Adaptation Options for the Central Artery/Tunnel System (Pilot Project Report). Details of the project and model are described in the Pilot Project Report which is available for download here: https://www.massdot.state.ma.us/Portals/8/docs/environmental/SustainabilityEMS/Pilot_Project_Report_MassDOT_FHWA.pdf (PDF 16mb).

These maps and data are provided without any guarantees or warranty. In association with the product, MassDOT makes no warranties of any kind, either express or implied, including but not limited to warranties of merchantability, fitness for a particular purpose, of title, or of noninfringement of third party rights. Use of these maps by a user is at the user's risk. No warranties of any kind, expressed or implied, are provided, including usage, merchantability, content, interpretation, sequence, accuracy, currency or timeliness.

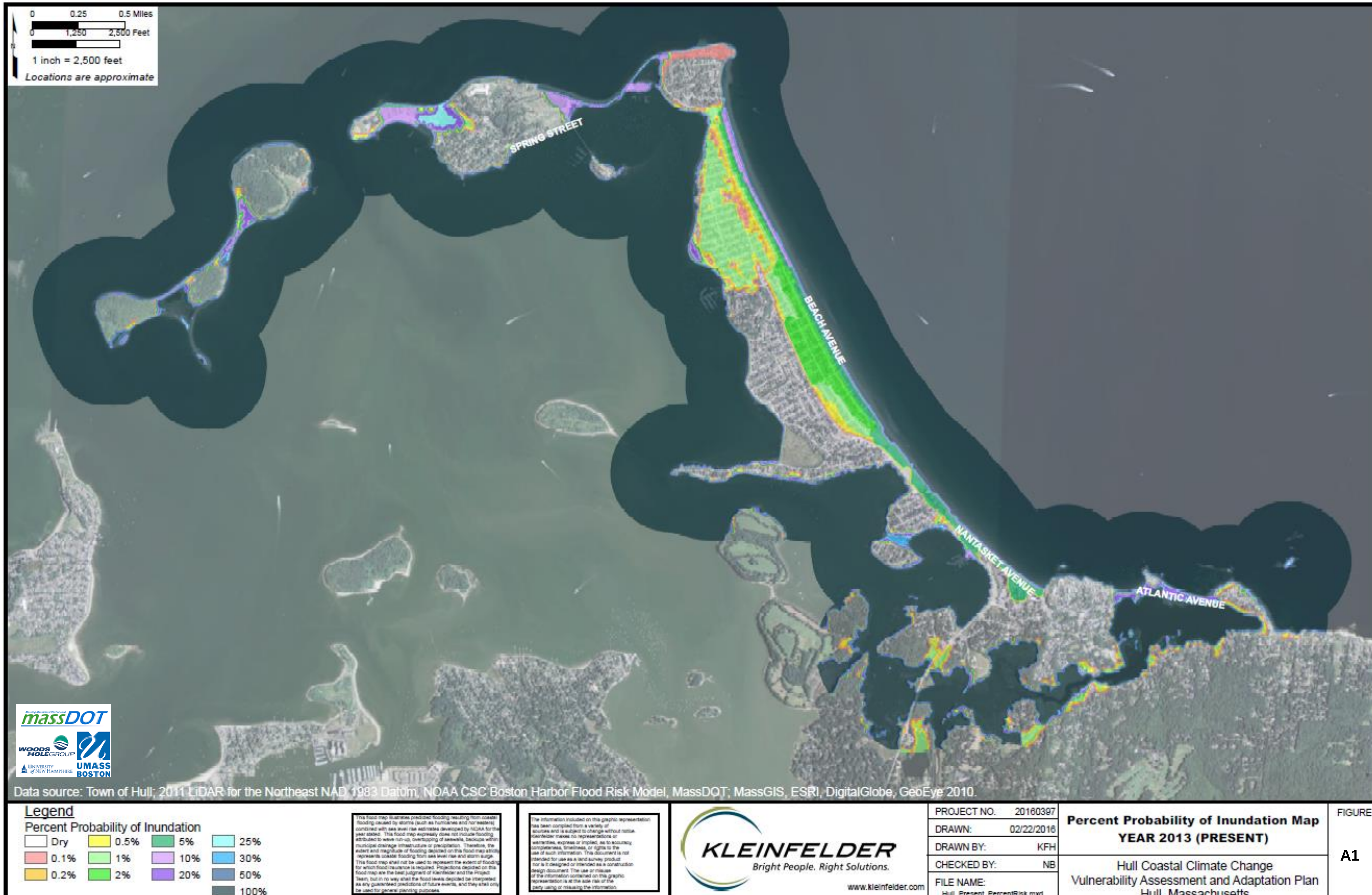
This information is not intended for use as a flood insurance determination, nor should it be directly related to FEMA FIRM maps or data since these data and FEMA data are for different purposes. This information cannot be used for the purpose of boundary resolution or location.

This public information is furnished by MassDOT and should be accepted and used by the recipient with the understanding that the maps and data received were developed and collected for future flooding analyses purposes only. No liability is assumed as to the accuracy, sufficiency or suitability of the information contained herein for any other particular use. MassDOT, Woods Hole Group, UMass Boston, and Kleinfelder assume no liability whatsoever associated with the use or misuse of such maps or data.

While every effort has been made to assure the accuracy and correctness of the data presented, it is hereby acknowledged that inherent mapping inaccuracies are present due to interpolation between BH-FRM calculation nodes. Any reliance upon the maps or data presented herein used to make decisions or conclusions is at the sole discretion and risk of the user. This information is provided with the understanding that these data are not guaranteed to be accurate, correct or complete and assumes no responsibility for errors or omissions. Data and documents may not be the most currently available data. All data are subject to constant change given the changing climate. BH-FRM data may lag behind real-world changes by varying periods of time.

Locations located near boundaries of a probability zone may or may not be within the probability zone due to mapping inaccuracies and interpolation between model nodes. BH-FRM nodal spacing varies throughout the Town of Hull. The rasters will interpolate the values between model nodes and create probabilities that may be inaccurate between model nodes. Therefore, care should be taken when using the raster data to evaluate site-specific properties or locations.

APPENDIX A – COASTAL FLOOD MAPS


0 0.25 0.5 Miles
0 1,250 2,500 Feet
1 inch = 2,500 feet
Locations are approximate
SPRING STREET
BEACH AVENUE
NANTASKET AVENUE
ATLANTIC AVENUE
massDOT
WOODS HOLE GROUP
UMASS BOSTON
Data source: Town of Hull; 2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC Boston Harbor Flood Risk Model, MassDOT; MassGIS, ESRI, DigitalGlobe, GeoEye 2010.
Legend
Percent Probability of Inundation
Dry
0.1%
0.2%
0.5%
1%
2%
5%
10%
20%
25%
30%
50%
100%
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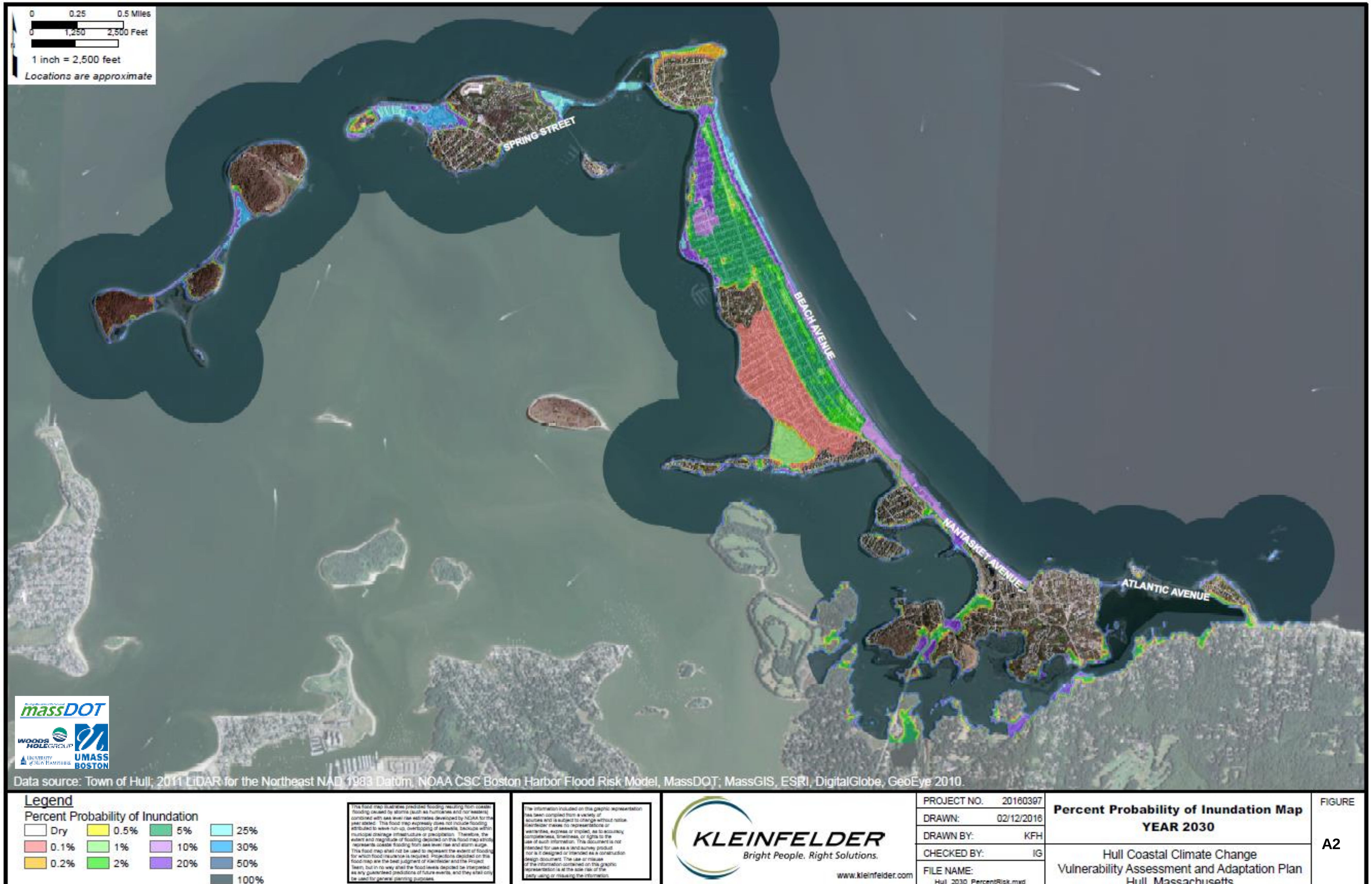
PROJECT NO. 20160397
DRAWN: 02/22/2016
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME: Hull_Present_PercentRisk.mxd
Percent Probability of Inundation Map
YEAR 2013 (PRESENT)
Hull Coastal Climate Change
Vulnerability Assessment and Adaptation Plan
Hull, Massachusetts
FIGURE
A1


0 0.25 0.5 Miles
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BEACH AVENUE
NANTASKET AVENUE
ATLANTIC AVENUE
massDOT
WOODS HOLE GROUP
UMASS BOSTON
Data source: Town of Hull; 2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC Boston Harbor Flood Risk Model, MassDOT; MassGIS, ESRI, DigitalGlobe, GeoEye 2010.
Legend
Percent Probability of Inundation
Dry
0.1%
0.2%
0.5%
1%
2%
5%
10%
20%
25%
30%
50%
100%
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PROJECT NO. 20160397
DRAWN: 02/12/2016
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME: Hull_2030_PercentRisk.mxd
Percent Probability of Inundation Map
YEAR 2030
Hull Coastal Climate Change
Vulnerability Assessment and Adaptation Plan
Hull, Massachusetts
FIGURE
A2

Legend

Percent Probability of Inundation

Dry	0.5%	5%	25%
0.1%	1%	10%	30%
0.2%	2%	20%	50%
			100%

This flood map illustrates predicted flooding resulting from coastal flooding caused by storms (such as hurricanes and nor'easters) combined with sea level rise estimates developed by NOAA for the year stated. This flood map expressly does not include flooding attributed to wave run-up, overtopping of seawalls, backups within municipal drainage infrastructure or precipitation. Therefore, the extent and magnitude of flooding depicted on this flood map strictly represents coastal flooding from sea level rise and storm surge. This flood map shall not be used to represent the extent of flooding for which flood insurance is required. Projections depicted on this flood map are the best judgment of Kleinfelder and the Project Team, but in no way shall the flood levels depicted be interpreted as any guaranteed predictions of future events, and they shall only be used for general planning purposes.

The information included on this graphic representation has been compiled from a variety of sources and is subject to change without notice. Kleinfelder makes no representations or warranties, express or implied, as to accuracy, completeness, timeliness, or rights to the use of such information. This document is not intended for use as a land survey product nor is it designed or intended as a construction design document. The use or misuse of the information contained on this graphic representation is at the sole risk of the party using or misusing the information.

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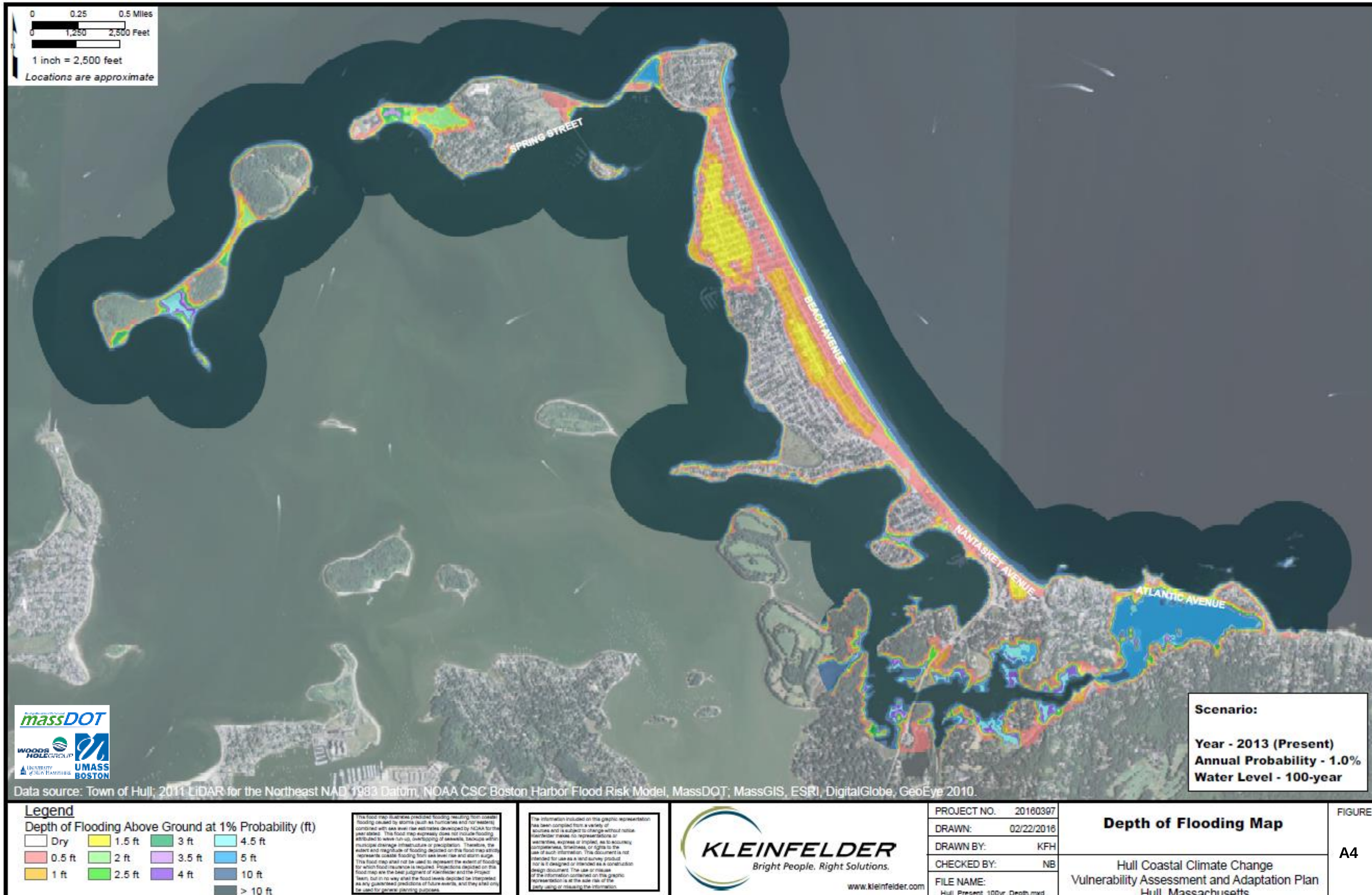
PROJECT NO.	20160397
DRAWN:	01/22/2016
DRAWN BY:	KFH
CHECKED BY:	IG
FILE NAME:	Hull_2070_PercentRisk.mxd

Percent Probability of Inundation Map
YEAR 2070

Hull Coastal Climate Change
Vulnerability Assessment and Adaptation Plan
Hull, Massachusetts

FIGURE
A3


0 0.25 0.5 Miles
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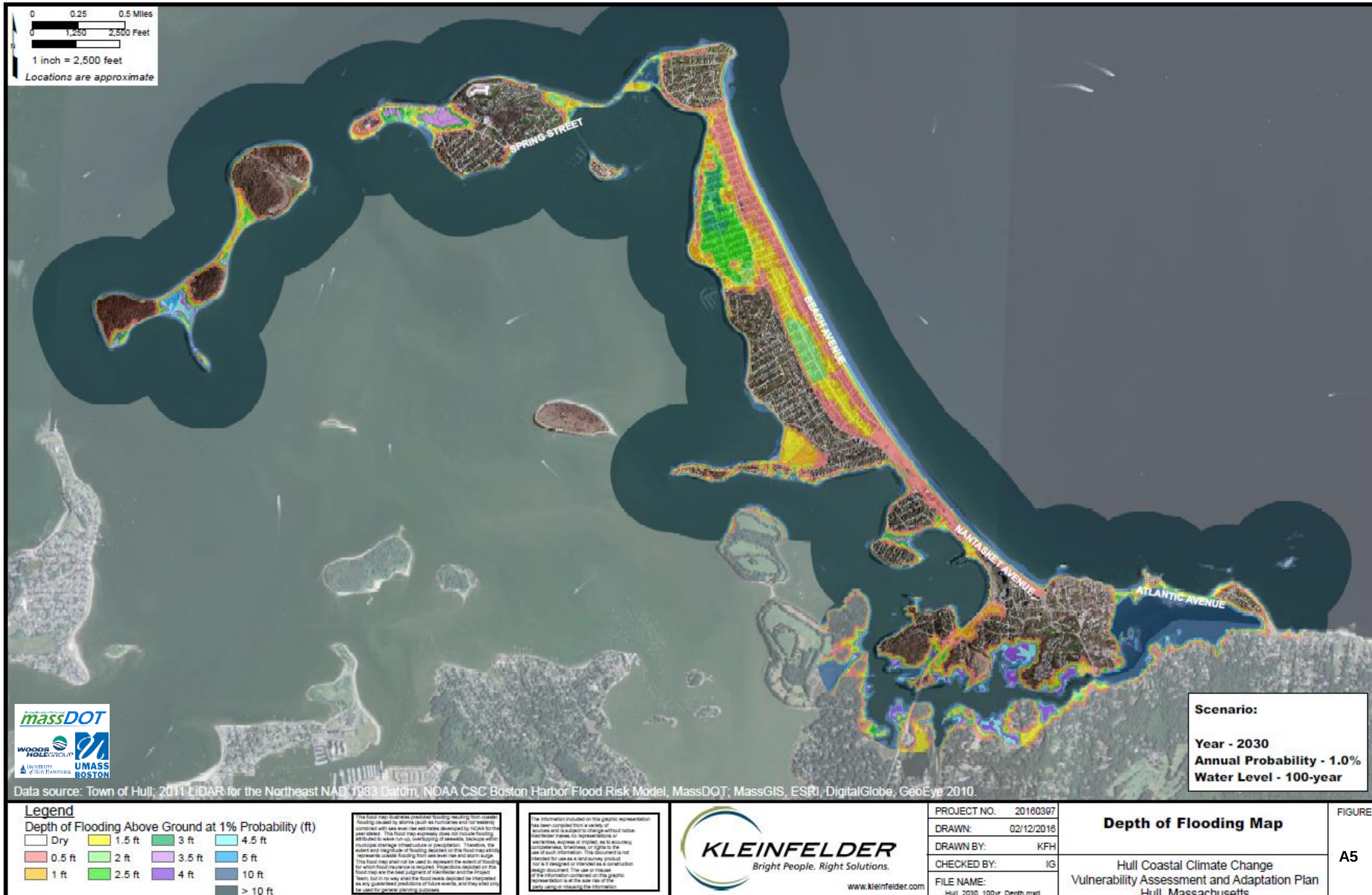
NANTASKET AVENUE
ATLANTIC AVENUE
massDOT
WOODS HOLE GROUP
UMASS BOSTON
Data source: Town of Hull; 2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC Boston Harbor Flood Risk Model, MassDOT; MassGIS, ESRI, DigitalGlobe, GeoEye 2010.
Scenario:
Year - 2013 (Present)
Annual Probability - 1.0%
Water Level - 100-year
Legend
Depth of Flooding Above Ground at 1% Probability (ft)
Dry
0.5 ft
1 ft
1.5 ft
2 ft
2.5 ft
3 ft
3.5 ft
4 ft
4.5 ft
5 ft
10 ft
> 10 ft
KLEINFELDER
Bright People. Right Solutions.
www.kleinfelder.com
PROJECT NO. 20160397
DRAWN: 02/22/2016
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME: Hull_Present_100yr_Depth.mxd
Depth of Flooding Map
Hull Coastal Climate Change
Vulnerability Assessment and Adaptation Plan
Hull, Massachusetts
FIGURE
A4


0 0.25 0.5 Miles
0 1,250 2,500 Feet
1 inch = 2,500 feet
Locations are approximate
SPRING STREET
BEACH AVENUE
NANTASKET AVENUE
ATLANTIC AVENUE
massDOT
WOODS HOLE GROUP
UMASS BOSTON
Data source: Town of Hull; 2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC Boston Harbor Flood Risk Model, MassDOT; MassGIS, ESRI, DigitalGlobe, GeoEye 2010.
Scenario:
Year - 2030
Annual Probability - 1.0%
Water Level - 100-year
Legend
Depth of Flooding Above Ground at 1% Probability (ft)
Dry
0.5 ft
1 ft
1.5 ft
2 ft
2.5 ft
3 ft
3.5 ft
4 ft
4.5 ft
5 ft
10 ft
> 10 ft
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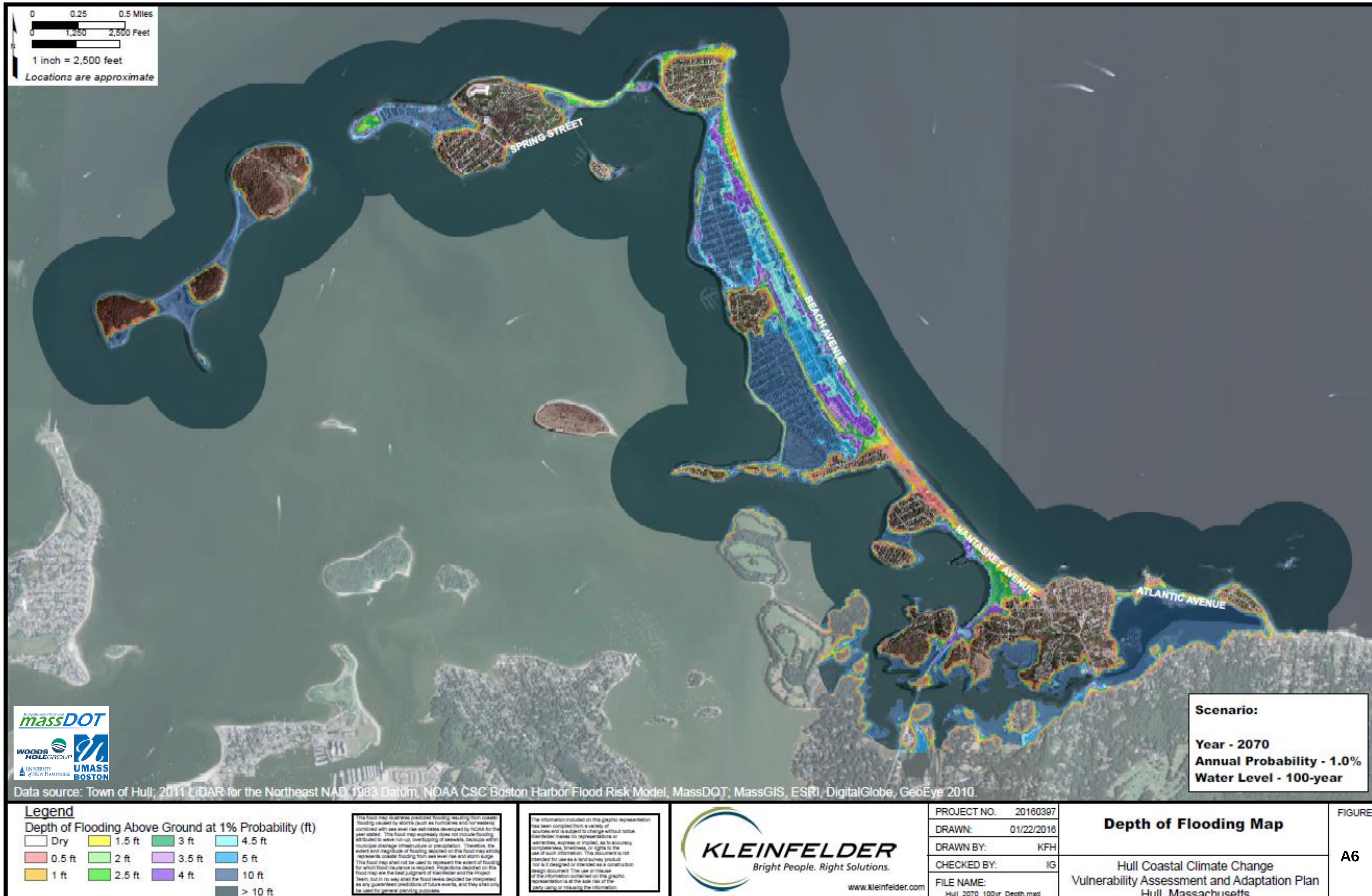
PROJECT NO. 20160397
DRAWN: 02/12/2016
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME: Hull_2030_100yr_Depth.mxd
Depth of Flooding Map
Hull Coastal Climate Change
Vulnerability Assessment and Adaptation Plan
Hull, Massachusetts
FIGURE
A5


0 0.25 0.5 Miles
0 1,250 2,500 Feet
1 inch = 2,500 feet
Locations are approximate
SPRING STREET
BEACH AVENUE
NANTASKET AVENUE
ATLANTIC AVENUE
massDOT
WOODS HOLE GROUP
UMASS BOSTON
Scenario:
Year - 2070
Annual Probability - 1.0%
Water Level - 100-year
Data source: Town of Hull; 2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC Boston Harbor Flood Risk Model, MassDOT; MassGIS, ESRI, DigitalGlobe, GeoEye 2010.
Legend
Depth of Flooding Above Ground at 1% Probability (ft)
Dry
0.5 ft
1 ft
1.5 ft
2 ft
2.5 ft
3 ft
3.5 ft
4 ft
4.5 ft
5 ft
10 ft
> 10 ft
This flood map illustrates predicted flooding resulting from coastal flooding caused by storms (such as hurricanes and nor'easters) combined with sea level rise estimates developed by NOAA for the year stated. This flood map expressly does not include flooding attributed to wave run-up, overtopping of seawalls, backups within municipal drainage infrastructure or precipitation. Therefore, the extent and magnitude of flooding depicted on this flood map strictly represents coastal flooding from sea level rise and storm surge. This flood map shall not be used to represent the extent of flooding for which flood insurance is required. Projections depicted on this flood map are the best judgment of Kleinfelder and the Project Team, but in no way shall the flood levels depicted be interpreted as any guaranteed predictions of future events, and they shall only be used for general planning purposes.
The information included on this graphic representation has been compiled from a variety of sources and is subject to change without notice. Kleinfelder makes no representations or warranties, express or implied, as to accuracy, completeness, timeliness, or rights to the use of such information. This document is not intended for use as a land survey product nor is it designed or intended as a construction design document. The use or misuse of the information contained on this graphic representation is at the sole risk of the party using or misusing the information.
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DRAWN BY: KFH
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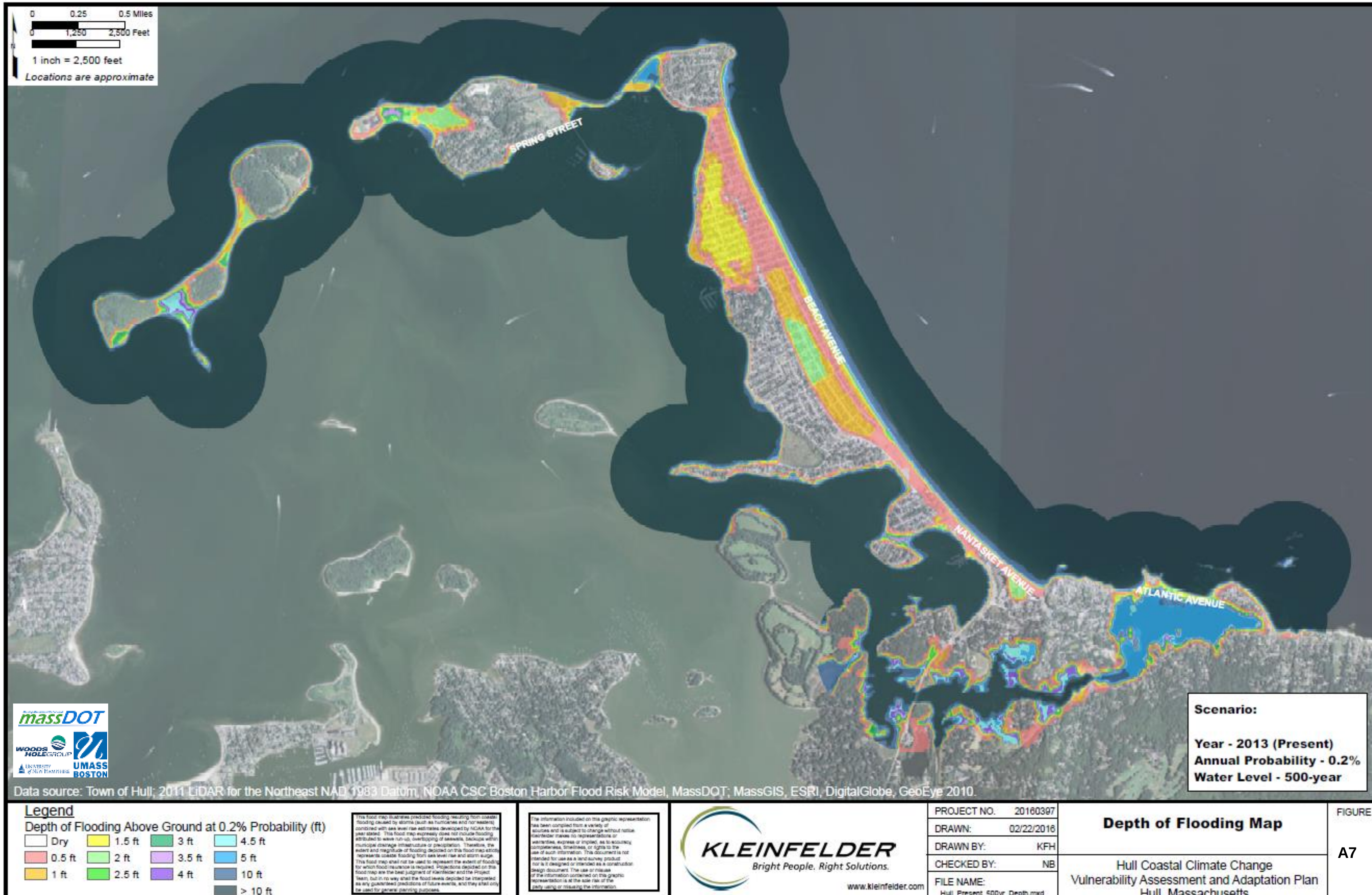
FILE NAME: Hull_2070_100yr_Depth.mxd
Depth of Flooding Map
Hull Coastal Climate Change Vulnerability Assessment and Adaptation Plan Hull, Massachusetts
FIGURE
A6


0 0.25 0.5 Miles
0 1,250 2,500 Feet
1 inch = 2,500 feet
Locations are approximate
SPRING STREET
BEACH AVENUE
NANTASKET AVENUE
ATLANTIC AVENUE
massDOT
WOODS HOLE GROUP
UNIVERSITY of NEW HAMPSHIRE
UMASS BOSTON
Scenario:
Year - 2013 (Present)
Annual Probability - 0.2%
Water Level - 500-year
Data source: Town of Hull; 2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC Boston Harbor Flood Risk Model, MassDOT; MassGIS, ESRI, DigitalGlobe, GeoEye 2010.
Legend
Depth of Flooding Above Ground at 0.2% Probability (ft)
Dry
0.5 ft
1 ft
1.5 ft
2 ft
2.5 ft
3 ft
3.5 ft
4 ft
4.5 ft
5 ft
10 ft
> 10 ft
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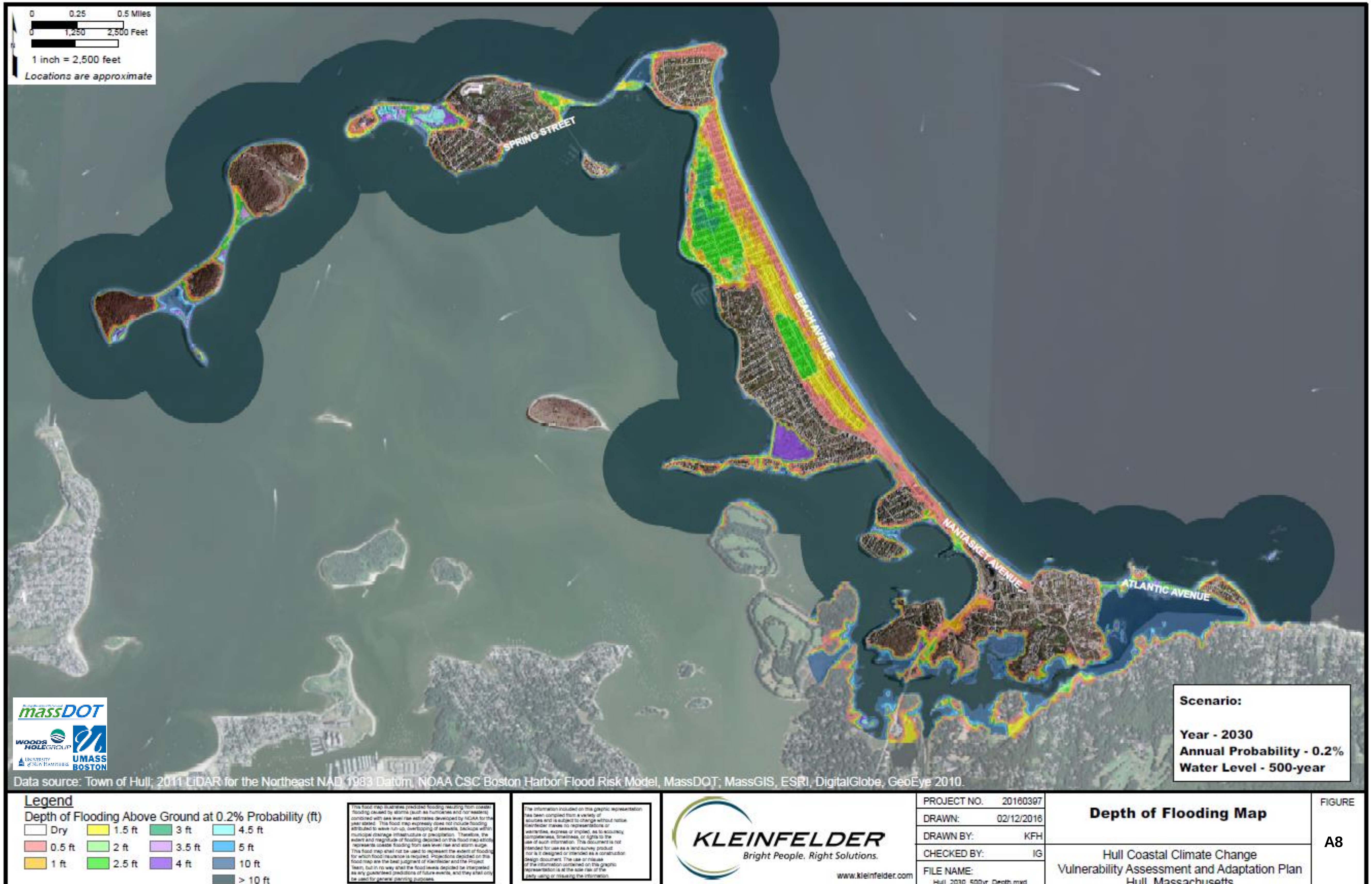
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME: Hull_Present_500yr_Depth.mxd
Depth of Flooding Map
Hull Coastal Climate Change
Vulnerability Assessment and Adaptation Plan
Hull, Massachusetts
FIGURE
A7


0 0.25 0.5 Miles
0 1,250 2,500 Feet
1 inch = 2,500 feet
Locations are approximate
SPRING STREET
BEACH AVENUE
NANTASKET AVENUE
ATLANTIC AVENUE
massDOT
WOODS HOLE GROUP
UMASS BOSTON
Scenario:
Year - 2030
Annual Probability - 0.2%
Water Level - 500-year
Data source: Town of Hull; 2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC Boston Harbor Flood Risk Model, MassDOT; MassGIS, ESRI, DigitalGlobe, GeoEye 2010.
Legend
Depth of Flooding Above Ground at 0.2% Probability (ft)
Dry
0.5 ft
1 ft
1.5 ft
2 ft
2.5 ft
3 ft
3.5 ft
4 ft
4.5 ft
5 ft
10 ft
> 10 ft
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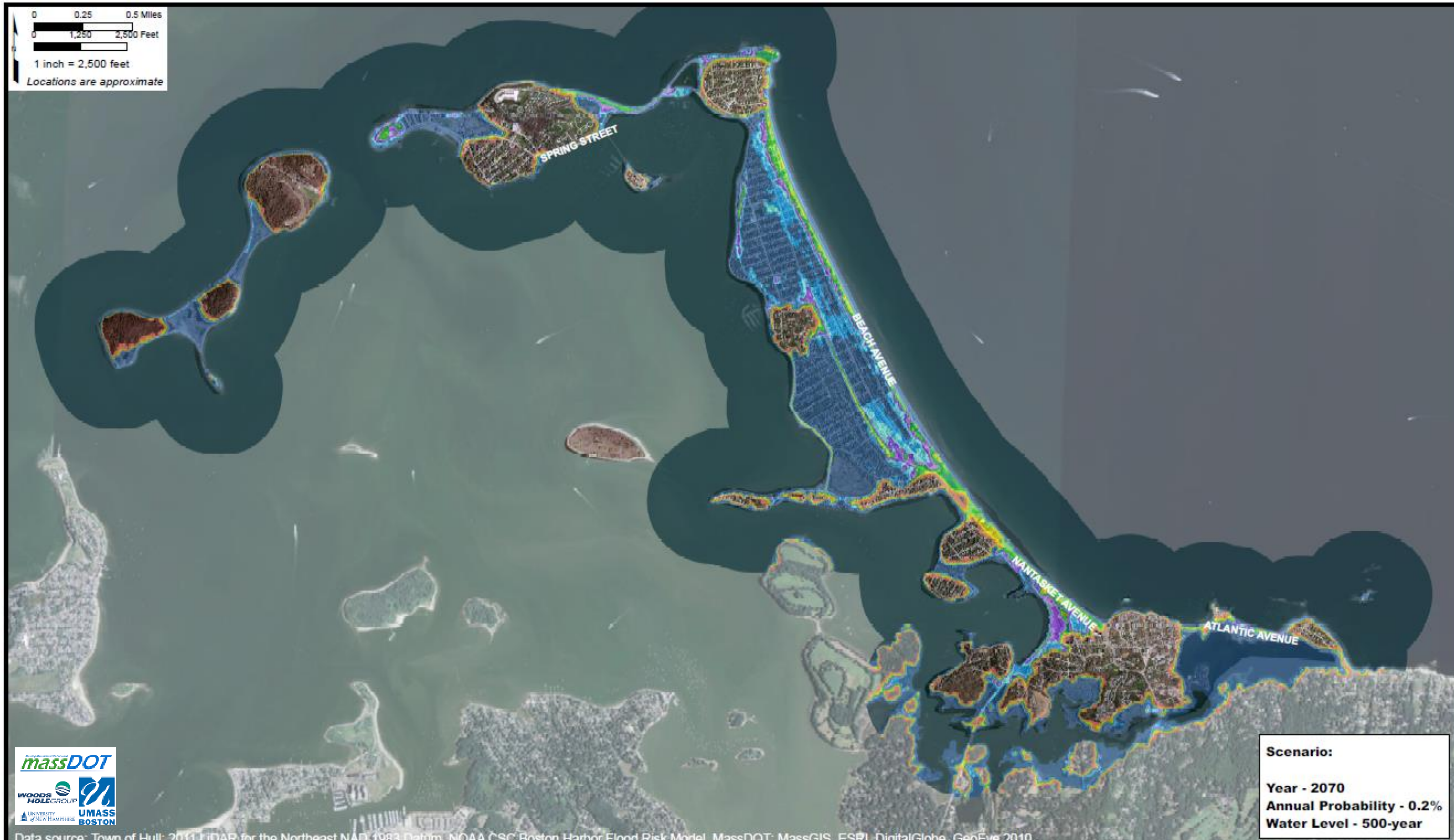
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME: Hull_2030_500yr_Depth.mxd
Depth of Flooding Map
Hull Coastal Climate Change
Vulnerability Assessment and Adaptation Plan
Hull, Massachusetts
FIGURE
A8



Data source: Town of Hull; 2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC Boston Harbor Flood Risk Model, MassDOT; MassGIS, ESRI, DigitalGlobe, GeoEye 2010.

Legend

Depth of Flooding Above Ground at 0.2% Probability (ft)

Dry, 0.5 ft, 1 ft, 1.5 ft, 2 ft, 2.5 ft, 3 ft, 3.5 ft, 4 ft, 4.5 ft, 5 ft, 10 ft, > 10 ft

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DRAWN BY:	KFH
CHECKED BY:	IG
FILE NAME:	Hull_2070_500yr_Depth.mxd

Depth of Flooding Map

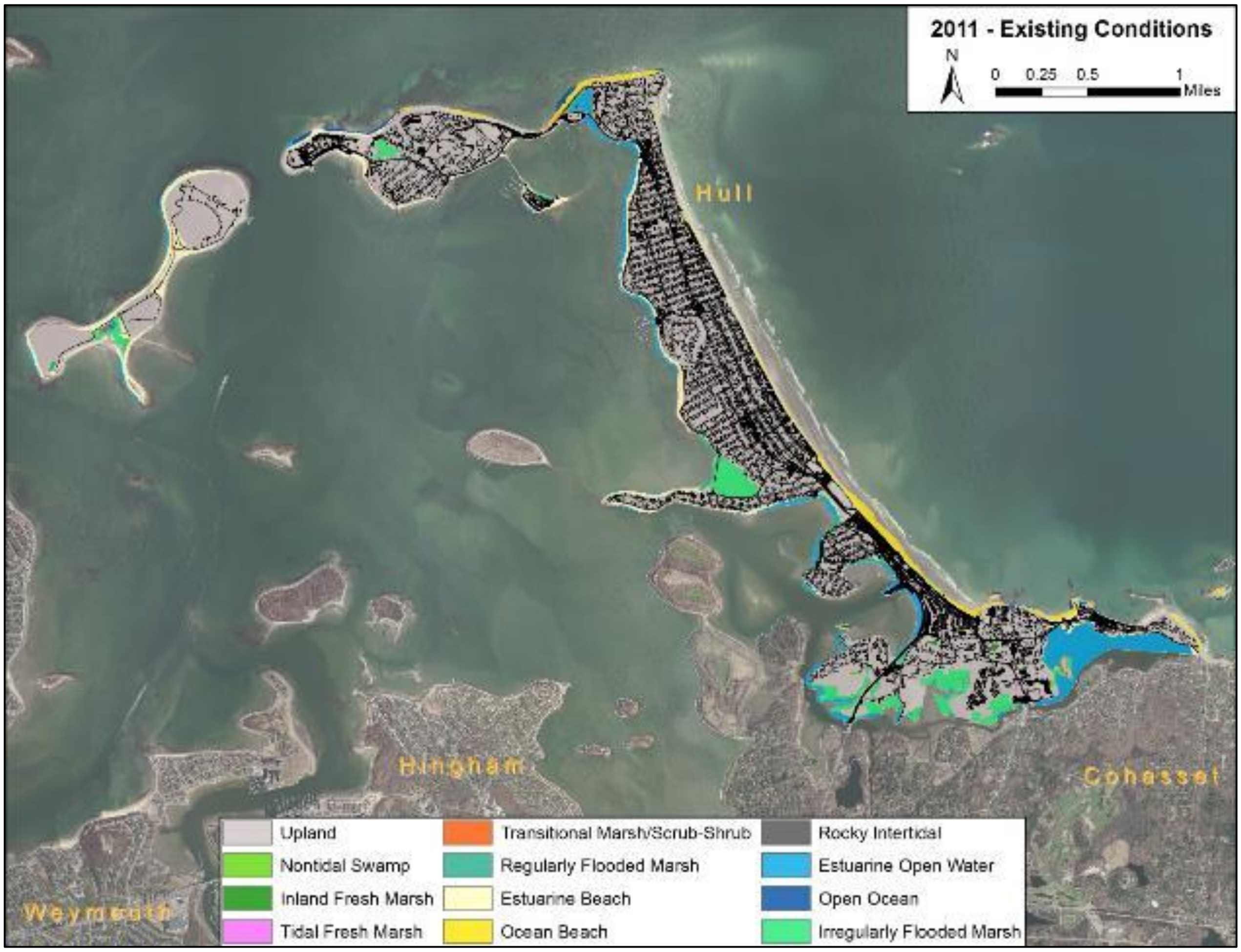
Hull Coastal Climate Change Vulnerability Assessment and Adaptation Plan
Hull, Massachusetts

FIGURE **A9**

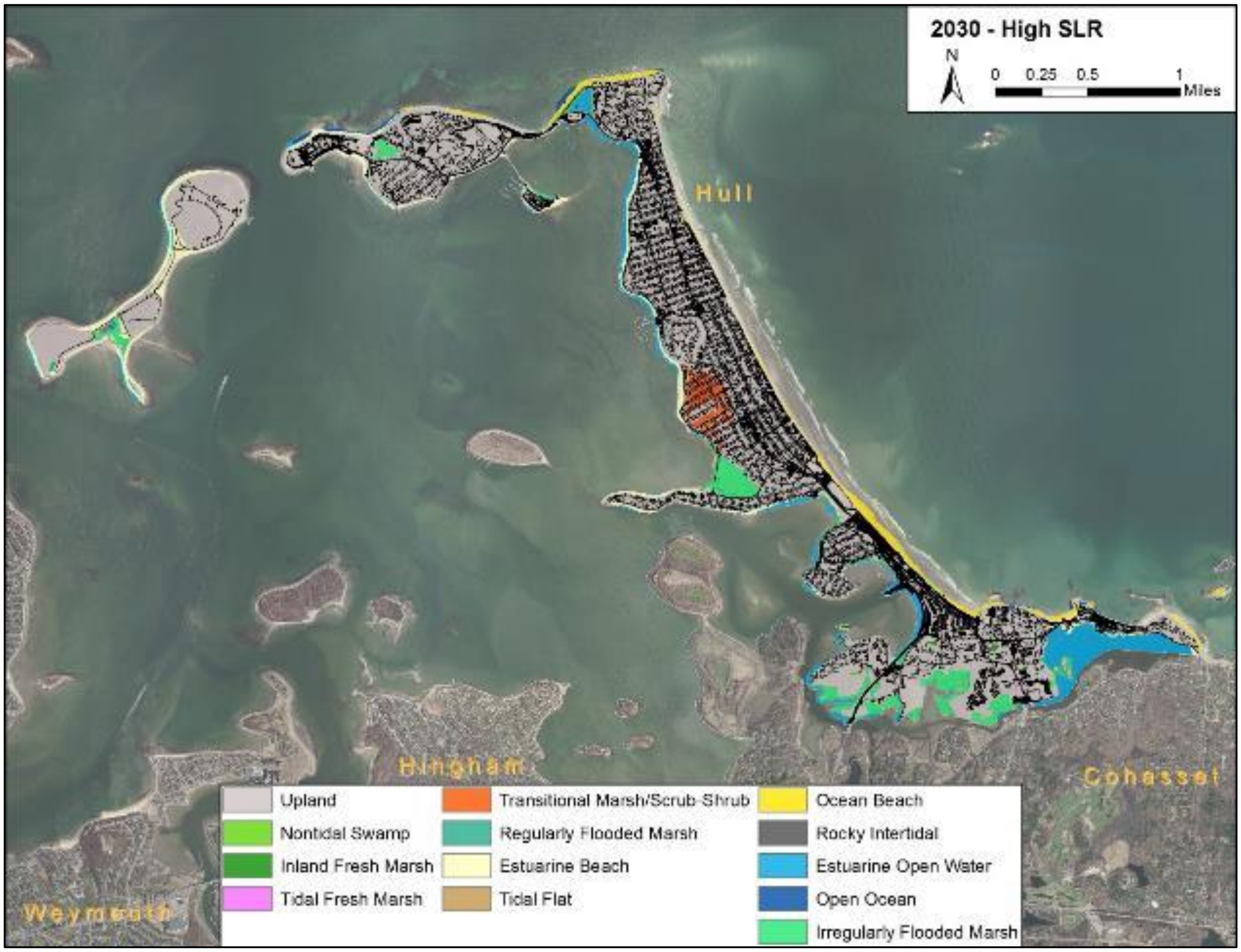
APPENDIX B – WETLAND CLASSIFICATION MAPS AND DATA

Note: Impervious surfaces are superimposed on the modeling results in all maps, indicating areas that would be precluded from marsh migration where the land is otherwise suitable.

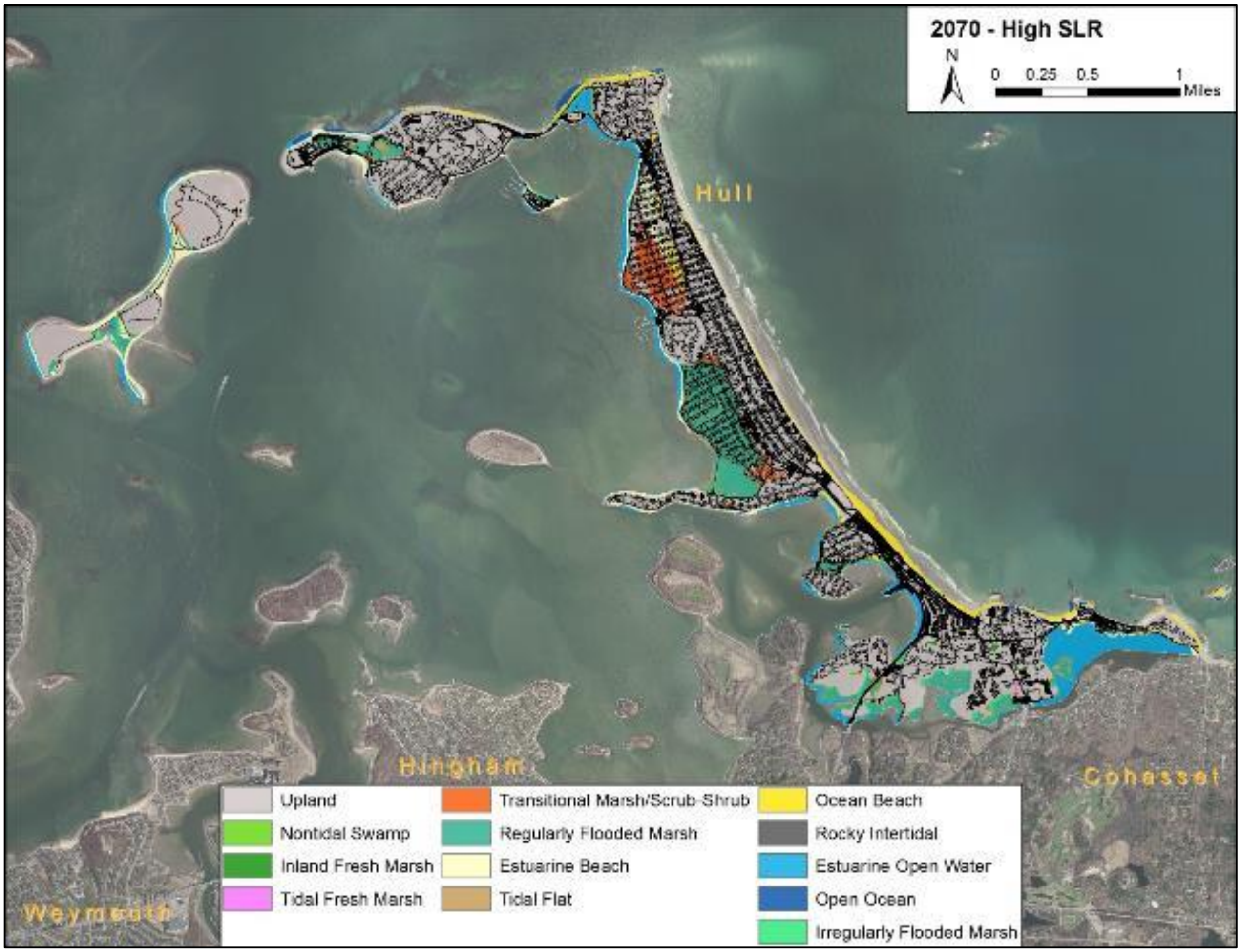
B1: 2011 – Wetland Classification Areas in Town of Hull



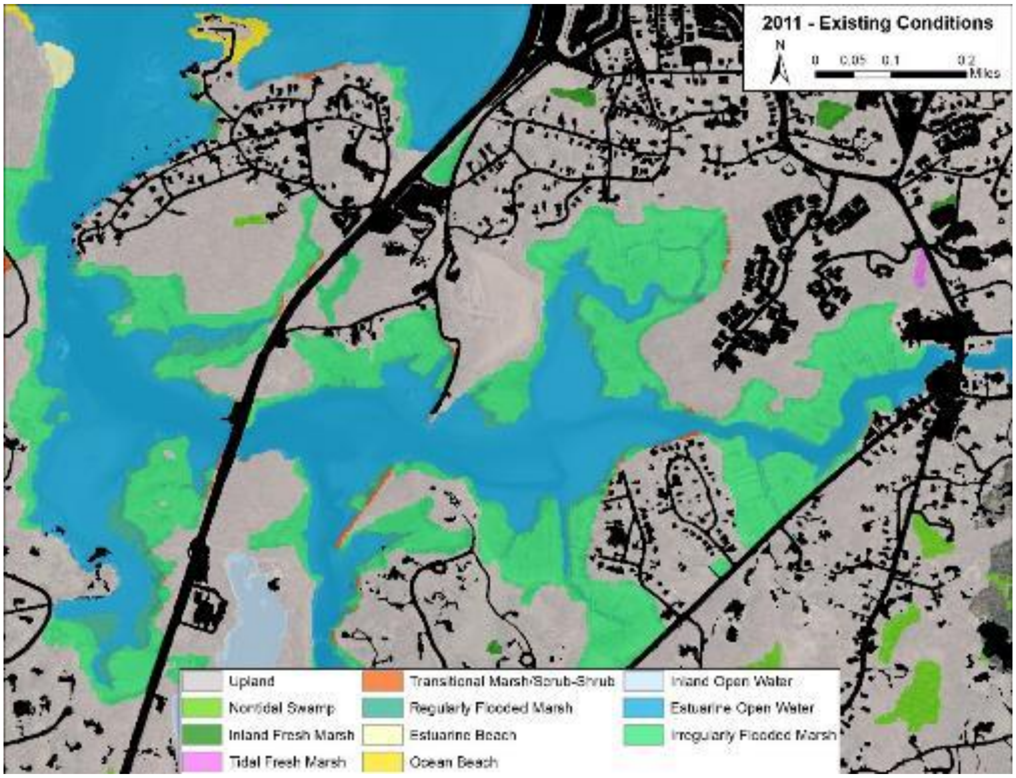
B2: 2030 – Wetland Classification Areas in Town of Hull



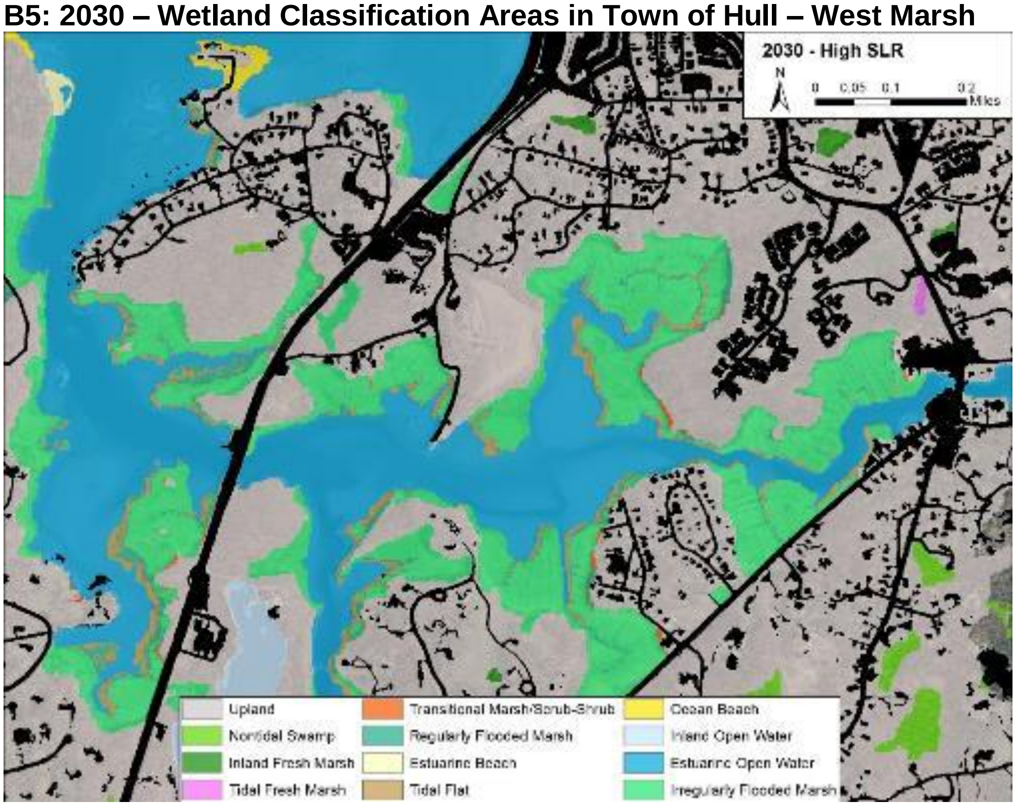
B3: 2070 – Wetland Classification Areas in Town of Hull



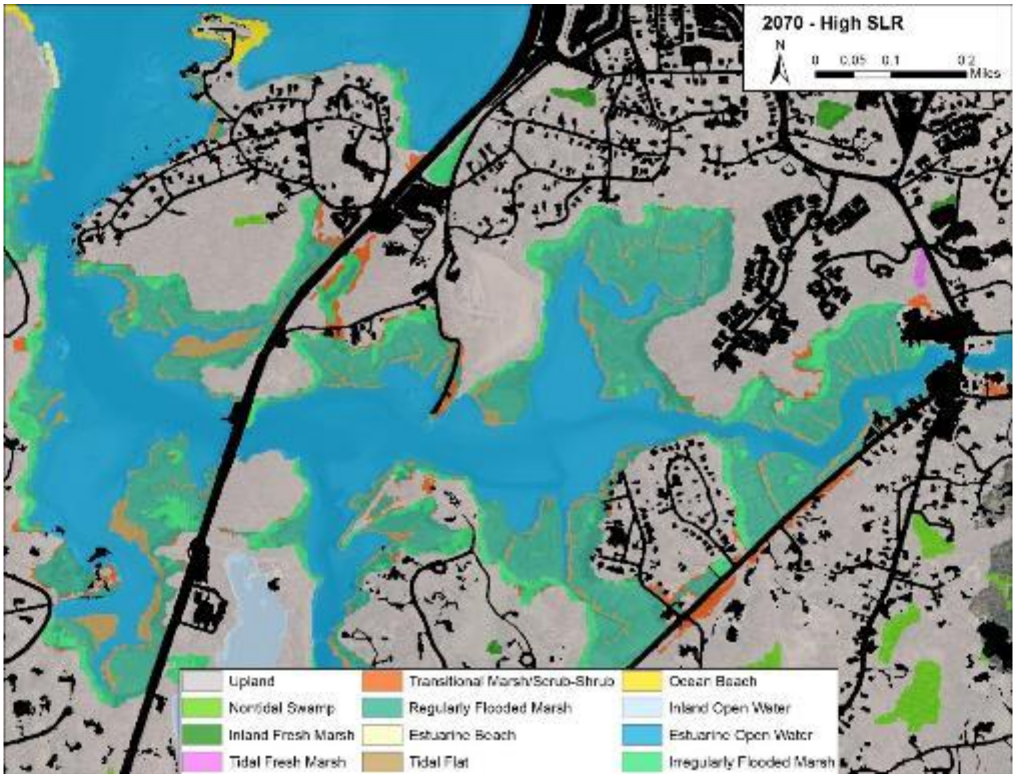
B4: 2011 – Wetland Classification Areas in Town of Hull – West Marsh



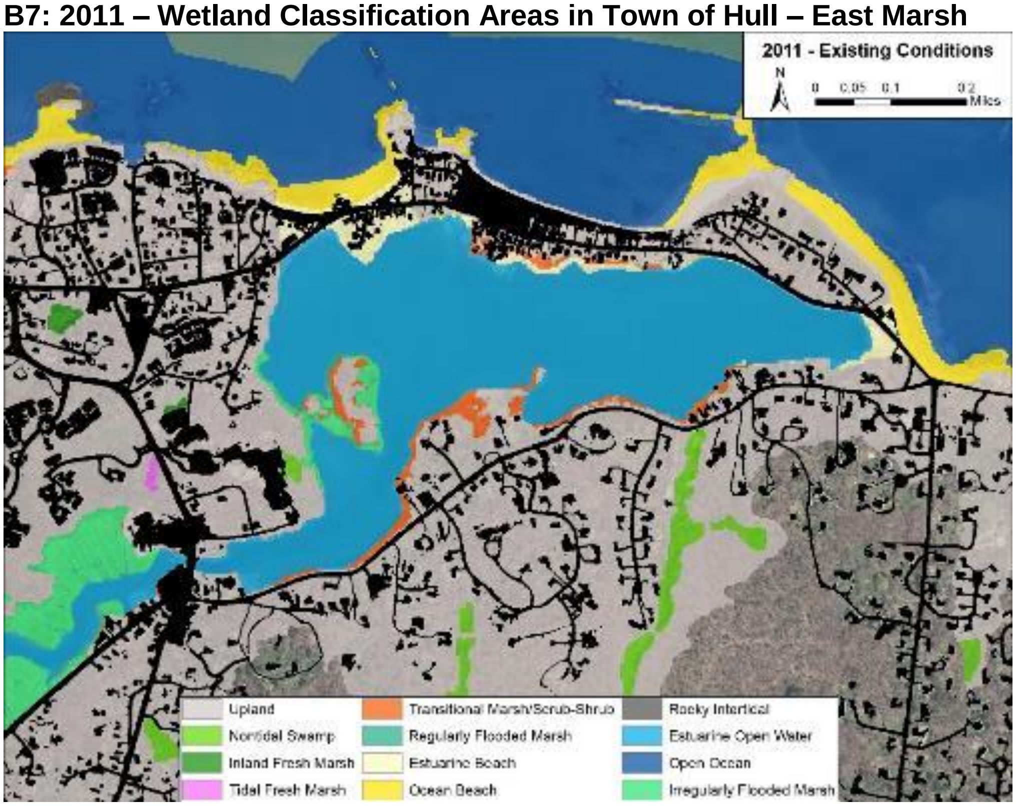
B5: 2030 – Wetland Classification Areas in Town of Hull – West Marsh



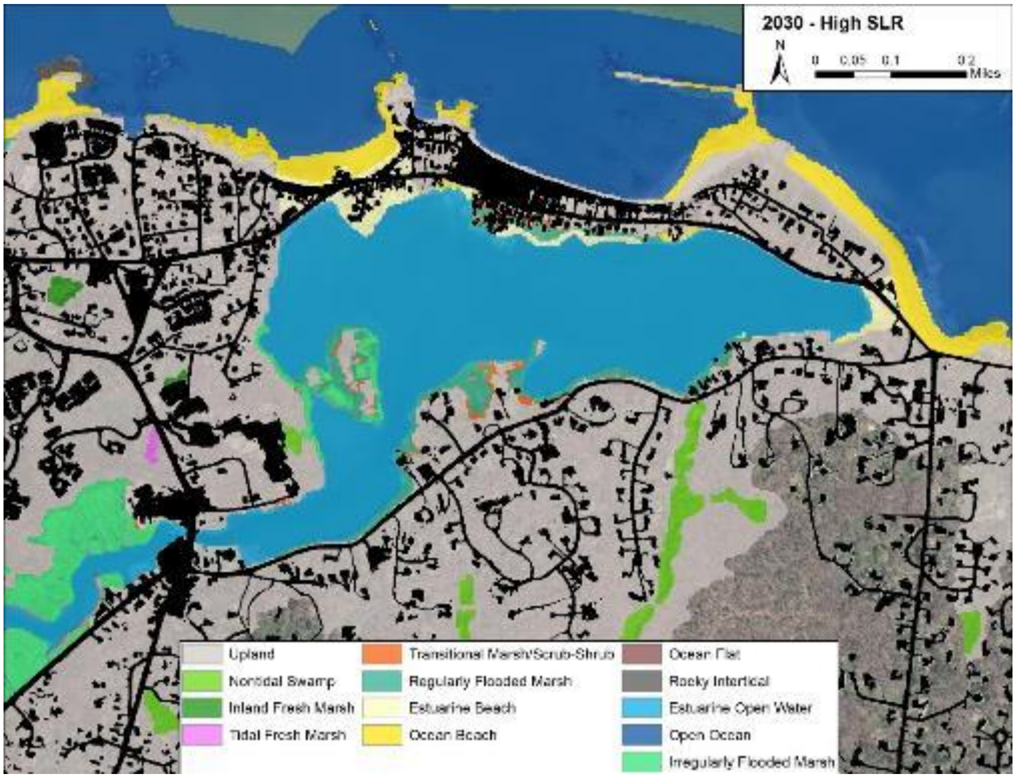
B6: 2070 – Wetland Classification Areas in Town of Hull – West Marsh



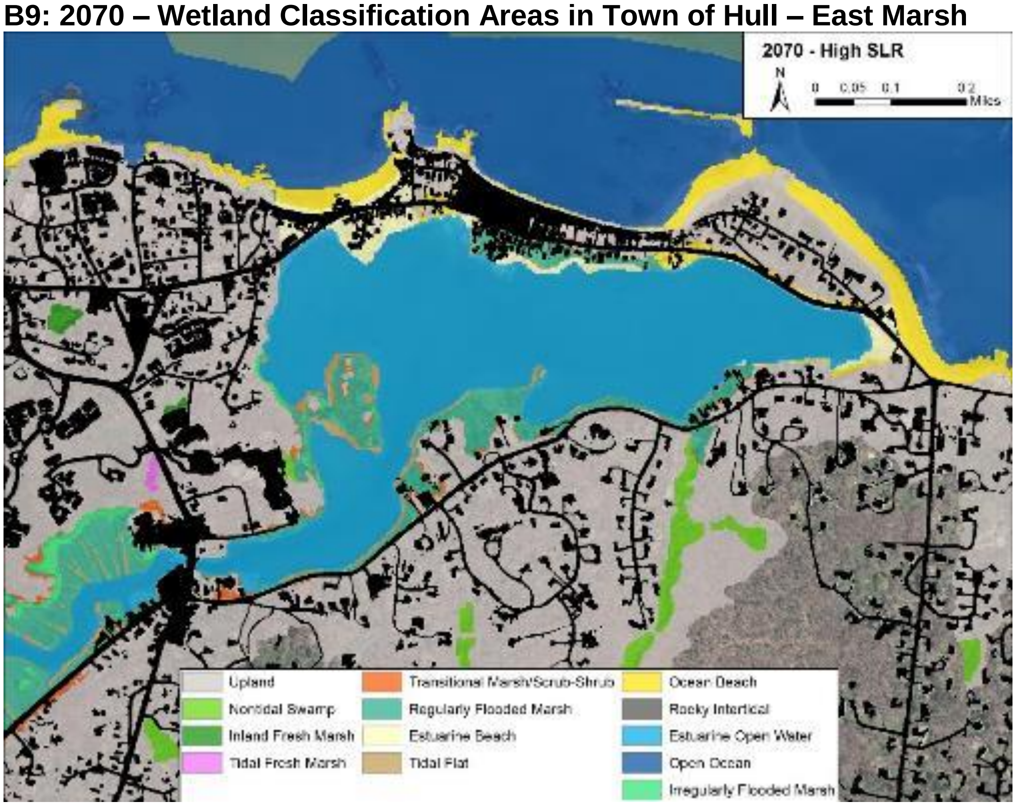
B7: 2011 – Wetland Classification Areas in Town of Hull – East Marsh



B8: 2030 – Wetland Classification Areas in Town of Hull – East Marsh

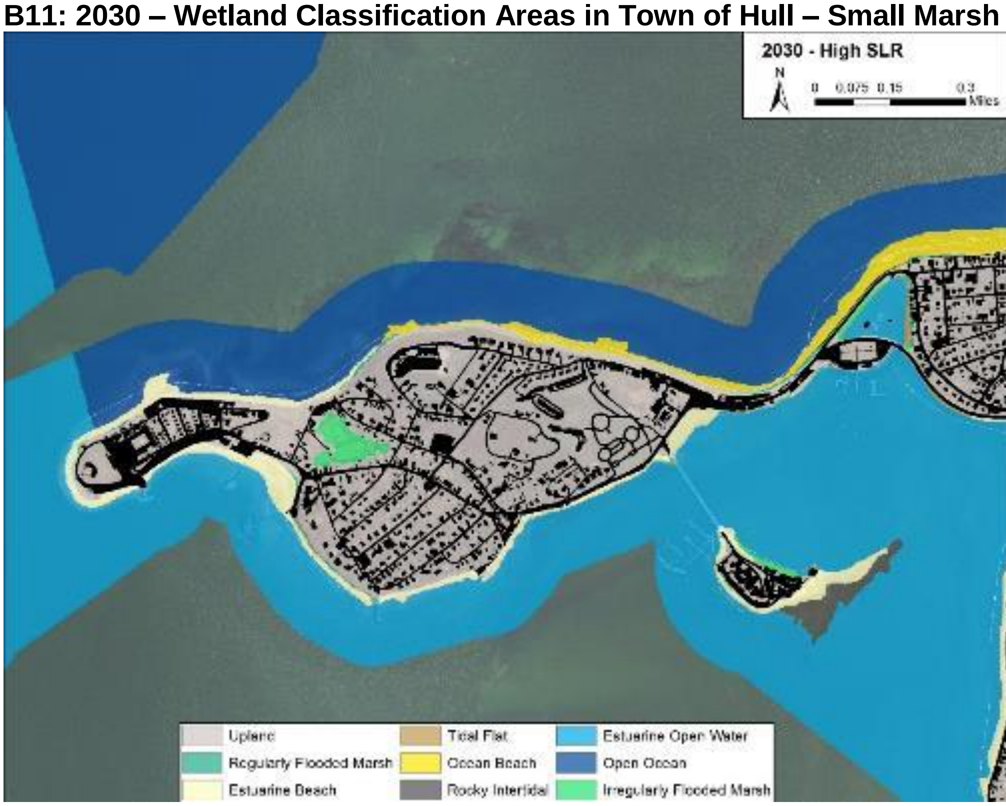


B9: 2070 – Wetland Classification Areas in Town of Hull – East Marsh



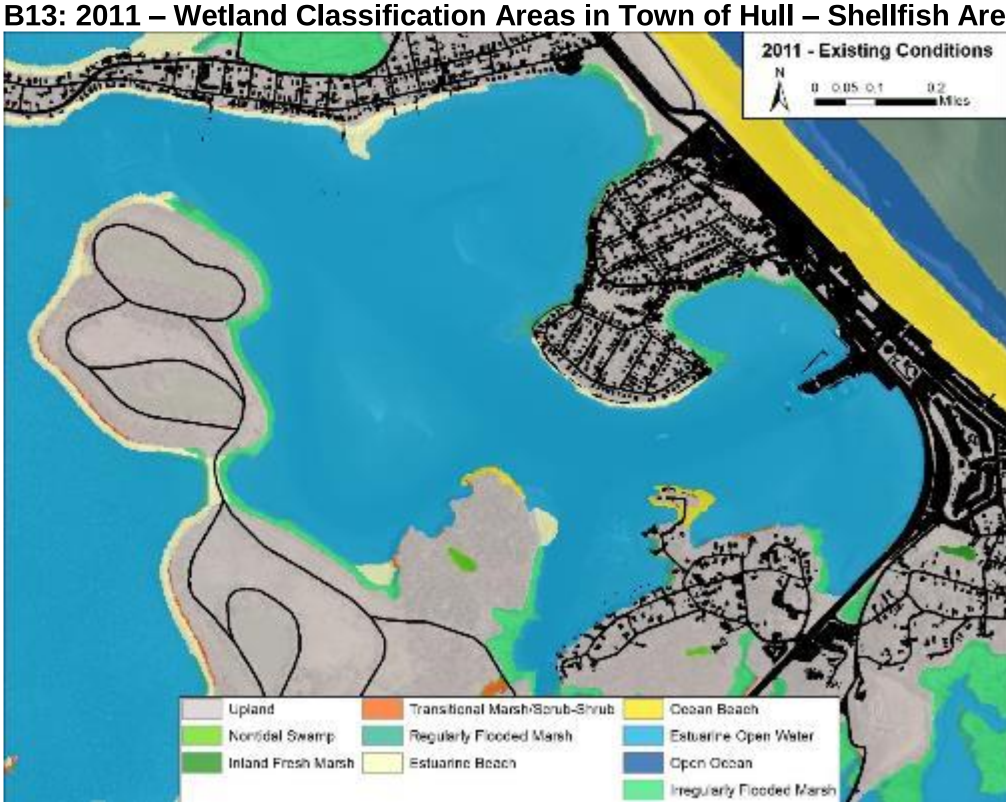
B10: 2011 – Wetland Classification Areas in Town of Hull – Small Marsh Areas

B11: 2030 – Wetland Classification Areas in Town of Hull – Small Marsh Areas

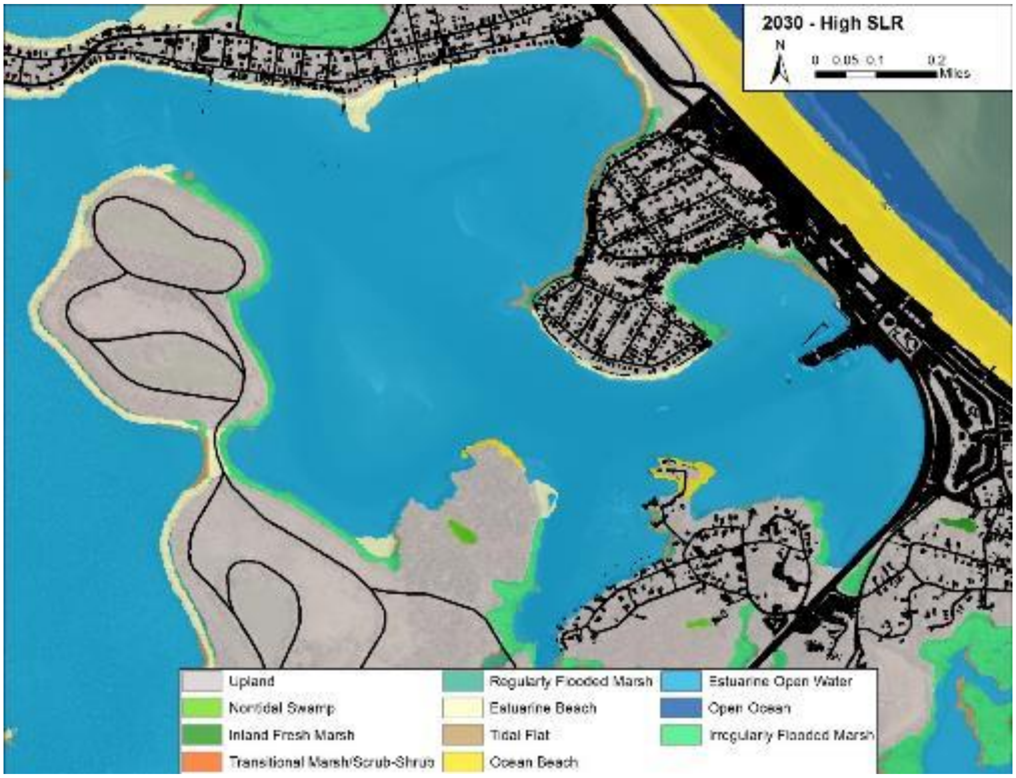


B12: 2070 – Wetland Classification Areas in Town of Hull – Small Marsh Areas

B13: 2011 – Wetland Classification Areas in Town of Hull – Shellfish Areas



B14 2030 – Wetland Classification Areas in Town of Hull – Shellfish Areas



B15: 2070 – Wetland Classification Areas in Town of Hull – Shellfish Areas

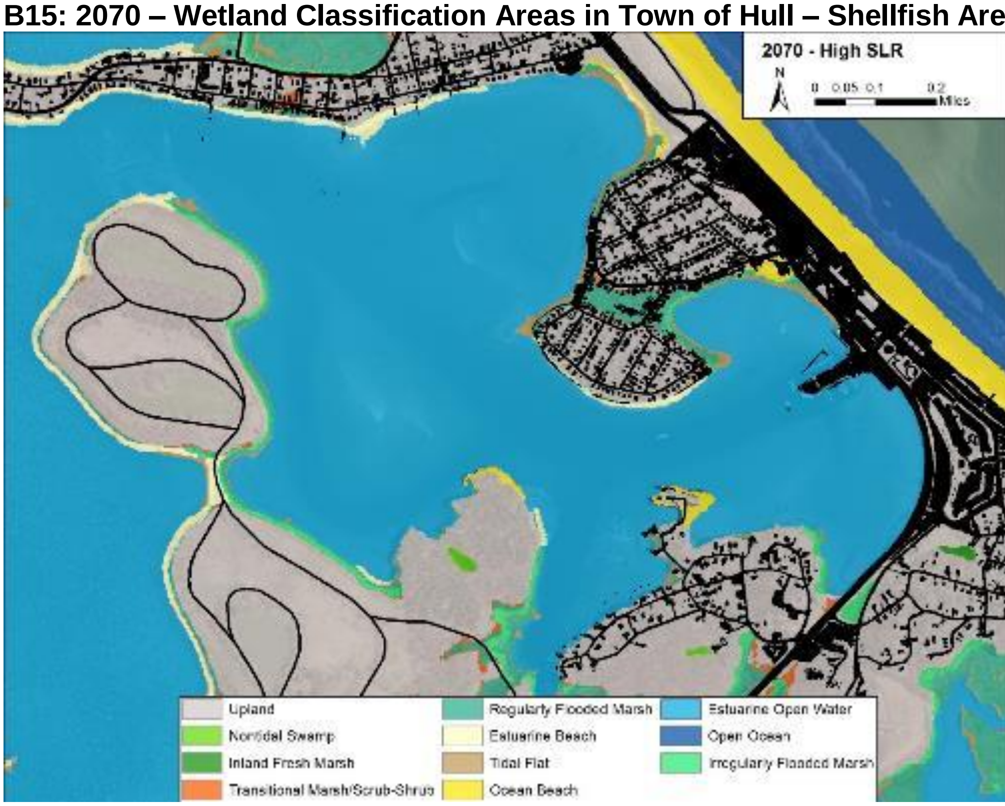


Table B1. NWI Category to SLAMM Code Conversion Table

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

APPENDIX C – RISK AND ADAPTATION DATA

Table C1. Consequence of Failure Scores for Municipal Critical Infrastructure Vulnerable to Flooding

Type	Facility Name	Location	Area of Service Loss	Duration of Service Loss	Cost of Damage	Impacts to Public Safety Services	Impacts to Economic Activities	Impacts to Public Health & Environment	Consequence Score
Wastewater	Hull Sewer Plant	1111 Nantasket Ave	4	4	4	2	4	4	92
Coastal Barrier	Barrier Dunes	Alphabet Streets	3	4	2	4	4	4	88
Coastal Barrier	Barrier Dunes	Lewis St	3	4	2	4	4	4	88
Coastal Barrier	Barrier Dunes	Phipps St to Malta St	3	4	2	4	4	4	88
School	Hull Memorial Middle School (Emergency Ops Center)	81 Central Ave	4	2	3	4	3	3	79
School	Hull High School	180 Main Street	4	2	3	2	3	3	71
Fire Station	A Street Fire Station	671 Nantasket Ave	3	1	2	4	2	3	63
Energy	Municipal Light Dep't	15 Edge Water Road	4	1	2	2	2	3	58
Maintenance	DPW Barn	5 Nantasket Ave	4	1	2	3	1	3	58
Wastewater	Waste Water Pump Station 6	765 Nantasket Ave	2	3	1	1	2	4	54
Maintenance	DPW Salt Shack	5 Nantasket Ave	4	2	1	2	1	3	54
Senior Center	Anne Scully Senior Center	197 Samoset Ave	4	2	1	3	0	3	54
Coastal Barrier	Newport Road Dike	Newport Rd	3	1	1	4	2	2	54
Major Bridge	West Corner Bridge	Nantasket Ave at Town Line	4	0	1	4	4	0	54
Major Roadway	George Washington Blvd	Gosnold St to Rockland Cir	4	0	1	4	4	0	54
Major Roadway	George Washington Blvd	Rockland Cir to Nantasket Ave	4	0	1	4	4	0	54
Major Roadway	Nantasket Ave	State Park Rd to George Washington Blvd	4	0	1	4	4	0	54
Major Roadway	Nantasket Ave	C St to H St	4	0	1	4	4	0	54
Major Roadway	Nantasket Ave	V St to Fitzpatrick Way	4	0	1	4	4	0	54
Major Roadway	Main Street	S Main St to Windmill Point	4	0	1	4	4	0	54
Major Roadway	Spring Street	Nantasket Ave to Main Street	4	0	1	4	4	0	54
Pier	Pemberton Pier	171 Main St	4	2	1	3	3	0	54
Wastewater	Waste Water Pump Station 1	157 Atlantic Ave	2	3	1	0	2	4	50
Wastewater	Waste Water Pump Station 5	70 Draper Ave	2	3	1	0	2	4	50
Wastewater	Waste Water Pump Station 3	13 Rockland Circle	2	3	1	0	2	4	50
Wastewater	Waste Water Pump Station 9	165 Main St	2	3	1	0	2	4	50
Wastewater	Waste Water Pump Station 4	13A Marginal Road	2	3	1	0	1	4	46
Stormwater	Storm Water Pump Station (D St & Cadish Ave)	D St & Cadish Ave	2	2	1	3	1	2	46
Stormwater	Draper Ave Storm Water Pump Station	220 Newport Rd	2	2	1	3	1	2	46
Major Bridge	MLK Bridge	Fitzpatrick Way	4	0	1	4	2	0	46
Major Roadway	Atlantic Ave	Summit Ave to Richards Rd	4	0	1	4	2	0	46
Pier	Nantasket Pier	McDuff Landing	2	2	1	0	2	0	29
Pier	A Street Pier	A Street & Cadish Ave	2	2	1	0	2	0	29
Pier	Town Pier (Public)	5 Fitzpatrick Way	2	2	1	0	2	0	29
Heliport	Kenberma Playground Heliport	Nantasket Ave at Nantasket Road	2	1	0	2	0	0	21
Heliport	L Street Playground Heliport	L Street at Nantasket Ave	2	1	0	2	0	0	21
Heliport	Dust Bowl Heliport	Main Street At Ocean Ave	2	1	0	2	0	0	21
Heliport	Roller Hockey Park Heliport	George Washington Blvd	2	1	0	2	0	0	21

Heliport	Mariners Park Heliport	3 Fitzpatrick Way	2	1	0	2	0	0	21
Energy	Hull Wind 1	1 Wind Mill Point	0	2	2	0	1	0	21

Table C2. Summary of Risks and Adaptation Strategies for Municipal Critical Infrastructure Vulnerable to Flooding

(Colors indicate which risk score quartile the asset is in for the given time horizon. Red = High, Orange = Moderate-High, Yellow = Moderate-Low, Green = Low. In addition, Pink = High risk score with very low consequence)

Type	Asset Name/Number	Location	Critical Elevation	Conseq. Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score	Adaptation Strategies - Near to Medium Term	Adaptation Strategies - Medium to Long Term
Wastewater	Hull Sewer Plant	1111 Nantasket Ave	10.2	92	0.1	9	1	92	50	4583	949	Maintain/repair existing floodproofing system	$3 million – perimeter flood wall system
Coastal Barrier	Barrier Dunes	Alphabet Streets	12.5	88	20	1750	25	2188	100	8750	3281	$150,000-$200,000 – Carry out coastal processes study to inform beach nourishment and dune enhancement designs	$25 million for all North Nantasket Beach
Coastal Barrier	Barrier Dunes	Lewis St	14.7	88	10	875	25	2188	100	8750	2844		
Coastal Barrier	Barrier Dunes	Phipps St to Malta St	15.0	88	5	438	10	875	100	8750	2231		
School / Emergency Ops Center	Hull Memorial Middle School	81 Central Ave	8.5	79	1	79	2	158	100	7917	1670	$184,000 – temporary flood barriers	$442,000 – permanent and temporary flood barriers
School	Hull High School	180 Main Street	11.5	71	0	0	0	0	10	708	142	Lower priority – 2030 probability of flooding < 1%	$650,000 – perimeter flood barrier
Fire Station	A Street Fire Station	671 Nantasket Ave	10.3	63	0	0	0.5	31	30	1875	384	Vehicle/equipment relocation plan for storm events	$200,000-400,000 – perimeter flood barrier
Energy	Municipal Light Dep't	15 Edge Water Road	8.9	58	0.5	29	5	292	100	5833	1269	$50,000 – wet floodproof building interiors $100,000 – dry floodproof buildings Vehicle/equipment relocation plan for storm events	
Maintenance	DPW Barn	5 Nantasket Ave	10.2	58	0	0	0.2	12	30	1750	354	Vehicle/equipment relocation plan for storm events	$300,000-750,000 – perimeter concrete or sheet pile flood wall with temporary barriers at openings
Major Roadway	Spring Street	Nantasket Ave to Main Street	8.2	54	10	542	30	1625	100	5417	1842	$1-2 million – raise road to 11.0 ft. NAVD88 Add $5-6 million to raise Nantasket Ave and Fitzpatrick Way to 11.0 ft. Debris management plan	
Major Roadway	Main Street	S Main St to Windmill Point	5.9	54	10	542	25	1354	100	5417	1760	$4 million – raise road to 10.0 ft. NAVD88 Evacuation planning, debris management plan	
Major Roadway	Nantasket Ave	V St to Fitzpatrick Way	8.0	54	1	54	20	1083	100	5417	1435	$2-4 million – raise road to 10.0-11.0 ft. NAVD88 (C to Fitzpatrick) Evacuation planning, debris management plan	$950,000 – raise Malta to Nantasket Rd to 13.0 ft. NAVD88
Major Roadway	Nantasket Ave	C St to H St	8.8	54	1	54	5	271	50	2708	650		
Major Roadway	Nantasket Ave	State Park Rd to George Washington Blvd	10.8	54	5	271	10	542	50	2708	840	$1-2 million – raise road to 12.0 ft. NAVD88 Evacuation planning, debris management plan	

Type	Asset Name/Number	Location	Critical Elevation	Conseq. Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score	Adaptation Strategies - Near to Medium Term	Adaptation Strategies - Medium to Long Term
Major Roadway	George Washington Blvd	Rockland Cir to Nantasket Ave	9.4	54	2	108	10	542	50	2708	758	MassDOT roadway	MassDOT roadway
Major Roadway	George Washington Blvd	Gosnold St to Rockland Cir	9.5	54	0.2	11	2	108	30	1625	363	$3-4 million – raise road to 11.0 ft. NAVD88 Evacuation planning, debris management plan	$8-10 million – raise road to 13.0 ft. NAVD88
Maintenance	DPW Salt Shack	5 Nantasket Ave	9.5	54	0.2	11	5	271	50	2708	628	Temporarily relocate salt supplies to Barn pre-flood	Elevate at time of replacement
Senior Center	Anne Scully Senior Center	197 Samoset Ave	9.1	54	1	54	2	108	50	2708	601	Relocate services to a less at-risk public building Vehicle/equipment relocation plan for storm events	
Wastewater	Waste Water Pump Station 6	765 Nantasket Ave	9.8	54	0.1	5	2	108	50	2708	577	$55,000 – perimeter berm with temporary flood barriers	$102,000 – concrete flood wall with temporary barriers
Major Bridge	West Corner Bridge	Nantasket Ave at Town Line	10.5	54	0	0	0.2	11	30	1625	328	Lower priority – 2030 probability of flooding < 1%	
Pier	Pemberton Pier	171 Main St	11.0	54	0	0	0	0	20	1083	217	Repair minor damages as needed; elevate fixed pier deck if major damage occurs	$150,000 – Extend MBTA floating dock pilings vertically
Coastal Barrier	Newport Road Dike	Newport Rd	13.6	54	0	0	0	0	0.2	11	2	Develop plans to repair or replace the tide gate	
Wastewater	Waste Water Pump Station 9	165 Main St	10.5	50	0	0	0.1	5	30	1500	302	Lower priority – 2030 probability of flooding < 1%	$250,000-400,000 – elevate pump station Alternatively, $200,000-300,000 – Pre-cast, flood-proofed (with flood panels), concrete enclosure
Wastewater	Waste Water Pump Station 5	70 Draper Ave	6.1	50	0	0	0.1	5	50	2500	502	Lower priority – 2030 probability of flooding < 1%	
Wastewater	Waste Water Pump Station 1	157 Atlantic Ave	10.8	50	0.1	5	10	500	25	1250	403	$250,000-400,000 – elevate pump station Alternatively, $200,000-300,000 – Pre-cast, flood-proofed (with flood panels), concrete enclosure	
Wastewater	Waste Water Pump Station 3	13 Rockland Circle	10.9	50	0	0	0	0	25	1250	250	Lower priority – 2030 probability of flooding < 1%	
Major Roadway	Atlantic Ave	Summit Ave to Richards Rd	5.2	46	50	2292	100	4583	100	4583	3438	$6-7 million – raise road to 12.0 ft. NAVD88 Evacuation planning, debris management plan	
Stormwater	Storm Water Pump Station (D St & Cadish Ave)	D St & Cadish Ave	7.9	46	2	92	5	229	100	4583	1031	Relocate, elevate, add emergency generator, and increase capacity – costs cannot be estimated at this time due to uncertain scope	
Wastewater	Waste Water Pump Station 4	13A Marginal Road	10.5	46	0	0	0.2	9	30	1375	278	Lower priority – 2030 probability of flooding < 1%	

Type	Asset Name/Number	Location	Critical Elevation	Conseq. Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score	Adaptation Strategies - Near to Medium Term	Adaptation Strategies - Medium to Long Term
Major Bridge	MLK Bridge	Fitzpatrick Way	11.5	46	0	0	0	0	10	458	92	Lower priority – 2030 probability of flooding < 1%	
Stormwater	Draper Ave Storm Water Pump Station	220 Newport Rd	11.4	46	0	0	0	0	10	458	92	Lower priority – 2030 probability of flooding < 1%	
Pier	A Street Pier	A Street & Cadish Ave	7.9	29	5	146	20	583	100	2917	831	Repair minor damages as needed; elevate fixed pier deck if major damage occurs	
Pier	Nantasket Pier	McDuff Landing	8.6	29	10	292	30	875	50	1458	700	Repair minor damages as needed; elevate fixed pier deck if major damage occurs	
Pier	Town Pier (Public)	5 Fitzpatrick Way	9.0	29	5	146	20	583	50	1458	540	Repair minor damages as needed; elevate fixed pier deck if major damage occurs	
Heliport	Dust Bowl Heliport	Main Street At Ocean Ave	5.0	21	25	521	30	625	100	2083	865	Pre-identify high ground contingency locations for flood events	
Heliport	Mariners Park Heliport	3 Fitzpatrick Way	9.7	21	0.5	10	5	104	50	1042	245	Pre-identify high ground contingency locations for flood events	
Heliport	L Street Playground Heliport	L Street at Nantasket Ave	9.5	21	0.2	4	1	21	50	1042	217	Pre-identify high ground contingency locations for flood events	
Heliport	Kenberma Playground Heliport	Nantasket Ave at Nantasket Road	9.7	21	0	0	0.1	2	50	1042	209	Pre-identify high ground contingency locations for flood events	
Heliport	Roller Hockey Park Heliport	George Washington Blvd	9.3	21	0	0	0	0	30	625	125	Pre-identify high ground contingency locations for flood events	
Energy	Hull Wind 1	1 Wind Mill Point	11.8	21	0	0	0	0	10	208	42	Lower priority – 2030 probability of flooding < 1%	$75,000 – Pre-cast, flood-proofed (with flood panels), concrete enclosure Alternatively, $150,000 – elevate electrical cabinets