Coastal Climate Change Vulnerability Assessment And Adaptation Plan

City of Gloucester, MA

June 29, 2015

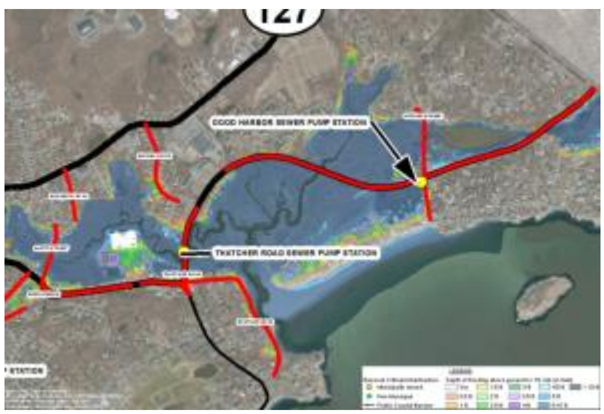

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TABLE OF CONTENTS

APPENDICIES

APPENDIX A – INUNDATION MAPS

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

APPENDIX B – WETLAND CLASSIFICATION MAPS AND DATA

- B1: 2011 – Wetland Classification Areas In Gloucester
- B2: 2030 – Wetland Classification Areas In Gloucester
- B3: 2070 – Wetland Classification Areas In Gloucester
- Table B1 – NWI Category to SLAMM Code Conversion Table

APPENDIX C – RISK ASSESSMENT DATA AND RANKING

- C1: Risk Assessment Summary Table

INTRODUCTION

The City of Gloucester is particularly vulnerable to sea level rise being a coastal community located on Cape Ann in Essex County, Massachusetts. Gloucester occupies most of the eastern end of Cape Ann, and the City is split in half by the Annisquam River, which flows northward through the middle of the City into Ipswich Bay. At its south end it is connected to Gloucester Harbor by the Blynman Canal. The land along the northwestern shore of the river is lined with salt marshes and several small islands. Gloucester Harbor is divided into several smaller coves, including the Western Harbor (site of the Fisherman's Memorial) and the Inner Harbor, home to the Gloucester fishing fleet. Floods caused by hurricanes, nor'easters, severe rainstorms and thunderstorms have been identified by local officials to be the most serious natural hazard for Gloucester.

Given its exposure to the combined effects of sea level rise and storm surge from extreme storm events, the City of Gloucester applied for and was a awarded a Coastal Community Resilience grant from the Massachusetts Coastal Zone Management Agency (CZM) under CZM's Pilot Grants Program for Fiscal Year 2014.

This project has four primary goals:

1. Identify areas of the city 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

Project Team

The City of Gloucester 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 inundation 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
- Indrani Ghosh, PhD – Kleinfelder – Project Engineer, Inundation Modeling and Vulnerability Assessment
- Kirk Bosma, PE – Woods Hole Group – Inundation and Natural Resources Modeling

Kleinfelder worked closely with the City's Working Group, which included the following members:

- Gregg Cademartori, Planning (Project Manager)
- Matt Coogan, Planning
- Shawn Henry, Planning Board
- Robert Gulla, Conservation Commission
- Damon Cummings, Resident
- Tom Daniel, Community Development
- Linda Stout-Saunders, Clean Energy Commission
- Rick Noonan, Planning Board
- Ken Whittaker, Conservation Division

- Ryan Marques, DPW
- Paul McGeary, City Council

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 strategies available to adapt to those changes over time. The City organized public outreach events at each milestone in the project's timeline to keep the public abreast of the latest findings, gather input at crucial junctures, and facilitate active engagement over the lifetime of the project. At these events, the Project Team shared information on climate change, flood modeling, Gloucester's coastal flood hazards, vulnerability and risk of Gloucester's public infrastructure and natural resources, and adaptation options and costs. Following is a list of the public outreach events organized as part of the project:

- Working Group meetings
  - November 12, 2014 (Kick-off and Phase I: Study Parameters)
  - March 10, 2015 (Phase II: Vulnerability Assessment)
  - May 14, 2015 (Phase II: Vulnerability Assessment)
  - June 11, 2015 (Phase III: Adaptation)
- City Council meetings
  - March 10, 2015
- Project-specific Public Meetings
  - May 21, 2015 (Vulnerability Assessment)
  - June 16, 2015 (Adaptation)

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).

We also wish to acknowledge the participation of Patricia Bowie of the Massachusetts Coastal Zone Management (CZM) during public presentations for this project.

INUNDATION MODELING

Sea Level Rise and Storm Surge Model

The hydrodynamic modeling utilized for this study is based on mathematical representations of the processes that affect coastal water levels including tides, waves, winds, storm surge, sea level rise, wave set-up, etc. at a fine enough resolution to identify site-specific locations that may require adaptation alternatives. The water surface was modelled using the ADvanced CIRCulation (ADCIRC) software to predict storm surge flooding and the Simulated WAves Nearshore (SWAN) software, a wave generation and transformation model. Water surface modeling was performed by the Woods Hole Group as part of the Boston Harbor Flood Risk Model (BH-FRM), which was developed for the Massachusetts Department of Transportation (MassDOT) and the Federal Highway Administration (FHWA) to assess potential flooding vulnerabilities in the Central Artery tunnel system and other transportation infrastructure. Since the BH-FRM model domain covers the entire coastline of Massachusetts, including the City of Gloucester, this model was ideally suited to assess the vulnerability and risk of coastal flooding to Gloucester's infrastructure and natural resources. Using this existing model was beneficial to the City of Gloucester since much of the upfront work in developing the model was already conducted as part of the MassDOT/FHWA project.

The ADCIRC model is tightly coupled with SWAN, dynamically exchanging physical processes information during each time step, to provide an accurate representation of water surface elevations, winds, waves, and flooding along the Gloucester coast and shoreline. The spatial resolution of the model is 10 meters or less, sometimes as low as 1 meter to capture important changes in topography and physical processes related to storm dynamics. This high-resolution model offers more accuracy than other storm surge models, such as SLOSH. This modeling approach is also far superior compared to a more rudimentary "bathtub" approach, since the latter does not account for critical physical processes that occur during a storm event, including waves and winds, nor can it determine the volumetric flux of water that may be able to access certain areas.

The model explicitly and quantitatively incorporates climate change influences on sea level rise, tides, waves, storm track, and storm intensity for the present (2013), 2030, and 2070 time horizons. It models a statistically-robust sample of storms, including tropical (hurricanes) and extra-tropical (nor'easters), based on the region's existing and evolving climatology, calculates associated water elevations, and runs mathematical and geospatial analyses on the water elevations generated to estimate the probability of different water elevations being exceeded at nodal points within the model boundary. The resulting flood risk maps and probability curves can be interpreted using geographic information systems (GIS) to identify the estimated annual probability, or likelihood, that any node within the model will experience flooding, and if so, up to what elevation.

The modeling approach is probability-based, which is beneficial to the City to assess the vulnerability and risk of infrastructure, evaluate its resiliency, and plan for adaptation options to mitigate future flooding damage for the City of Gloucester. It also produces information that can be used to inform engineering design criteria since it provides the probability of an event occurring in this changing regime, such as the "new" 1% event flood levels (equivalent to a 100 year recurrence event). This risk-based approach uses a fully optimized Monte Carlo approach, simulating a statistically robust set of storms (both tropical and extra-tropical) for each sea level rise (SLR) scenario. Results of the Monte Carlo simulations are used to generate Cumulative probability Distribution Functions (CDFs) of the storm surge water levels at a high degree of spatial precision. In particular, an accurate and precise assessment of the exceedance probability of combined SLR and storm surge is provided that can help decision makers identify areas of existing vulnerability requiring immediate action in Gloucester, as well as areas that benefit from present planning for future preparedness.

Some of the unique aspects of the BH-FRM model include the following:

- An extensive understanding of the physical system as a whole.
- Inclusion of significant physical processes affecting water levels (e.g., tides, waves, winds, storm surge, sea level rise, wave set-up, etc.).
- Full consideration of the interaction between physical processes.
- Characterization of forcing functions that correspond with real world observations.
- Resolution that will be able to resolve physical and energetic processes, while also being able to identify site-specific locations that may require adaptation alternatives.

Storm Events and Storm Climatology

Figure 1 - Storms input into ADCIRC/SWAN model

The types of storms included in the Monte Carlo simulations included both tropical storms (hurricanes) and extra-tropical storm (nor'easters). Figure 1 shows a representation of the number of storms included in the model. The storm climatology parameters that are included in the BH-FRM model include wind directions and speeds, radius of maximum winds, pressure fields, and forward track of the storms in the Boston region. 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") is usually 3-4 times that of hurricanes, and therefore they impact much larger areas of inland as well. 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. Figure 1 shows a representation of storms included in the model. The probability of flooding due to both hurricanes and nor'easters was estimated by developing composite probability distributions for flooding. Under current (circa 2013) and near-term future (2030) climate conditions, 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).

The storm climatology for the hundreds of different types of storms are all factored in the Monte Carlo simulations of these storm events. The storm climatology is based on present climate for planning horizons until 2050, but for storm simulations beyond 2050, 21st century climatology is used to simulate the storms. The latter half of 21st century climatology projections factored into the BH-FRM model are based on climatology projections by the notable MIT professor Dr. Kerry Emmanuel.

Selection of Sea Level Rise Scenarios

Sea level rise (SLR) scenarios recommended by Parris et al. (2012) for 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) were utilized in this study (Figure 2). These scenarios are the same scenarios recommended by Massachusetts CZM for assessing sea level rise, as well as those being used by the Massachusetts Department of Transportation and other state agencies and communities for vulnerability assessments.

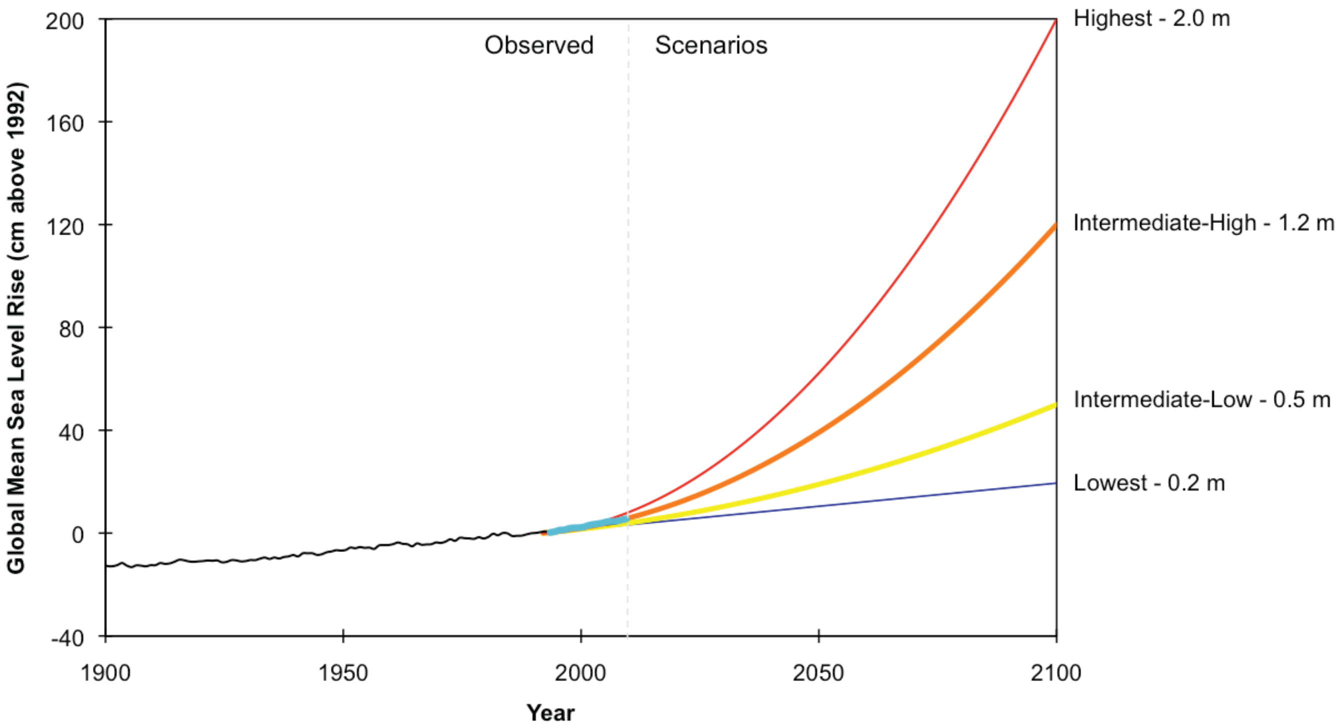


Figure 2 - Global mean sea level rise scenarios

In addition to global SLR, local mean sea level changes are also factored in. Local mean sea level changes were estimated by considering local tide gage records in combination with models or actual measurements of the Earth's local tectonic movements. The NOAA tidal gage at Boston Harbor (station ID 8443970) has recorded an increase in relative mean sea level of 2.63 mm (+/- 0.18 mm) annually based on monthly mean sea level data from 1921 to 2006 (Figure 3). Over that same time period, the global rate of sea level rise was about 1.7 mm annually. This difference implies that there is about 1 mm (0.04 in./yr) per year local land subsidence in the relative sea level record for the Boston area (MA Adaptation report 2011). Since there are no long-term (> 50 years) tidal gages available for the Gloucester Harbor area, the rate of subsidence recorded at Boston Harbor was deemed appropriate to be factored in with the global SLR scenarios to determine the relative SLR projections for Gloucester.

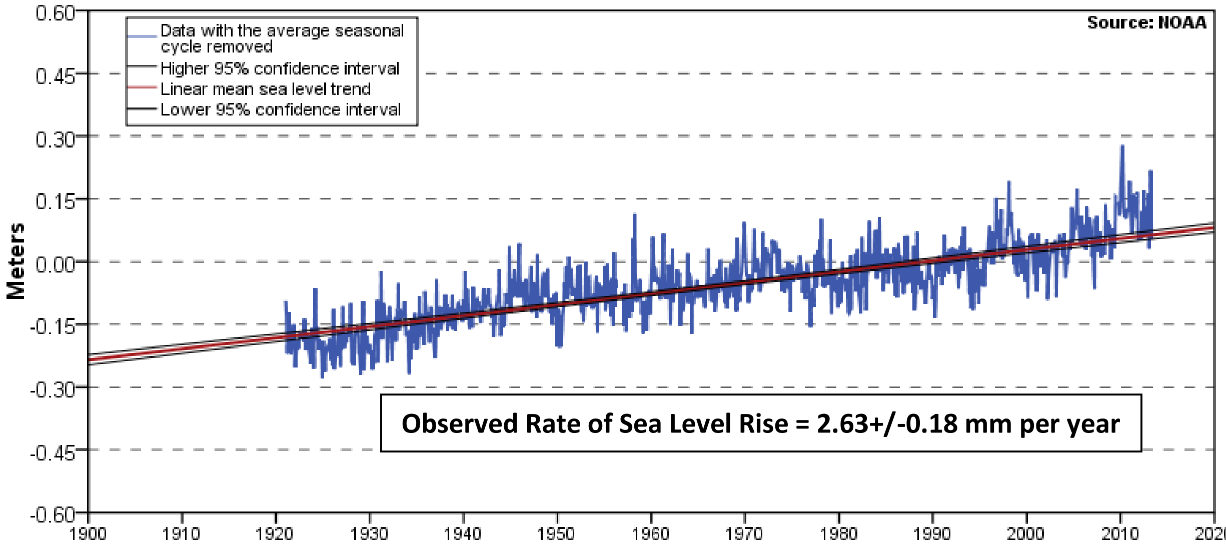


Figure 3 - Mean sea level trend at Boston Tide Gage (#8443970)

Figure 4 below presents the total relative SLR values (global SLR and local land subsidence rate of 0.04 in./yr) for years 2020 through 2100 in 10 year increments for the City of Gloucester, considering a start year of 2013 (since 2013 was used as the start year for the SLR calculations in the BH-FRM model). Calculations were also performed using 2015 as the start year, considering 2015 will be the completion year of this project, and it was found that the difference in SLR projections between using 2013 and 2015 as the start years is less than one-tenth of a foot. Hence it was agreed to use the same SLR values that have been used in the BH-FRM model. Figure 4 presents the SLR projections for Gloucester using the NOAA “Highest”, “Intermediate-High” and “Intermediate-Low” scenarios for the purposes of comparison.

While selection of the “Highest” scenario may be interpreted as conservative, this selection also allows for representing a range of scenarios that allows decision makers to consider multiple future conditions and to develop multiple response options. For example the value for the “Highest” scenario at 2030, is also similar to the “Intermediate-High” value at that same time period, and approximately the “Intermediate-Low” value for 2070.

The SLR scenarios that were utilized in the Gloucester vulnerability assessment are:

- Existing conditions for the current time period (considered to be 2013).
- The value for the “Highest” scenario at 2030 (0.66 ft of SLR), which is also close to the “Intermediate-High” value at that same time period, and approximately the “Intermediate-Low” value for 2050.
- The value for the “Highest” scenario at 2070 (3.39 ft of SLR), which is also approximately the “Intermediate-High” scenario value for 2090.

Scenarios	2020	2030	2040	2050	2060	2070	2080	2090	2100
Global SLR (from 2013-year of interest) "Highest" (feet)	0.21	0.61	1.10	1.70	2.40	3.21	4.11	5.12	6.23
Global SLR (from 2013-year of interest) "Intermediate-High" (feet)	0.14	0.38	0.68	1.04	1.46	1.93	2.46	3.05	3.69
Global SLR (from 2013-year of interest) "Intermediate-Low" (feet)	0.07	0.18	0.32	0.47	0.63	0.82	1.02	1.24	1.48
Land subsidence (feet) @ 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" (feet)	0.24	**0.66**	1.19	1.82	2.56	**3.39**	4.33	5.37	6.52
Total Relative SLR – "Intermediate-High" (feet)	0.16	0.44	0.77	1.16	1.61	2.12	2.68	3.30	3.98
Total Relative SLR – "Intermediate-Low" (feet)	0.09	0.24	0.40	0.59	0.79	1.01	1.24	1.50	1.77

Figure 4 – Sea level rise estimates for Gloucester using the 2012 NOAA NCA SLR scenarios

Planning Horizons

2030 and 2070 were selected as appropriate planning horizons for Gloucester's vulnerability analysis to provide an estimate of short-term and mid-term vulnerabilities. As discussed above, risk-based scenarios are used to assess potential vulnerabilities in the City of Gloucester.

The BH-FRM model was developed for the years 2030, 2070, and 2100. Upon the recommendation of the project team, the Working Group agreed that the study include only two future planning horizons, 2030 and 2070, as well as the present. The 2030 and 2070 future planning horizons, with their corresponding sea level rise projections, were chosen for the following reasons:

- The BH-FRM model developed for the greater Boston area includes the coastline of Gloucester and the current shoreline of the Annisquam River. The City benefits from using best-available model results at a lower cost than it would take to run any other modeling scenario. In addition, the model's performance and accuracy has already been peer-reviewed by MassDOT's scientific advisory team.

- 2030 (15 years from 2015) planning horizon for near-term inundation modeling are consistent with planning horizons used in the majority of studies in Eastern Massachusetts, therefore allowing for easy comparisons.

- 2070 (55 years from 2015) was recommended as a more useful long-term planning horizon for the following reasons:
  (a) The level of uncertainty associated with sea rise projections for the end-of-century (2100 and beyond) are quite high.
  (b) The expected service life of most infrastructure to be evaluated for risk is much less than 100 years, and 2070 is closer to the expected life of typical infrastructure.

(c) The 2070 timeframe is more consistent with other regional climate change vulnerability studies (e.g. Cities of Cambridge and Boston, MassDOT/FHWA).

Modeling the Effects of Coastal Storms and Climate Change

The first step in building the BH-FRM ADCIRC/SWAN model was construction of the modeling grid. The grid is a digital representation of the domain geometry that provides the spatial discretization on which the model equations are solved. The grid was developed at three resolutions:

1) A regional-scale mesh, which is a previously validated model mesh used in numerous Federal Emergency Management Agency (FEMA) studies, National Oceanic and Atmospheric Administration (NOAA) operational models, and most recently the United States Army Corps of Engineers North Atlantic Coast Comprehensive Study (NACCS);
2) A local-scale mesh providing an intermediate level of mesh resolution to transition from the regional-scale mesh to the highly resolved mesh along the Massachusetts coastline; and
3) A site-specific mesh of sufficient resolution to ensure that all critical topographic and bathymetric features that influence flow dynamics along the near shore are captured. The site-specific mesh includes areas of open water, along with the entire coast and shoreline subject to present and future flooding. A screenshot of the model mesh for Gloucester is shown in Figure 5.

Figure 5 - Model mesh for BH-FRM ADCIRC/SWAN model

The ADCIRC model in the area of Gloucester does not include upland topography, and the boundary of the model is at the approximate edge of shoreline. As an example, Figure 6 shows a close-up view of the model limits at Good Harbor Beach. To determine flooding impacts landward of the model's boundary, the water surface generated by the model is propagated towards the shore as a plane until it meets the ground elevation as represented by the LiDAR topographic map (Figure 7). Although the propagated surface is approximate, it gives a relatively accurate representation of the effects of flooding suitable for planning purposes. A representative number of model nodes are propagated, so at any given location along the model boundary there may be slight elevation discrepancies between the model surface and the propagated surface as shown in Figure 8. The inundation results in this example area are shown in Figure 7.

MassDOT is planning to extend the upland modeling of the BH-FRM model to include the upland areas throughout all coastal areas of the Massachusetts, including Gloucester, up to approximately the 30 foot contour (NAVD88). Results from the extended model, which may be available in about two years, could be used to refine the vulnerability analysis.

Figure 6 – Model limits at Good Harbor Beach

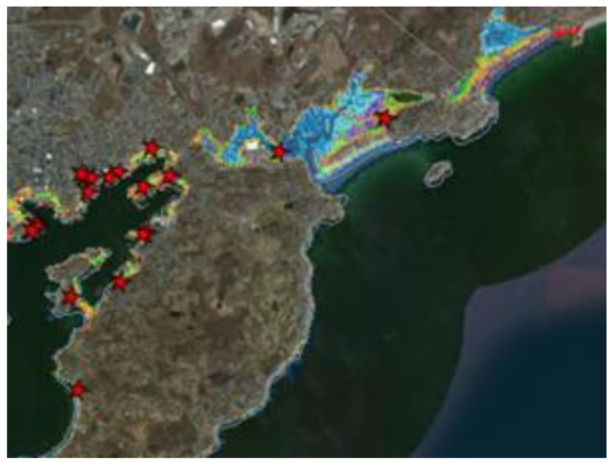


Figure 7 – Inundation results based on propagated water surface at Good Harbor Beach

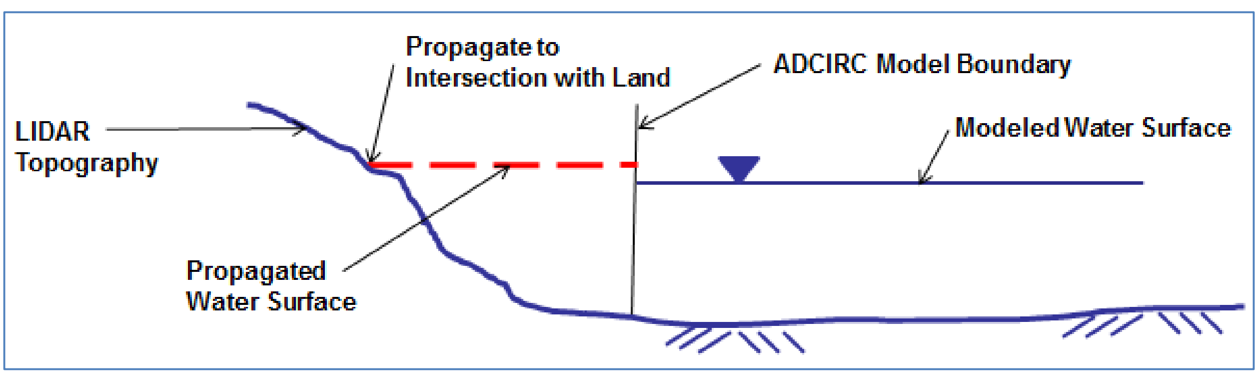


Figure 8 – Propagation of water surface landward of model limits

Model Calibration and Validation

The BH-FRM model was calibrated and validated at three levels. First, the BH-FRM 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 feet 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 Gloucester area. The water surface elevation time series comparison had a bias of less than a 0.25 inch, RMSE (Root-Mean-Square Error) 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 ¼ inch and RMSE of ¾ of an inch. This storm also had significant impacts in the Gloucester area, hence was an appropriate storm for validation in this area as well.

In order to select appropriate historical storm events for model calibration and validation, a number of key factors were considered, including:

- The historic storm must be considered a significant storm for the Boston area (a historic storm of record) that was of large enough magnitude to produce substantial upland flooding.
- The historic storm must have adequate meteorological conditions to be able to generate pressure and wind fields for ADCIRC input. This required the use of global reanalysis data, which was generally available for historic storm events post-1957.
- The historic storm must have sufficient observations and/or measurements of flooding within the northeast and Boston area. This could consist of high water marks data, tide station observations, wave observations, and other data measures.

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.

Inundation Maps

The results of BH-FRM simulations for 2013, 2030 and 2070 were used to generate maps of potential flooding and associated water depths throughout the City of Gloucester. Two different types of maps were produced:

- Percent Risk of Flooding Maps - These maps can be used to identify locations, structures, assets, etc. that lie within different flood risk levels. For example, a building that lies within the 2% flood exceedance probability zone would have a 2% chance of flooding occurring in that study year. Stakeholders can then determine if that level of risk is acceptable, or if some action may be required to improve resiliency, engineer an adaption, consider relocation, or implement an operational plan.

- Depth of Flooding Maps – These maps show the estimated difference between the projected water surface elevation for a given percent risk of flooding during the study year and existing ground elevations derived from the 2011 Northeast LiDAR survey. 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 inundation maps are included in Appendix A:

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

NATURAL RESOURCES MODELING

Modeling

Impacts to natural resources including beaches, coves and salt marsh, were assessed on a qualitative basis. Woods Hole Group is currently working 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) is being used to assess the impacts to natural resources for that project. The SLAMM results are also being linked to results from the Marsh Equilibrium Model (MEM). Final model simulations are currently being run 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 is 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 inundation 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 inundation.

For this project, LiDAR was acquired from MassGIS. The majority of the state was covered with the 2011 USGS LiDAR for the Northeast project, and this covers the Gloucester area. 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 feet (NAVD88) were clipped from the input files.

Wetland Classification Information

The 2011 wetland layer developed by the National Wetlands Inventory (NWI) is used as the baseline source for the wetlands input file for marsh migration modeling.

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. 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 Sea Level Rise (SLR) projections used in the marsh migration modeling are consistent with those used in the BH-FRM modeling to produce the inundation risk maps.

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. Fortunately, the Gloucester 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. 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 protected areas (e.g., impervious surfaces not subject to change) to see how the marshes and other natural resources would migrate, and if they had room to migrate. As such, the ecological modeling assumes that the existing infrastructure may not remain in place. The mapping results therefore do not reflect certain realities. For example, areas of the Inner Harbor downtown area are shown to convert to beach – an obviously unlikely scenario. However, as part of the ongoing Statewide project (not the study which this report is the subject of), an additional post-processing step will likely be applied to overlay the impervious layer and indicate areas that are expected to not change in heavy urban areas. This can be done since the model was run without any protected areas. If the model had been run the other way, then it would not be apparent what might happen if protection breaks down.

For complete details, 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 marsh migration SLAMM modeling.

<u>Major changes from 2011 to 2030</u>:

City-wide there is potential significant loss of area identified in two major classifications:

- Loss of approximately 185 acres of irregularly flooded marsh. This is primarily due to conversion of irregularly flooded marsh (high marsh) to regularly flooded marsh (low marsh), as sea level rises over time. Conversion of high marsh to low marsh is not necessarily a problem, as low marsh still provides a variety of ecosystem services, including habitat and protection from storm surge. Most of these losses occur along the Annisquam River, with big changes in northwest quadrant of the River. Some significant changes also occur to the marsh system landward of the Good Harbor barrier beach.

- Loss of approximately 45 acres of upland area. The loss of upland area due to increasing sea levels occurs primarily along the upper fringes of the Annisquam River. A number of roads and property areas would potentially begin to convert from uplands to wetlands, if allowed to do so.

City-wide there is potential significant gain of area identified in two major classifications, due to conversions from other classifications:

- Gain of approximately 138 acres of regularly flooded marsh (low marsh). This is not a net gain of marsh. It is primarily due to the conversion of high marsh areas to low marsh, as noted above. These conversions are primarily occurring in the northwest area of the Annisquam River. Some tidal swamp and tidal fresh marsh systems in the southern part of the river (near Route 133) also transition to salt marsh.

- Gain of approximately 67 acres of tidal flats. The more frequent and higher levels of inundation in these areas makes the areas unsuitable for low marsh vegetative cover to survive, resulting in the conversion of low marsh regions to non-vegetated tidal flats. This is loss of marsh habitat, primarily occurring along the edges of the islands in the Annisquam River, as well as existing inter-tidal shoal regions.

Overall the changes are primarily focused along the Annisquam River, Good Harbor Marsh system, and the eastern edge of Essex Bay (in Gloucester) by 2030. Much of the remaining city resource areas are relatively unaffected over the next 15 years from present.

Major changes from 2030 to 2070:

City-wide there is potential significant loss of area identified in two major classifications:

- Loss of approximately 750 additional acres of irregularly flooded marsh (high marsh). By 2070, the high marsh in Gloucester has been all but eliminated (only 36 acres total remain). The areas have been converted to low marsh, tidal flats, tidal creeks, or estuarine open water. All of the salt marsh systems in Gloucester (Essex Bay, Annisquam River, Good Harbor region) have insignificant high marsh remaining, indicating a breakdown of the diversity in the marsh system.

- Loss of approximately 215 additional acres of upland area. This is due to conversion of uplands to wetlands as sea levels rise over time. Most of the upland area loss occurs in the low lying Annisquam River complex and the Essex Bay area.

City-wide there is a significant gain of area identified in three major classifications, due to conversions from other classifications:

- Gain of approximately 729 additional acres of regularly flooded marsh (low marsh). As above, this is not a net gain of marsh. The gains are primarily the result of conversion from areas that are high marsh in 2030 (some of which are uplands at present time) to low marsh in 2070. These conversions occur in all city salt marsh regions (Essex Bay, Annisquam River, and Good Harbor area are the major regions).

- Gain of approximately 136 additional acres of tidal flats. This is loss of marsh habitat, primarily occurring at all the islands in the marsh system, which have transitioned to non-vegetated tidal flats and indicate the signs of marsh breakdown and degradation.

- Gain of approximately 113 acres of Tidal Creeks. All tidal creeks, particularly the Annisquam River channel, widen under the pressure of increased water levels and tidal exchange. Tidal creeks and tidal flats become more significant in all marsh systems.

Overall, by 2070, the Good Harbor barrier beach potentially narrows significantly and the backing marsh becomes all regularly flooded marsh with expanded tidal flats and larger tidal creeks. There could also be potential loss of surrounding upland (e.g., CVS, Stop and Shop) in this area, if it were allowed to convert to marsh. Essex Bay and the Annisquam River have fully converted to low marsh, tidal flats, open water and tidal creeks. This region is close to transitioning to open water (harbor). Due to the relatively steep elevation changes in the Gloucester area, there is minimal ability of the marsh and other natural systems to migrate, resulting in continued loss of the resources.

The protective aspects of the marsh and natural resource systems also are reduced substantially by 2070, as storm surges can more readily propagate through various degraded areas and impact upland infrastructure.

INFRASTRUCTURE VULNERABILITY ASSESSMENT

Scope of Infrastructure Vulnerability Assessment

A vulnerability assessment was performed on municipally-owned infrastructure subject to flooding. Municipally-owned infrastructure includes sewer pump stations, roads, bridges, wharves, seawalls, and other critical facilities such as schools, police stations, fire stations, etc. owned and operated by the City of Gloucester. Critical infrastructure was selected based on the inundation modeling results, using infrastructure information obtained from the City of Gloucester Hazard Mitigation Plan, and by information provided by the Planning Division. Infrastructure that is not municipally owned (e.g. federal, state or privately owned) that is subject to flooding is shown on the maps, but vulnerability assessments are not performed on these assets. In some limited cases, state-owned roadways, which are critical transportation links in Gloucester, are included in the discussion of adaptation options.

Survey data for public coastal stabilization structures, including sea walls, revetments and groins, were obtained from the LiDAR and from Massachusetts office of Coastal Zone Management (CZM) as part of a report titled *Mapping and Analysis of Privately Owned Coastal Structures Along the Massachusetts Shoreline* (March, 2013).

A risk-based vulnerability assessment was performed for each of the municipally-owned assets impacted by flooding. These assets 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 failing times the consequence of that asset failing. Put into mathematical terms:

$$\text{Risk (R)} = \text{Probability of Failure (P) x Consequence of Failure (C)}$$

or

$$R = P \text{ x } C$$

For this flood-related vulnerability assessment application, the Probability of Failure (P) is considered as the Percent Risk of Flooding. Each node in the mesh for the ADCIRC model has a unique Probability of Exceedance curve associated with it, which gives the probabilities of exceeding various water 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 is 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. <u>Determine Critical Assets Subject to Flooding</u>

All identified municipally-owned infrastructure are located as an overlay in the GIS project map. The Percent Risk map for flooding for 2070 was then used to screen out assets that show no probability of flooding in 2070. Any assets that show no probability of flooding are excluded from further analysis.

The following municipally-owned infrastructure assets have been identified in Figures 9 (Facilities/Buildings), 10 (Coastal Stabilization Structures) and 11 (Roadways) as being vulnerable to flooding at the indicated time between the present time and 2070:

Time Horizon	Facility	Location
Present	Mill Pond Dam	Washington St at Hodgkins St
	Thatcher Road Pump Station	6a Thatcher Road
	Good Harbor Sewer Pump Station	111 Thatcher Road
	Council on Aging Senior Center	6 Manuel Lewis Street
2030	Water Pollution Control Facility	50 Essex Avenue
	Reynard Street Sewer Pump Station	Reynard Street at Washington Street
	Hodgkins Street Sewer Pump Station	382a Washington Street
	Corliss Avenue Sewer Pump Station	Corliss Avenue
	DPW Sewer Pump Station	26 Poplar Street
2070	Parker Street Sewer Pump Station	20 Parker Street
	Department of Public Works	26 Poplar Street
	Hartz Street Pump Station	3 Hartz Street
	Gloucester High School / Emergency Dispensing Site	32 Leslie O Johnson Road
	Riverside Avenue Sewer Pump Station	31 Riverside Avenue

Figure 9 - Facilities/Buildings Vulnerable to Flooding

Time Horizon	Structure Type	Structure Number	Location
Present	Bulkhead/ Seawall	028-007-000-005-100	Harbor Cove Wharf
	Revetment	028-130-000-011-200	Rocky Neck Avenue
	Bulkhead/ Seawall	028-058-000-040-200	Cripple Cove Public
	Bulkhead/ Seawall	028-130-000-011-100	Rocky Neck Avenue
	Revetment	028-058-000-040-100	Cripple Cove Public Landing
	Bulkhead/ Seawall	028-142-000-038-200	Lanes Cove
	Breakwater	028-142-000-038-400	Lanes Cove
	Revetment	028-142-000-038-300	Lanes Cove
	Bulkhead/ Seawall	028-079-000-001-100	Robinson Landing
	Breakwater	028-142-000-052-100	Lanes Cove
	Bulkhead/ Seawall	028-142-000-038-100	Lanes Cove
	Bulkhead/ Seawall	028-007-000-016-200	Town Landing
	Bulkhead/ Seawall	028-054-000-108-200	State Fish Pier
	Bulkhead/ Seawall	028-131-000-018-100	Wonson Cove
	Revetment	028-053-000-016-100	Head of the Harbor
	Bulkhead/ Seawall	028-009-000-014-100	Solomon Jacobs Park
	Revetment	028-007-000-016-100	St. Peter's Marina
	Bulkhead/ Seawall	028-001-000-001-100	Fort Point
	Bulkhead/ Seawall	028-139-000-010-100	Washington Street
2030	Bulkhead/ Seawall	028-064-000-061-100	East Main Street
2070	Revetment	028-216-000-140-200	Crescent Beach
	Bulkhead/ Seawall	028-003-000-072-200	Stacey Boulevard - West
	Bulkhead/ Seawall	028-003-000-072-100	Stacey Boulevard - West
	Bulkhead/ Seawall	028-003-000-072-400	Stacey Boulevard - East
	Bulkhead/ Seawall	028-003-000-072-300	Stacey Boulevard - East
	Bulkhead/ Seawall	028-133-000-017-100	Niles Beach

Figure 10 – Coastal Stabilization Structures Vulnerable to Flooding

Time Horizon	Facility	Location
Present	Rocky Neck Avenue	Entire
	Commercial Street	From Washington St to Fort Square
	Parker Street	From East Main St to East Main St
	Beach Court	From Commercial St to Dead End
	Causeway Street	From Concord St to Yankee Division Highway (Rt 128)
	Leslie O Johnson Road	Entire
	Centennial Avenue	From Washington St to Western Ave
	Washington Street	At Hodgkins St
	Witham Street	From Beachcroft Rd to Salt Island Rd
	Rogers Street	From Flannigan Square to Washington Street
	Thatcher Road	From Bass Avenue to Rockport Town Line
	Atlantic Street	From Atlantic Ave to Concord St
	Gaffney Street	Entire
	Ye Olde County Road	East
	East Main Street	From Bass Ave to Rocky Neck Ave
	Hodgkins Street	From Wesley St to Washington St
	Hartz Street	From Bass Ave to Eastern Ave
	Stevens Lane	From Rocky Neck Ave to Wonson St
	Eastern Point Road	At Rocky Neck Ave
	Porter Street	From Rogers St to Main St
	River Road	From Bridgewater St to Leonard St
	Fort Square	Entire
	Washington Street	Bridge Approach
	Main Street	From East Main St to Western Ave
	Wonson Street	From Rocky Neck Ave to Clarendon St
	Mansfield Way	From Main St to Rogers St
	Concord Street	Near Landing Rd
	Marina Drive	Entire
	Nautilus Road	Entire
	Veterans Way	Entire
	Sumner Street	From Concord St to Essex Ave
2030	Ye Olde County Road	West
	Manuel F Lewis Street	From Rogers St to Main St
	Holly Street	From Washington St to Dennison St
	Concord Street	Near Cedarwood Rd
	Concord Street	Near Sumner St
	Hampden Street	From Hovey St to Granite St

Time Horizon	Facility	Location
2030 cont.	Kent Circle	From Western Ave to Essex Ave
2070	Bass Avenue	At Hartz Street
	Eastern Point Boulevard	Eastern Point Blvd to Dead End
	Middle Street	From Western Ave to Pleasant St
	Farrington Avenue	From Atlantic Rd to Eastern Pt Blvd
	Poplar Street	From Washington St to Maplewood Ave
	Concord Street	Near Cabot Ln
	Mondello Square	From Bass Ave to Dead End
	Harbor Loop	From Rogers St to Rogers St
	Leonard Street	From Washington St
	Dennison Street	From Washington St to Dead End
	Sayward Street	From East Main St to Bass Ave
	Reynard Street	From Cherry St to Washington St
	Washington Street	At Lanes Cove
	Fremont Street	From Wonson St to Dead End
	Magnolia Avenue	From Essex Ave to Raymond St

Figure 11 – Roadways Vulnerable to Flooding

2. <u>Determine Critical Elevations</u>

Critical elevations (NAVD88 datum) for each asset, that may be subject to flooding at some point, were then determined. 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 City 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 are determined using LiDAR survey data. The low points of a roadway section subject to flooding are used as the critical elevation. Critical elevations for bridges are set as the lowest approach road elevations at the ends of the bridge.

Critical elevations for coastal stabilization structures are determined using LiDAR data or survey elevations included in CZM's *Mapping and Analysis of Privately Owned Coastal Structures Along the Massachusetts Shoreline* (March, 2013).

3. Obtain Probability of Exceedance Data

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

A representative example of Probability of Exceedance data from the Thatcher Road Pump Station is shown in Figure 12. For this facility, the critical elevation is 9.58 NAVD88. This data shows some of the following information:

- For the present year time frame, there is a 0.5% probability that flood water will exceed the critical elevation of 9.58 NAVD.
- In the 2030 time frame, there is a 1% chance that water will exceed the critical elevation of 9.58 feet, and at a 1.0% (100 year recurrence interval) the water level would be approximately 0.00 feet above the critical elevation.
- In the 2070 time frame, the probability of exceeding the 9.58 feet critical elevation increases to 100% while the depth of water above the critical elevation at a 1% (100 year recurrence interval) increases to about 3.22 feet.

	Present		2030		2070	
% Probability	Flood elevation	Depth above critical elev.	Flood elevation	Depth above critical elev.	Flood elevation	Depth above critical elev.
0.1	9.80	0.22	10.70	1.12	14.0	4.42
0.2	9.60	0.02	10.50	0.92	13.9	4.32
0.5	9.58	0.00	10.00	0.42	13.4	3.82
1	dry	N/A	9.58	0.00	12.8	3.22
2	dry	N/A	dry	N/A	12.5	2.92
5	dry	N/A	dry	N/A	12.1	2.52
10	dry	N/A	dry	N/A	11.5	1.92
20	dry	N/A	dry	N/A	11.0	1.42
25	dry	N/A	dry	N/A	10.8	1.22
30	dry	N/A	dry	N/A	10.6	1.02
50	dry	N/A	dry	N/A	10.2	0.62
100	dry	N/A	dry	N/A	9.58	0.00

Figure 12– Probability of Exceedance Data for Thatcher Road Pump Station

4. Determine Consequence of Failure Score

The Consequence of Failure for each infrastructure asset subject to flooding was rated for six different potential impacts in accordance with the guide shown in Figure 13. Each impact is rated separately and then a composite consequence of failure score is determined by summing the scores and normalizing to 100 using the following equation:

$$\text{Composite Consequence of Failure Score} = \frac{\sum \text{all six ratings}}{30} \text{x } 100$$

Figure 14 shows a representative example of the Consequence of Failure rating for the Mill Street Pump Station with a total rating of 63 out of a possible 100. The higher the rating, the more is the consequence of failure of the asset.

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
5	Whole town/city	> 30 days	> $10m	Very high	Very high	Very high
4	Multiple neighborhoods	14 - 30 days	$1m - $10m	High	High	High
3	Neighborhood	7 - 14 days	$100k - $1m	Moderate	Moderate	Moderate
2	Locality	1 - 7 days	$10k - $100k	Low	Low	Low
1	Property	< 1 day	< $10k	None	None	None

Figure 13 – Consequence of Failure Rating Guide

	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
Rating	2	4	2	1	5	5	**63**

Figure 14 – Consequence of Failure Scoring Example for Thatcher Road Pump Station

5. Calculate Risk Scores and Rankings

The risk score for an infrastructure asset subject to flooding for a given time horizon was calculated using the following equation:

$$R_{tn} = P_{tn} \text{ x } C_{tn}$$

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)

This risk score can be used to rank an asset's vulnerability to flooding for a given time horizon. A composite ranking can also be developed taking into account the rankings 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 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 Working Group decided to only include the present and 2030 in the composite scoring, using the following weighting:

- $W_{Present}$ = 70% (or 0.70)
- W_{2030} = 30% (or 0.30)
- W_{2070} = 0% (or 0.00)

100%

The Working Group felt that the 2070 scores, with their substantially higher probabilities of flooding, skewed the rankings too much to 2070 which may not be as important to the City of Gloucester as dealing with flooding issues between now and 2030.

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 the Thatcher Road Pump Station is shown in Figure 15.

	Probability of Exceedance	Consequence Score	Risk Score	Weight	Composite Risk Score
Present	0.5	63	32	0.7	41
2030	1	63	63	0.3	
2070	100	63	6333	0.0	

Figure 15 - Risk Scoring Example Matrix for Thatcher Road Pump Station (Note – Multiplication not exact due to round-off of Consequence Score)

Note that the Consequence of Failure score remains constant for an asset over the life of the asset, 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

Using the risk-based ranking methodology described above, the top 20 ranked assets in terms of vulnerability to flooding based on composite scores (present and 2030) are shown in Figure 16.

The top 20 ranked assets in terms of vulnerability to flooding based on risk scores for the present day time horizon are shown in Figure 17.

The top 20 ranked assets in terms of vulnerability to flooding based on risk scores for the 2030 time horizon are shown in Figure 18.

The top 20 ranked assets in terms of vulnerability to flooding based on risk scores for the 2070 time horizon are shown in Figure 19.

Appendix C includes a summary table that show the risk and consequence scores for all infrastructure assets.

Type	Name/Number	Location	Conseq. Score	Present Probability (%)	2030 Probability (%)	2070 Probability (%)	Composite Risk Score
Bulkhead/ Seawall	028-007-000-005-100	Harbor Cove Wharf	47	100	100	100	4667
Revetment	028-130-000-011-200	Rocky Neck Avenue	47	100	100	100	4667
Roadway	Rocky Neck Avenue	Entire	53	50	100	100	3467
Bulkhead/ Seawall	028-058-000-040-200	Cripple Cove Public	50	50	100	100	3250
Bulkhead/ Seawall	028-130-000-011-100	Rocky Neck Avenue	53	20	100	100	2347
Roadway	Commercial Street	From Washington St to Fort Sq	47	20	100	100	2053
Revetment	028-058-000-040-100	Cripple Cove Public Landing	40	25	100	100	1900
Roadway	Parker Street	From East Main St to East Main St	40	20	100	100	1760
Roadway	Beach Court	From Commercial St to Dead End	33	25	100	100	1583
Roadway	Causeway Street	From Concord St to Yankee Div Highway	23	50	100	100	1517
Roadway	Leslie O Johnson Road	Entire	23	50	100	100	1517
Roadway	Centennial Avenue	From Washington St to Western Ave	20	50	100	100	1300
Bulkhead/ Seawall	028-142-000-038-200	Lanes Cove	27	25	100	100	1267
Roadway	Washington Street	At Hodgkins St	43	20	50	100	1257
Facility	Mill Pond Dam	Washington St at Hodgkins St	37	20	50	100	1073
Breakwater	028-142-000-038-400	Lanes Cove	20	30	100	100	1020
Roadway	Witham Street	From Beachcroft Rd to Salt Isl. Rd	33	20	50	100	967
Revetment	028-142-000-038-300	Lanes Cove	20	25	100	100	950
Bulkhead/ Seawall	028-079-000-001-100	Robinson Landing	37	20	30	100	843
Roadway	Rogers Street	From Flannigan Sq to Washington St	57	10	20	100	737

Figure 16 – Top 20 Ranked Infrastructure Assets Vulnerable to Flooding, Ranked by Composite Risk Score

Type	Name/Number	Location	Consequence Score	Present Probability (%)	Present Risk Score
Bulkhead/ Seawall	028-007-000-005-100	Harbor Cove Wharf	47	100	4667
Revetment	028-130-000-011-200	Rocky Neck Avenue	47	100	4667
Roadway	Rocky Neck Avenue	Entire	53	50	2667
Bulkhead/ Seawall	028-058-000-040-200	Cripple Cove Public	50	50	2500
Roadway	Causeway Street	From Concord St to Yankee Division Highway (Rt 128)	23	50	1167
Roadway	Leslie O Johnson Road	Entire	23	50	1167
Bulkhead/ Seawall	028-130-000-011-100	Rocky Neck Avenue	53	20	1067
Revetment	028-058-000-040-100	Cripple Cove Public Landing	40	25	1000
Roadway	Centennial Avenue	From Washington St to Western Ave	20	50	1000
Roadway	Commercial Street	From Washington St to Fort Square	47	20	933
Roadway	Washington Street	At Hodgkins St	43	20	867
Roadway	Beach Court	From Commercial St to Dead End	33	25	833
Roadway	Parker Street	From East Main St to East Main St	40	20	800
Facility	Mill Pond Dam	Washington St at Hodgkins St	50	20	740
Bulkhead/ Seawall	028-079-000-001-100	Robinson Landing	37	20	733
Bulkhead/ Seawall	028-142-000-038-200	Lanes Cove	27	25	667
Roadway	Witham Street	From Beachcroft Rd to Salt Island Rd	33	20	667
Breakwater	028-142-000-038-400	Lanes Cove	20	30	600
Roadway	Rogers Street	From Flannigan Square to Washington Street	57	10	567
Roadway	Thatcher Road	From Bass Avenue to Rockport Town Line	53	10	533

Figure 17– Top 20 Ranked Infrastructure Assets Vulnerable to Flooding, Ranked by Present Day Risk Scores (Note – Multiplication not exact due to round-off of Consequence Score)

Type	Name/Number	Location	Consequence Score	2030 Probability (%)	2030 Risk Score
Roadway	Rocky Neck Avenue	Entire	53	100	5333
Bulkhead/ Seawall	028-130-000-011-100	Rocky Neck Avenue	53	100	5333
Bulkhead/ Seawall	028-058-000-040-200	Cripple Cove Public	50	100	5000
Bulkhead/ Seawall	028-007-000-005-100	Harbor Cove Wharf	47	100	4667
Revetment	028-130-000-011-200	Rocky Neck Avenue	47	100	4667
Roadway	Commercial Street	From Washington St to Fort Square	47	100	4667
Revetment	028-058-000-040-100	Cripple Cove Public Landing	40	100	4000
Roadway	Parker Street	From East Main St to East Main St	40	100	4000
Roadway	Beach Court	From Commercial St to Dead End	33	100	3333
Bulkhead/ Seawall	028-142-000-038-200	Lanes Cove	27	100	2667
Roadway	Causeway Street	From Concord St to Yankee Division Highway (Rt 128)	23	100	2333
Roadway	Leslie O Johnson Road	Entire	23	100	2333
Roadway	Washington Street	At Hodgkins St	43	50	2167
Roadway	Centennial Avenue	From Washington St to Western Ave	20	100	2000
Breakwater	028-142-000-038-400	Lanes Cove	20	100	2000
Revetment	028-142-000-038-300	Lanes Cove	20	100	2000
Facility	Mill Pond Dam	Washington St at Hodgkins St	50	50	1850
Roadway	Witham Street	From Beachcroft Rd to Salt Island Rd	33	50	1667
Roadway	Rogers Street	From Flannigan Square to Washington Street	57	20	1133
Bulkhead/ Seawall	028-079-000-001-100	Robinson Landing	37	30	1100

Figure 18 – Top 20 Ranked Infrastructure Assets Vulnerable to Flooding, Ranked by 2030 Risk Scores (Note – Multiplication not exact due to round-off of Consequence Score)

Type	Name/Number	Location	Consequence Score	2070 Probability (%)	2070 Risk Score
Facility	Thatcher Road Pump Station	6a Thatcher Road	63	100	6333
Roadway	Rogers Street	From Flannigan Square to Washington Street	57	100	5667
Roadway	Rocky Neck Avenue	Entire	53	100	5333
Bulkhead/ Seawall	028-130-000-011-100	Rocky Neck Avenue	53	100	5333
Roadway	Thatcher Road	From Bass Avenue to Rockport Town Line	53	100	5333
Bulkhead/ Seawall	028-058-000-040-200	Cripple Cove Public	50	100	5000
Facility	Good Harbor Sewer Pump Station	111 Thatcher Road	50	100	5000
Bulkhead/ Seawall	028-007-000-005-100	Harbor Cove Wharf	47	100	4667
Revetment	028-130-000-011-200	Rocky Neck Avenue	47	100	4667
Roadway	Commercial Street	From Washington St to Fort Square	47	100	4667
Bulkhead/ Seawall	028-007-000-016-200	Town Landing	47	100	4667
Bulkhead/ Seawall	028-054-000-108-200	State Fish Pier	47	100	4667
Roadway	Fort Square	Entire	47	100	4667
Revetment	028-053-000-016-100	Head of the Harbor	47	100	4667
Roadway	Main Street	From East Main St to Western Ave	47	100	4667
Roadway	Mansfield Way	From Main St to Rogers St	47	100	4667
Bulkhead/ Seawall	028-009-000-014-100	Solomon Jacobs Park	47	100	4667
Revetment	028-007-000-016-100	St. Peter's Marina	47	100	4667
Facility	Water Pollution Control Facility	50 Essex Avenue	93	50	4667
Roadway	Washington Street	At Hodgkins St	43	100	4333

Figure 19 – Top 20 Ranked Infrastructure Assets Vulnerable to Flooding, Ranked by 2070 Risk Scores

ADAPTATION STRATEGIES

GENERAL

There are three general approaches for adapting to the long-term effects of flooding due to sea level rise and storm surge from extreme weather events:

- Protection
- Accommodation
- Retreat

Protection - Protection includes adaptation strategies that try to prevent damage to essential infrastructure by creating a barrier between the flood water and the infrastructure being protected. Sea walls, dikes, bulkheads, levees, revetments, flood gates, temporary flood protection barriers, and hurricane barriers are all examples of protection strategies that aim to prevent water from reaching sensitive areas. Infrastructure outside of these structures is left unprotected.

Accommodation - Accommodation adaptation strategies allow flood waters to reach essential infrastructure, but damage to the infrastructure is minimized and controlled. Accommodation strategies acknowledge that structures and infrastructure will be exposed to flood water and will get wet, but actions are taken to minimize potential damage. Examples of accommodation adaptation strategies include raising structures above flood elevations, constructing sacrificial dunes and structures that are designed to absorb the impact of large storms to prevent major damage to infrastructure behind them with the understanding that they will need repair or replacement if destroyed, protecting utilities in waterproof enclosures; flood-proofing structures; temporary flood barriers; instituting new building codes and zoning, such as increased setbacks, that require accommodation strategies to be implemented for all new construction and major renovation projects.

Retreat - Retreat adaptation 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 the structures and infrastructure from harm's way. Retreat strategies relocate affected infrastructure away from the ocean to higher ground and transform the affected areas back to natural barriers which can migrate landward naturally. Examples of retreat adaptation strategies include property buyouts, relocation of roads, buildings and infrastructure, and implementation of new zoning or other regulations limiting new construction, reconstruction, or expansion of existing structures.

Adaptation strategies investigated in this study are generally a combination of protection and accommodation strategies. Full retreat strategies do not appear to be warranted within the time horizons studied, as feasible protection and accommodation alternatives exist to adapt critical municipal infrastructure to the impacts of sea level rise and storm surge. However, the potential use of “rolling easements” to perhaps acquire interest and eventually ”reclaim” properties that have exhibited repetitive flood losses is presented as an option.

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 an infrastructure asset is adapted to.

Figure 20 shows representative water surface elevations, or flood elevations, at different probabilities of exceedance for present, 2030 and 2070 time horizons. The cumulative contributions of tide, sea level rise, storm surge, wind, and mean wave height are incorporated in these flood elevations. These flood elevations do not include additional height for wave run-up and overtopping (height above the mean wave height that water can penetrate up to from waves breaking up or over a sloped shoreline or structure), nor do they include "freeboard" (height added above the expected flood level for additional safety, depending on the importance of the structure being protected).

For the purposes of this study, we have based most recommended adaptation options on a base flood elevation equivalent to the 1% probability of exceedance flood levels in 2030 and 2070 (approximately 100 year recurrence interval). This decision reflects the high criticality of the facilities in question and sets a reasonable design parameter for planning. These recommendations should periodically be reviewed (e.g., once every five to ten years) and adjusted as needed based on the latest climate change science and sea level rise observations and projections.

Selecting a more conservative base flood elevation (e.g., 0.2% flood elevation) will generally make adaptation options more costly, particularly if planning for the longer term (i.e., 2070). However, there may still be some locations where it is feasible and desirable to protect up to a higher level (e.g., Water Pollution Control Facility). The 1% event in 2070 (12.8 ft NAVD88) is 3.8 ft. higher than the 2030 1% event (9.0 ft NAVD88). Such a dramatic increase makes incremental strategies that much more difficult. Higher base flood elevations introduce more significant design challenges and costs to modify what exists today in vulnerable areas.

Exceedance Probability (%)	Present Water Surface Elevation (ft – NAVD88)	2030 Water Surface Elevation (ft – NAVD88)	2070 Water Surface Elevation (ft – NAVD88)
0.1	10	10.7	14.0
0.2	9.9	10.5	13.9
0.5	9.0	9.9	13.4
1	8.8	9.0	12.8
2	8.4	8.9	12.5
5	8.1	8.3	12.1
10	7.7	8.2	11.5
20	7.2	7.8	11.0
25	7.0	7.7	10.8
30	6.8	7.5	10.6
50	6.1	7.4	10.2
100	6.0	6.4	9.0

Recommended Base Flood Elevations

Figure 20 – Water Levels at Different Probabilities of Exceedance for Present, 2030 and 2070

Recommendations for Infrastructure

The highest risk assets, according to the 2030 Composite Risk ranking, are shown in Figure 16. They are predominantly low-lying roadways and coastal stabilization structures (seawalls, revetments, breakwaters). These roadways and seawalls all have low critical elevations, which put them and infrastructure on their landward sides at a high risk of being flooded, even based on present day climate and sea levels. By the 2030 timeframe, almost all of these assets are projected to flood on an annual basis. In addition, there are a few low-lying critical facilities that could have significant consequences if a low probability extreme event were to occur in the 2030 timeframe. In the sections below, adaptation priorities and options for high risk assets are described.

All estimates of costs presented herein to implement adaptation recommendations are order-of-magnitude estimates, in 2015 dollars, for use in long-term planning purposes. The 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 construct a project.

Coastal Stabilization Structures

Inner Harbor

Recommended Base Flood Elevation for 2030:

- 9.0 ft NAVD88 (1% Flood)

Recommended Base Flood Elevation for 2070:

- 12.8 ft NAVD88 (1% Flood)

The Inner Harbor currently has an estimated nine (9) municipally-owned coastal stabilization structures (mostly seawalls and a couple of revetments) that have critical elevations (meaning the lowest elevation along the top of the structure) which are too low to prevent the 1% flood from overtopping them, even based on present day climate and sea levels (Figure 21). Inundation maps in Appendix A show that, over time, climate change will increase the likelihood that the central business area and maritime industrial zones in the Inner Harbor will experience flooding due in part to the insufficient height of these and other private structures.

Due to a variety of site-specific challenges, there is no single solution for adapting the downtown area to future risks from sea level rise and storm surge. Therefore flooding will need to be dealt with holistically. A major challenge for adaptation in this area is that the inner harbor waterfront consists predominantly of private structures and wharfs that the City does not own or have control over. These structures are non-contiguous and vary in terms of their design elevations, construction type and condition. That means that even if the City raises all of its municipally-owned structures to a higher elevation, flood water would flow around them unless private owners raise their wharfs and seawalls to equivalent protection levels. Due to the nature of the working waterfront, any waterfront flood protection system would have to have many openings fitted with temporary closures to accommodate traffic in and out of properties during normal operations. In addition, while elevating existing structures by 0.2 ft. to 3.0 ft. to reach the recommended base flood elevation for 2030 is technically feasible (though by no means simple), raising them by 4.0 ft. to 6.8 ft. to meet the recommended base flood elevation for 2070 may not be technically feasible while trying to maintain the water-dependent uses of the waterfront facilities (Figure 22). There is also very limited room to install flood barriers, and even more-limited room to install green floodproofing infrastructure such as landscaped berms.

Within the inner harbor flood protection area, the total perimeter length of wharfs, piers and coastal engineered structures (seawall, bulkheads, revetments, etc.) is estimated to be about 30,000 ft. to 35,000 ft. The exact length is difficult to estimate without performing a detailed survey of all the inner harbor facilities.

There are two basic options to protect the inner harbor:

- Option A – Raise all the waterfront structures, both public and private, to a common elevation of minimum 9.0 NAVD88 to protect for the 2030 timeframe or 12.8 NAVD88 to protect for the longer-term 2070 time horizon. This would protect the inner harbor business district, but would be extremely difficult to achieve, both technically and politically. Assuming a cost to raise or replace coastal stabilization structures in this area ranging from $2,000 to $5,000 per foot, the cost to upgrade the perimeter structures alone could range from $60 million to $175 million. This cost does not include the cost of required improvements to the wharfs and piers to maintain their water-dependent uses. In addition, raising the bulkhead elevations may not be technically feasible due to the need to maintain a working elevation that is suitable for working alongside moored fishing vessels.

Structure Type	Structure Number	Location	Critical Elevation	Consequence Score	Present Probability (%)	2030 Probability (%)	2070 Probability (%)
Bulkhead/ Seawall	028-007-000-005-100	Harbor Cove Wharf	6.0	47	100	100	100
Revetment	028-130-000-011-200	Rocky Neck Avenue	6.0	47	100	100	100
Bulkhead/ Seawall	028-058-000-040-200	Cripple Cove Public	6.4	50	50	100	100
Bulkhead/ Seawall	028-130-000-011-100	Rocky Neck Avenue	6.2	53	20	100	100
Revetment	028-058-000-040-100	Cripple Cove Public Landing	7.1	40	25	100	100
Bulkhead/ Seawall	028-079-000-001-100	Robinson Landing	7.6	37	20	30	100
Bulkhead/ Seawall	028-007-000-016-200	Town Landing	8.6	47	2	5	100
Bulkhead/ Seawall	028-054-000-108-200	State Fish Pier	8.8	47	2	5	100
Bulkhead/ Seawall	028-131-000-018-100	Wonson Cove	8.3	27	5	5	100

Figure 21 - Inner Harbor Seawall and Revetment Flood Risk

Structure Type	Structure Number	Location	Critical Elevation	Conseq. Score	Additional Height (ft) to Present 1%	Additional Height (ft) to 2030 1%	Additional Height (ft) to 2070 1%
Bulkhead/ Seawall	028-007-000-005-100	Harbor Cove Wharf	6.0	47	2.8	3.0	6.8
Revetment	028-130-000-011-200	Rocky Neck Avenue	6.0	47	2.8	3.0	6.8
Bulkhead/ Seawall	028-058-000-040-200	Cripple Cove Public	6.4	50	2.4	2.6	6.4
Bulkhead/ Seawall	028-130-000-011-100	Rocky Neck Avenue	6.2	53	2.6	2.4	6.6
Revetment	028-058-000-040-100	Cripple Cove Public Landing	7.1	40	1.7	1.9	5.7
Bulkhead/ Seawall	028-079-000-001-100	Robinson Landing	7.6	37	1.2	1.4	5.2
Bulkhead/ Seawall	028-007-000-016-200	Town Landing	8.6	47	0.2	0.4	4.2
Bulkhead/ Seawall	028-054-000-108-200	State Fish Pier	8.8	47	0	0.2	4.0
Bulkhead/ Seawall	028-131-000-018-100	Wonson Cove	8.3	27	0.5	0.7	4.5

Figure 22 - Existing Inner Harbor Seawall and Revetment Elevations and Additional Height Required

- Option B – Install permanent flood barriers along sections of Rodgers Street, Parker Street and East Main Street that are subject to flooding. The estimated total length of barrier required to raise the minimum road elevation to 9.0 ft. NAVD88 to protect to the 2030 time frame is approximately 4,200 ft., while the length required to protect to elevation 12.8 ft. NAVD88 for the 2070 time frame is about 8,000 ft. Assuming a flood barrier construction cost ranging from $1,000 to $2,500 per foot, the estimated cost to install flood barriers to elevation 9.0 NAVD88 could be on the order of $4.2 million to 10.5 million, while constructing them to elevation 12.8 NAVD888 could be on the order of $8.0 million to $20.0 million. Although these costs are significantly lower than those presented in Option A, there are a number of drawbacks to this option, including:

    - The amount of infrastructure protected would be relatively small because the majority of privately-owned commercial property would be on the water side of the barrier and would be flooded during a flood.

    - The permanent flood barrier would have to have many openings to allow for traffic to get to the commercial wharfs and for pedestrian traffic to access stores, restaurants, museums and other facilities along the waterfront. Each of these openings would have to be closeable with flood gates or other temporary closure devices that would need to be deployed in advance of an impending severe storm.

  - The barriers, due to their height, would likely be unsightly in the congested downtown commercial district.

Both of these options are very expensive, technically difficult to implement, and difficult to get approved from a political point of view, given the large number of private commercial property owners that would have to participate in the project.

Hurricane Barrier

An alternative to Options A and B is to construct a hurricane barrier system in the outer harbor which would avoid the need to flood proof the inner harbor and the Route 127 (Western Avenue) waterfront. Figure 23 illustrates a conceptual layout of a hurricane barrier system. It would have to have three primary components:

- The main barrier would be located in the outer harbor from about Black Bess Point on the east to Dolliver Neck on the west. Alternatively it could be located slightly farther south from Eastern Point on the east to Mussel Point on the west. This alternative location would have the Eastern Point Yacht Club's mooring area located behind the barrier. The barrier would need to have an opening in the main channel large enough to accommodate the fishing fleet and any other shipping using the harbor. The opening would have a flood gate that would normally be in the open position. In advance of an impending storm, the flood gate would be closed.

- A secondary barrier would need to be located on the Annisquam River to prevent flood waters from entering the harbor via the river. Three alternative locations are shown in Figure 23 for barriers on the Annisquam River.

  - The preferred location would be at Route 128. This location would require raising a low section of Route 128 and constructing a lock gate in the main section of the Annisquam River under or close to the Route 128 bridge. Installing a barrier at this location would maximize the amount of flood protection along the Annisquam River, especially along the southern portion with the Gloucester High School and the Gloucester Water Pollution Control Facility. The lock gate would remain in the open position to allow passage of boat traffic on the river, until just before an impending storm, when it would be closed.

  - The next best location would be at the MBTA Railroad Causeway or somewhere nearby. A lock gate would be installed at this relatively narrow section of the river. At this location, there is less flood protection along the Annisquam River, but much of the densely populated area between there and the Blynman Canal would still be protected. The lock gate would remain in the open position to allow passage of boat traffic on the river, until just before an impending storm, when it would be closed.

  - The least attractive location is right at the Blynman Canal. This location offers no protection of flood plain along the Annisquam River, so additional flood protection measures would have to be taken to protect facilities in this area. It would also likely be a more expensive option as the existing Western Avenue bridge structure would have to be replaced and incorporated into the lock system.

- Another secondary barrier would have to be located at the north end of the Inner Harbor to prevent flood water from coming into the harbor via the Good Harbor marsh system to the north.

This barrier would consist of raising the roadway and installing a tide control structure that can be closed in advance of an impending storm. Two alternate locations in this area are shown in Figure 23.

- The preferred location would be at Thatcher Road, because at this location the Stop and Shop and other commercial properties and a number of residences would be protected behind the barrier.
- An alternate location would be at Hartz Street.

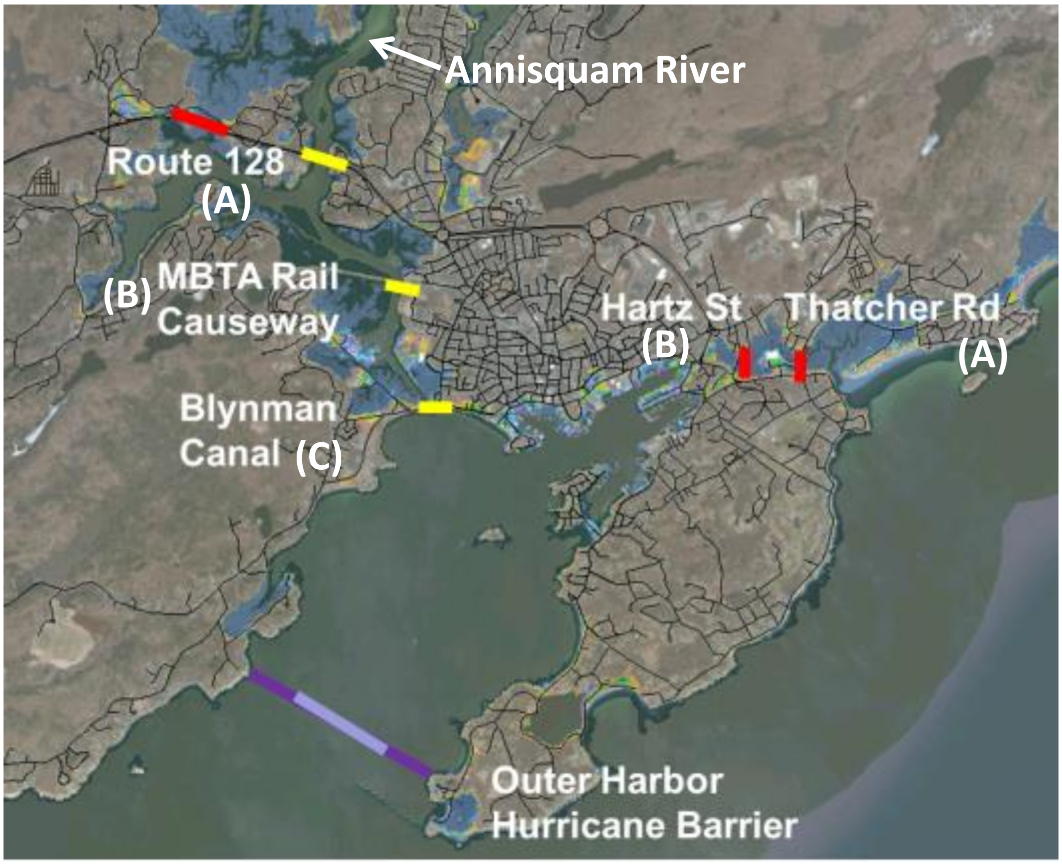


Figure 23 – Potential Hurricane Barrier System (Red = Raised roadway with self-regulating tide gate; Yellow = Surge lock gate; Purple = Hurricane surge barrier)

The estimated total length of hurricane barriers is approximately 8,000 ft. as shown in Figure 24.

Barrier Location	Barrier Type	Approximate Length
Outer Harbor	Concrete/Stone with Gate in Channel for Boat Passage	5,500 ft.
Annisquam River at Rt. 128	Raised Roadway with Gate Lock for Boat Passage	1,950 ft.
Thatcher Road	Raised Road with Tidal Control Structure	550 ft.

Figure 24 – Estimated Lengths of Hurricane Barrier Structures

It is not possible to generate an accurate construction cost estimate for such a hurricane barrier system at this time without sufficient survey, bathymetric data, subsurface exploration and engineering design as well as understanding permitting restrictions that will be imposed on the project. One way is to provide an order-of-magnitude comparative cost estimate using order-of-magnitude costs derived from other hurricane barriers constructed in the region. For the purposes of developing a cost range, costs for three hurricane barriers were obtained and updated to 2015 dollars as shown in Figure 25.

Barrier	Construction Cost	Approx. Length	Year Constructed	Cost/Ft in 2015 Dollars @ 5% Inflation Rate
New Bedford, MA	$18,700,000	18,000	1962	$13,800
Stamford, CT	$14,500,000	11,640	1969	$11,800
Providence, RI	$16,000,000	3,000	1966	$58,200

Figure 25 – Cost Data from Existing Hurricane Barriers

Based on more complex construction and permitting requirements today, it is safe to assume that the unit costs of construction will be higher today than in the 1960s. For the purpose of this report, assume that the range of construction costs for a hurricane barrier will be from $30,000 to $65,000 per foot. Therefore, for general planning purposes, the cost of a hurricane barrier system might be in the range of $240 million to $520 million, and would likely be substantially higher depending on the water depths, height of the structure and permitting requirements. Further conceptual study is required to develop a more accurate cost estimate for a hurricane barrier system.

Facilities/Buildings

Water Pollution Control Facility

Recommended Base Flood Elevation for 2030:

- 11.1 ft NAVD88 (0.2% Flood)

Recommended Base Flood Elevation for 2070:

- 13.9 ft NAVD88 (0.2% Flood)

The Water Pollution Control Facility is the most critical City-owned infrastructure at risk of flooding due to sea level rise and storm surge. There is an existing berm along the boundary of the facility property, presumably built to protect it from flooding. However, in the 2030 time horizon, the perimeter protection, particularly at the southeast corner of the property, would not be high enough to prevent floodwaters from entering the property in a low probability flood event. The facility would be impacted by flooding emanating from the adjacent wetland on the southern side of the facility and from the southern reach of the Annisquam River which could inundate Route 133 and block access to the facility. The first area to flood would be the access gate and parking lot on the southeast corner of the property.

Currently, the first floor elevation of the main building is estimated to be approximately 10.2 ft NAVD88. This elevation is almost 1 ft. lower than the 0.2% flood elevation in 2030 and almost 4 ft. lower than the 0.2% flood elevation in 2070 (Figure 26). Due to its criticality, it is recommended that this facility be adapted to the higher 0.2% flood elevation for 2030 and 2070. These higher levels of protection can be accommodated within the existing property boundaries with no impacts on adjacent uses (Figure 27).

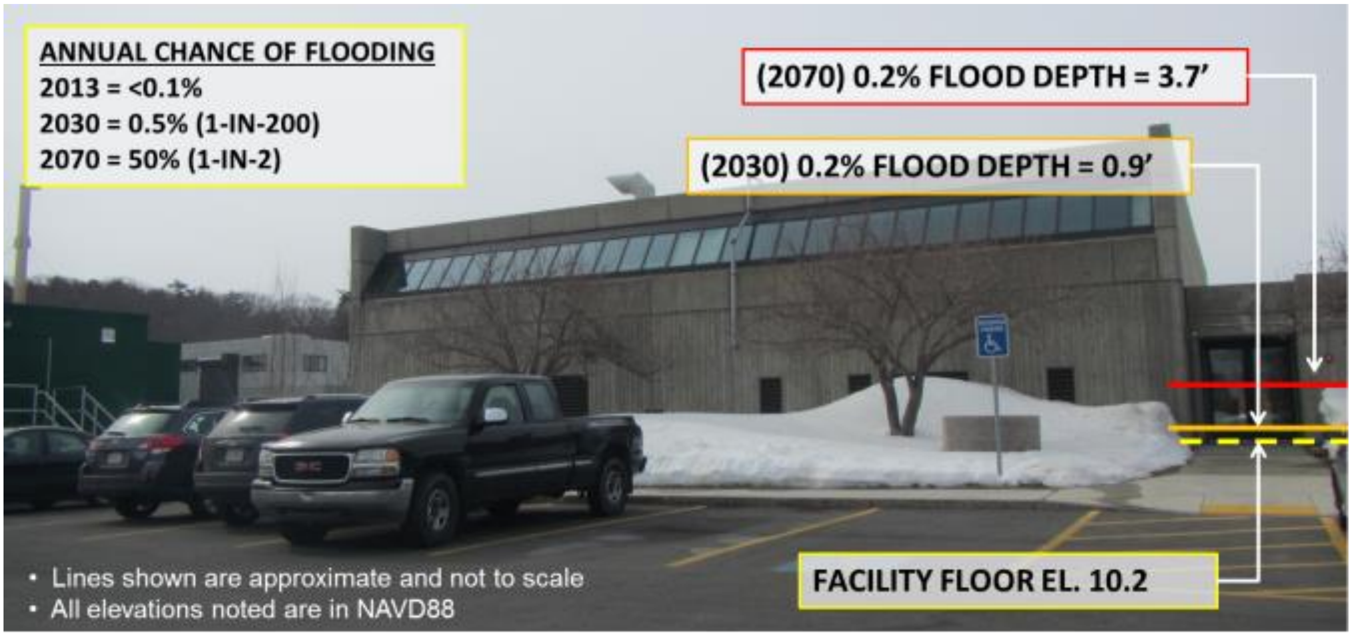


Figure 26 - Water Pollution Control Facility Elevation and Flood Risk

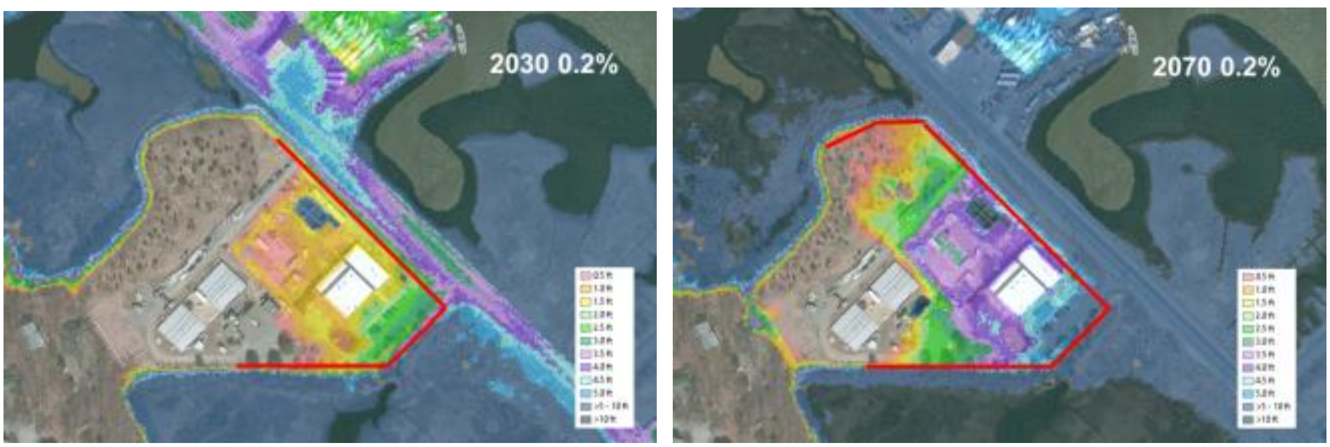


Figure 27 - Water Pollution Control Facility - Incremental Adaptation Options for 0.2% Flood Protection

Recommendation:

- (2030) Use existing protective berm and topography to build up from. Design, permit and construct a higher berm along the southern side of the property. Build a flood wall along Route 133 with a temporary closure at the property entrance. Top elevation should be a minimum of 11.1 ft NAVD88 (2030 0.2% flood elevation). Assuming that the flood barrier will be eventually raised to elevation 13.9 NAVD88 to meet the higher expected flood levels in 2070, it would make sense to construct the first section of the wall an additional 2.8 ft. so that it does not have to be raised in the future. (Approximate cost to build 750 ft. of wall to elevation 13.9 NAVD88 = $375,000)
- (2030) Increase the capacity of existing sump pump systems and ensure connections to emergency generators for powering pumps. (Approximate cost = $15,000)
- (2030) Seal interior conduits for water entry (e.g., electrical conduits and through-floor pipes). (Approximate cost = $3,000)

- (2030) Monitor observed changes in sea level and storm surge to determine scale of actions needed to prepare for likely conditions in 2070
- (2070) If needed, extend flood wall at elevation 13.9 ft NAVD88 (2070 0.2% flood elevation) for an additional 250 ft. (Approximate cost = $125,000)

Thatcher Road Pump Station

Recommended Base Flood Elevation for 2030:
- 9.5 ft NAVD88 (1% Flood)

Recommended Base Flood Elevation for 2070:
- 12.8 ft NAVD88 (1% Flood)

The Thatcher Road Pump Station consists of a below-ground vault with pumping equipment and wet well, accessed by a hatch located at grade in the existing sidewalk, and an above ground electrical and controls equipment enclosure (Figure 28). The pump station is located adjacent to a salt marsh wetland, which would be the immediate source of flooding during a storm surge event. The bottom of the enclosure is at an approximate elevation of 9.5 ft NAVD88 (equivalent to the 1% flood elevation in 2030).

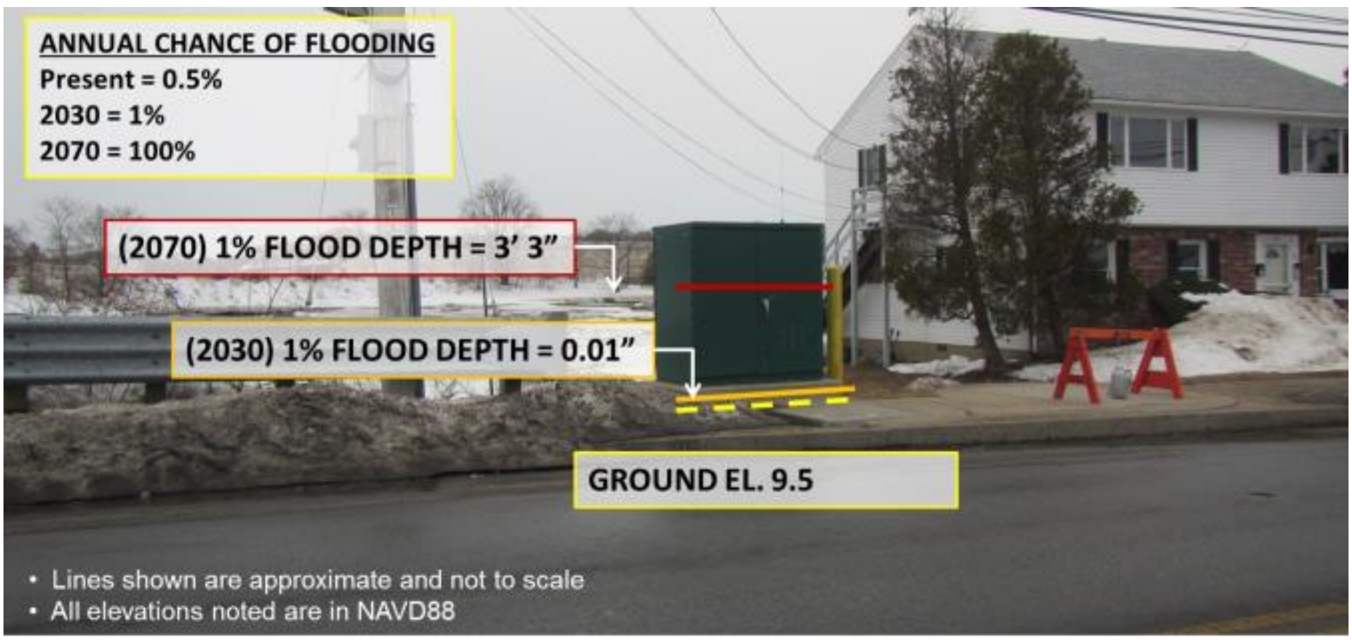


Figure 28 - Thatcher Road Pump Station Elevation and Flood Risk

Recommendation:
- (2030) Install a water-tight manhole cover on the access hatch to underground equipment. (Approximate cost = $5,000).
- (2070) During the next major upgrade of the pump station, raise the above-ground enclosure for electrical and controls equipment by 3.25 ft to the recommended 2070 base flood elevation. (Approximate cost = $50,000).
- (2070) Alternatively, purchase a temporary flood barrier system that can be deployed around the pump station in advance of major storms. (Approximate cost for 100 ft. of barrier = $40,000).

Good Harbor Pump Station

Recommended Design Flood Elevation for 2030:
- 9.5 ft NAVD88 (1% Flood)

Recommended Design Flood Elevation for 2070:
- 12.8 ft NAVD88 (1% Flood)

Good Harbor Pump Station is located on the corner of Thatcher Road and Witham Street, adjacent to the extensive Good Harbor salt marsh wetland (Figure 29). The first floor of the pump station is nearly sufficiently elevated to prevent flooding predicted for 2030 with a 1% probability of exceedance.

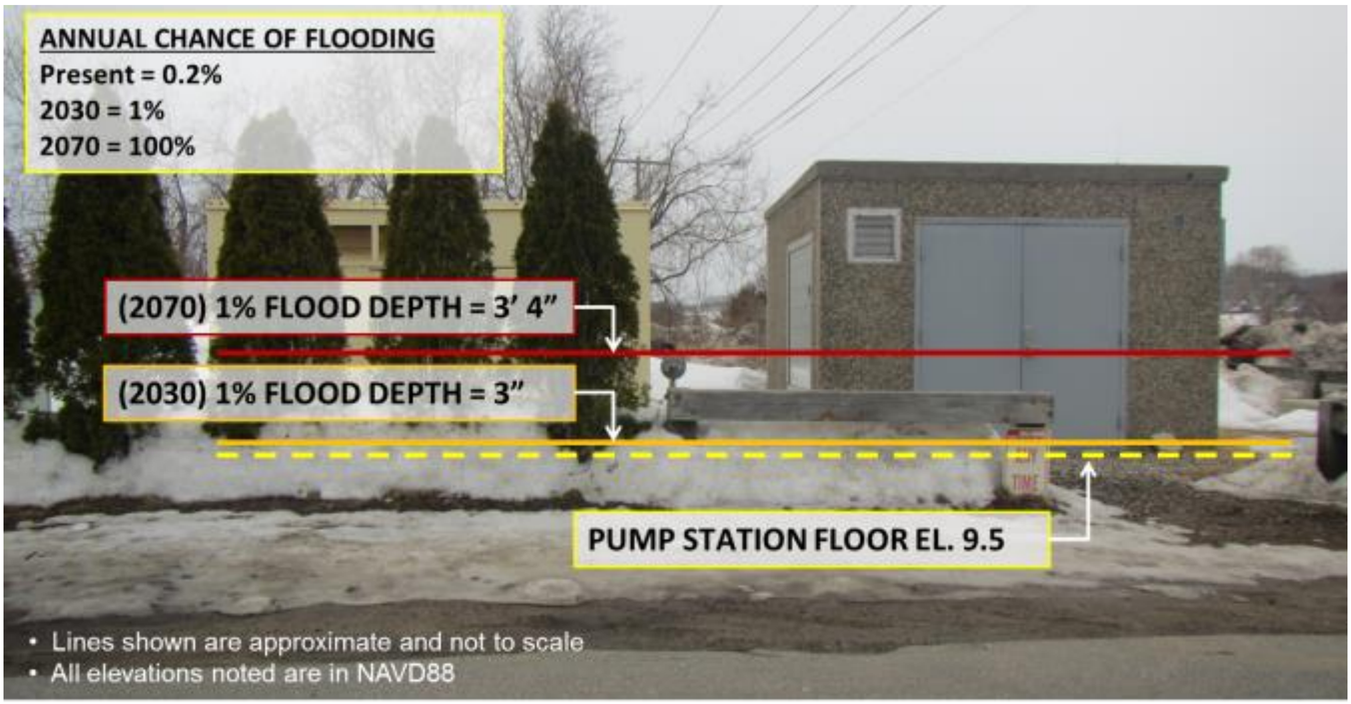


Figure 29 – Good Harbor Pump Station

Recommendation:
- (2030) Install drop-in flood panels at doorway. (Approximate cost = $8,000)
- (2070) Seal interior conduits for water entry (e.g., through-floor/wall pipes, utility conduits) to 12.8 ft NAVD88. (Approximate cost = $3,000)
- (2070) Construct permanent or temporary flood barrier with a minimum top elevation of 12.8 ft NAVD88 around the pump station, emergency generator, and exterior transformer. Include a temporary access closure at the front entrance. (Approximate cost for 150 ft. of barrier = $105,000)
- (2070) Purchase and install a pumping system connected to the existing generator to remove seepage and rainwater collecting on the inside of the barrier during a storm. (Approximate cost = $10,000)

Roadways

Recommended Design Flood Elevation for 2030:
- 9.5 ft NAVD88 (1% Flood)

Recommended Design Flood Elevation for 2070:
- 12.8 ft NAVD88 (1% Flood)

Most major evacuation routes from eastern Gloucester and Rockport could be impacted by flooding in the future (Figure 30), including Route 127 (Washington Street), Route 127A (Thatcher Road), Route 128, Route 133 (Essex Street), and Atlantic Street (from Wingaersheek Beach in West Gloucester). These roads could be closed due to public safety concerns prior to the onset of flooding, limiting evacuation options after that point. These roads could also be physically impassable during and immediately after a flood, resulting in hazardous driving conditions and longer emergency response times for public safety and medical services. If these roads were significantly damaged by flooding, transportation of supplies, equipment, and personnel needed for disaster relief and recovery could also be impacted.

High-risk municipal roadways identified in this study, in addition to those noted above, were mostly located in the Inner Harbor area. These roads serve as important economic corridors for tourism, maritime industry, and commercial enterprises (e.g. Rogers Street and Western Avenue). Some of them also serve as single access routes for residential communities that could be temporarily isolated if the roads were to flood (e.g. Rocky Neck Avenue). Risk of roadway flooding in this area is a proxy for risk to those enterprises from flooding, as most are located at or slightly above the roadway grade.

Roadways require longer-term strategies for adaptation, since the planning and implementation timelines are generally long, the infrastructure is long-lived, and the improvements can be very costly. Another challenge is to make roadway-related resiliency improvement aesthetically pleasing. Roadway adaptation improvements should also avoid negatively impacting, and where feasible, seek to enhance natural resources, particularly wetland systems such as marshes which provide protective ecosystem services.

As the City owns and can act on its own initiative to adapt some of the high priority roadways, particularly Route 127/Washington Street, and Route 127A/Thatcher Road, these should be priorities for roadway resiliency investment. Other municipal roads located in the Inner Harbor area may not be feasible to adapt, without a broader transformation of the infrastructure in the area. As noted above, most commercial, industrial, and residential structures in this area have doorways or other access located at grade with the roadway or sidewalk. Potential adaptation strategies for dealing with flooding in the inner harbor area are discussed above.

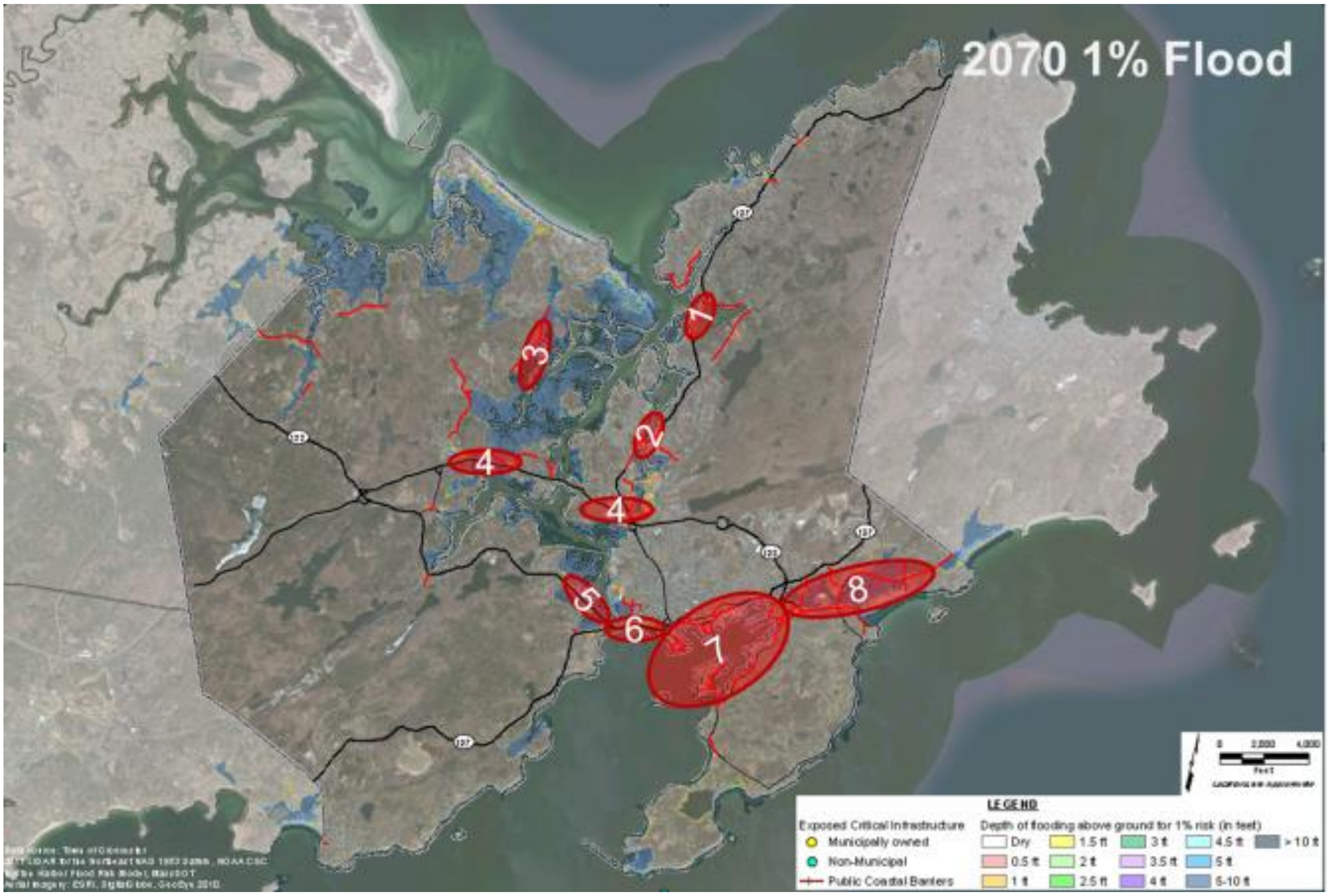


Figure 30 - Critical Roadways at Risk in 2070 1% Flood

It is not possible to generate accurate construction cost estimates for roadway adaptation improvements at this time without sufficient survey, subsurface exploration, traffic engineering and engineering design. For the purposes of this study, we will use the following order-of-magnitude costs in 2015 dollars to estimate roadway improvements based on the length of roadway needing to be elevated and the number of lanes:

- Elevate roadways up to 2 ft.: $750 to $1,000 per foot per lane (assumes 12 ft. lanes, 5 ft. shoulders, 8 ft. sidewalks on both sides of the road, granite curbing, guardrail on both sides, replacement of 5 underground utilities at $100/ft. each, asphalt pavement, traffic management, engineering at 10% and 25% contingency).

- Install four (4) ft. high flood barriers along one side of road to protect against the 2070 predicted storm levels: $1,000 to $2,000 per foot.

Figure 31 provides a simplified conceptual representation, using Route 127 (Washington Street) at the Mill Pond Dam as an example, of the two general adaptation strategies recommended (raising roads and installing flood barriers at the roadside) and how they can be implemented incrementally over time to provide a robust and modular solution. Note that, while building a short flood wall at the water side edge of the sidewalk can provide sufficient flood protection to meet the 2030 1% annual flood elevation, raising that flood wall over time without raising the roadway become unsustainable in terms of aesthetic and view impacts. In contrast, early investment in roadway raising, where feasible, can provide a robust flood protection solution in the 2030 time frame, while preserving the option to raise floodwalls of reasonable height in the future.

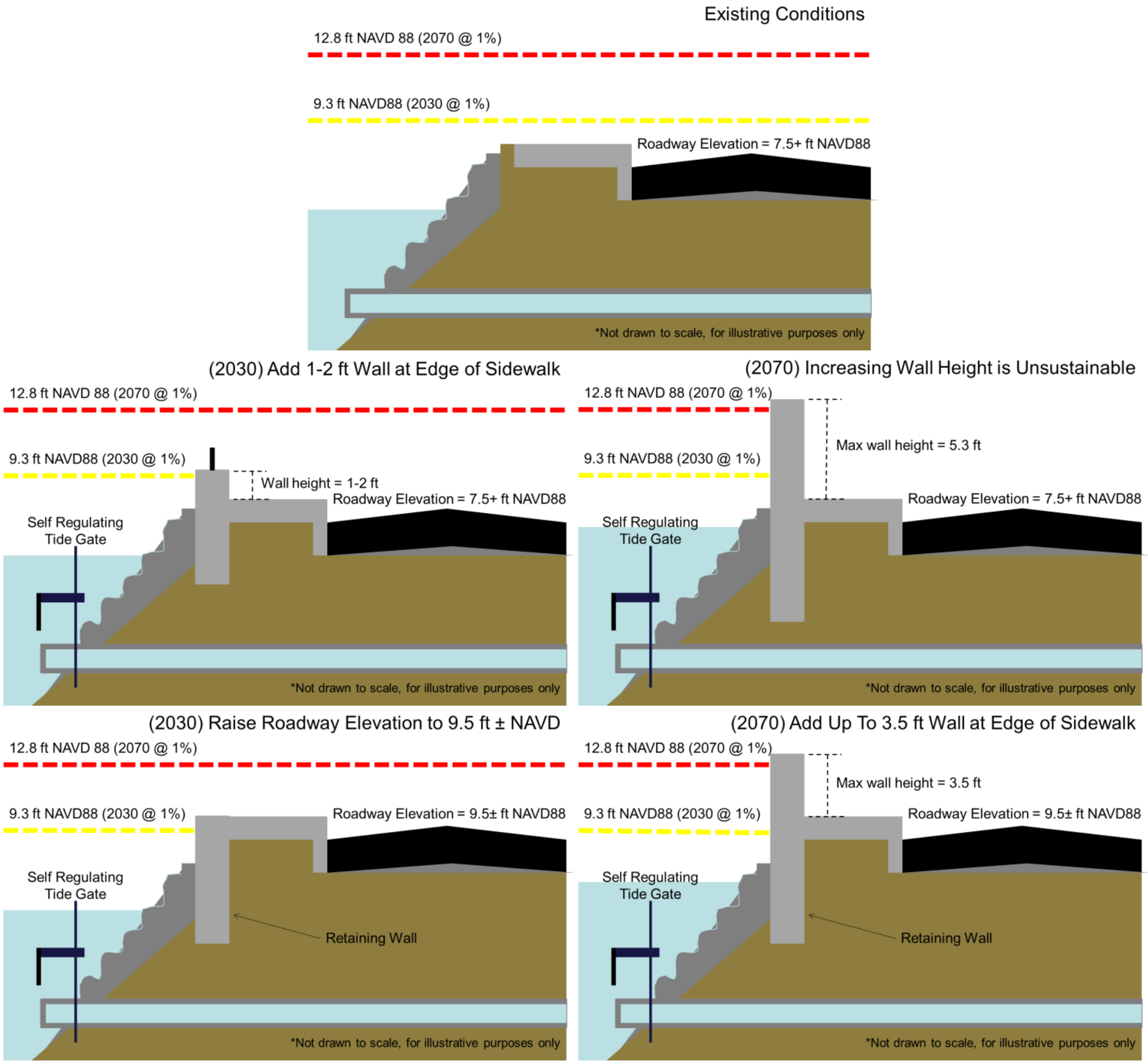


Figure 31 – Route 127 at Mill Pond Dam – Incremental Adaptation Options

Route 127: Washington Street at Goose Cove

The causeway carrying Route 127 (Washington Street) over Goose Cove is an important link to Rockport. The road is a two-lane road. A portion of the causeway, approximately 200 ft. long, is below elevation 9.5 NAVD88, which is the 1% flood elevation for 2030. A total of 330 ft. is below elevation 12.8 NAVD88, which is the 1% flood elevation for 2070. It appears that the little bridge at the north end of the causeway does not appear to be flooded in 2070, and therefore a cost for raising this bridge is not included. Figure 32 shows an elevation of the causeway.

Using the above order-of-magnitude unit costs, the cost ranges to adapt this roadway are as follows:

- Raise road to minimum elevation of 9.5 NAVD88: $300,000 to $400,000
- Construct flood barriers on one side to minimum elevation 12.8 NAVD88: $330,000 to $660,000

Figure 32 – Route 127 (Washington Street) at Goose Cove

Route 127A: Thatcher Road, Hartz Street and Witham Street

Route 127A (Thatcher Road) is another important link to Rockport. The low elevation portion of the road is two lanes with relatively low density. Approximately 4,250 ft. of Thatcher Road is below the 2030 1% flood elevation of 9.5 NAVD88. Approximately 7,930 ft. of Thatcher Road is below the 2070 1% flood elevation of 12.8 NAVD88.

Thatcher Road may be more easily raised due to the relatively lower density of development along its vulnerable sections (Figure 33). In addition, Thatcher Road can provide some opportunities to enhance both the roadway resiliency and the ecological health of the salt marsh system it runs through, by coupling roadway raising with the installation of improved tide control structures (e.g., self regulated tide gates) that allow greater tidal exchange during normal conditions and also provide improved flood control during storms. Bundling projects that include similar improvements at vulnerable segments of Thatcher Road, Witham Street, and Hartz Street can provide even greater regional flood protection and ecological benefits, and may provide some economies of scale.

Using the above order-of-magnitude unit costs, the cost ranges to adapt this roadway are as follows:

- Raise road to minimum elevation of 9.5 NAVD88: $6.38 million to $8.50 million.
- Construct flood barriers on one side to minimum elevation 12.8 NAVD88: $7.93 million to $15.86 million.

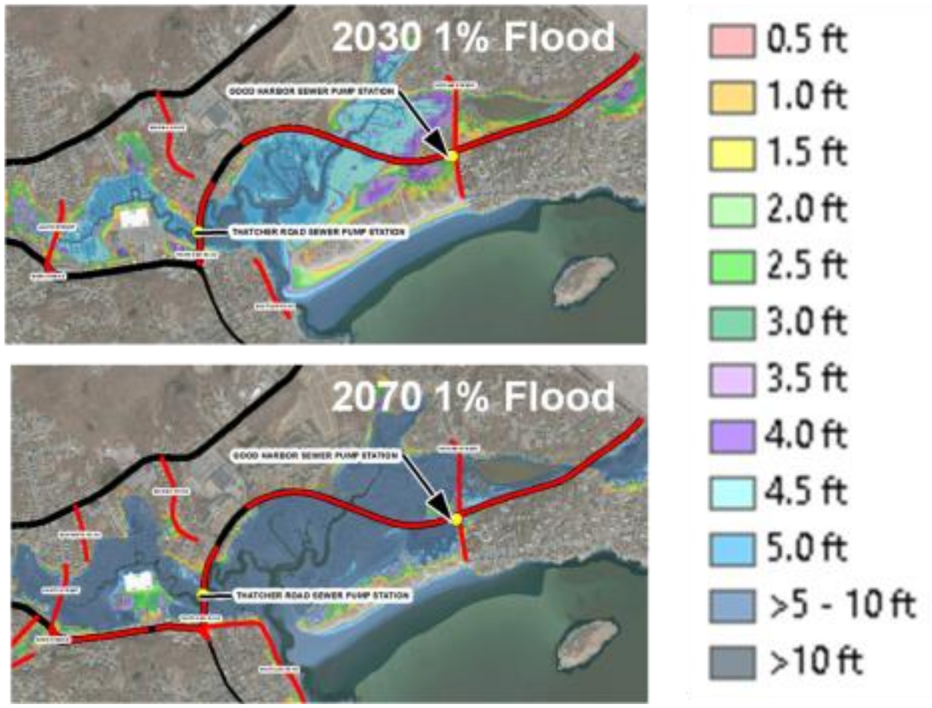


Figure 33 - Thatcher Road (Rt. 127A), 1% Flood Depth in 2030 and 2070 (vulnerable segments in red)

Route 127: Washington Street at Mill Pond Dam

Route 127 (Washington Street) at the Mill Pond Dam is another important link within Gloucester. The low elevation portion of the road is two lanes with relatively high density and commercial development. Approximately 650 ft. of roadway is below the 2030 1% flood elevation of 9.5 NAVD88. Approximately 800 ft. of roadway is below the 2070 1% flood elevation of 12.8 NAVD88 (Figure 34).

Raising the roadway will be more challenging than along Thatcher Road due to the higher density of adjacent residential and business properties. Conditions here present a challenge in terms of transitioning from higher roadway elevations to meeting existing driveways and entrances, so temporary and/or permanent flood walls may be more appropriate. However, if elevations are raised along this vulnerable segment, by whatever means, it will provide improved flood protection to various municipal infrastructure, such as the Department of Public Works building and pump station, Reynard Street pump station, Hodgkins Street pump station, and roads such as Reynard Street, Hodgkins Street, Veterans Way, and Poplar Street. The avoided costs of adapting these other assets or risking their damage or functional loss may make the investment at the Mill Pond Dam more cost effective.

Using the above order-of-magnitude unit costs, the cost ranges to adapt this roadway are as follows:

- Raise road to minimum elevation of 9.5 NAVD88: $975,000 to $1.30 million.

- Construct flood barriers on one side to minimum elevation 12.8 NAVD88: $800,000 to $1.60 million.

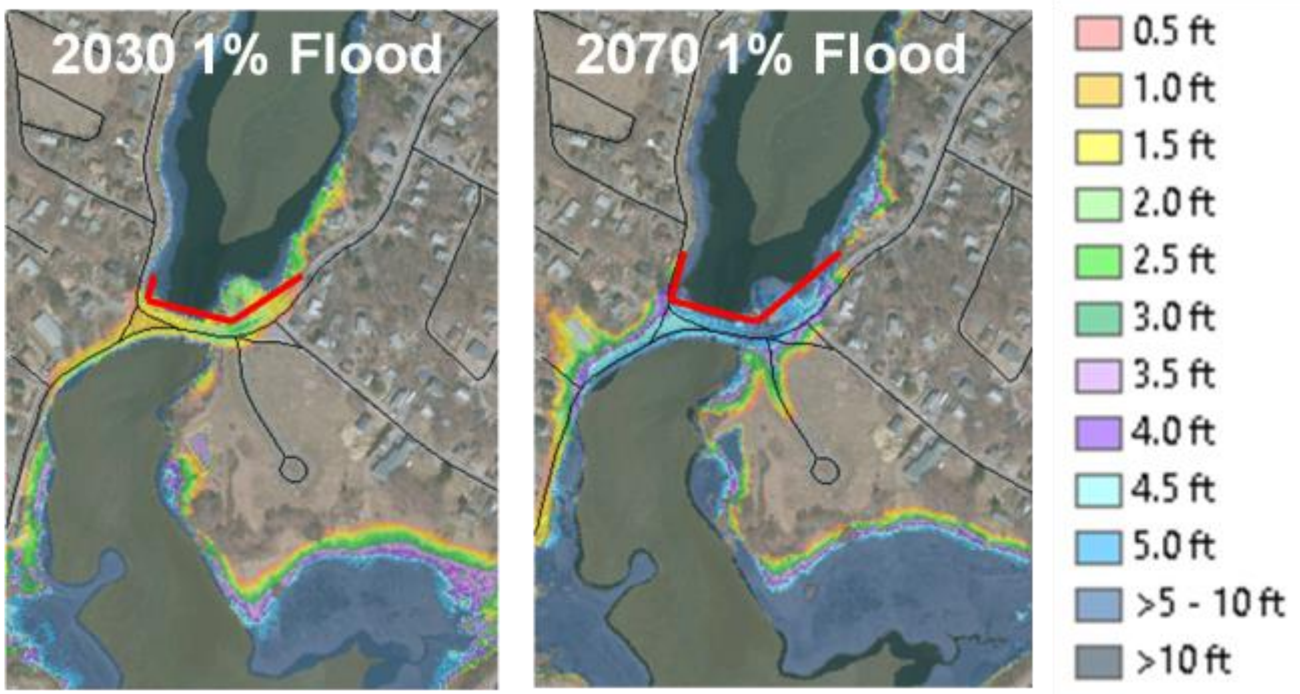


Figure 34 - Washington Street (Rt. 127) at Mill Pond Dam - Incremental Adaptation Options for 1% Flood Protection

Route 127: Western Avenue (Stacy Boulevard)

This section of Route 127 (Western Avenue) is a main route leading into Gloucester's Inner Harbor commercial district. The low elevation portion of the road is two lanes with parking lanes on both side of the roadway. There is a park/promenade on the southern side of the road. Approximately 430 ft. of roadway is below the 2030 1% flood elevation of 9.5 NAVD88. Approximately 2,580 ft. of roadway is below the 2070 1% flood elevation of 12.8 NAVD88 (Figure 35).

Raising the roadway to elevation 9.5 NAVD88 can be achieved relatively easily because there appears to be sufficient room to taper out the roadway fill into the park area. Also the residential density is relatively low, and there is no development on the seaward side of the road.

Using the above order-of-magnitude unit costs, the cost ranges to adapt this roadway are as follows:

- Raise road to minimum elevation of 9.5 NAVD88: $645,000 to $860,000.

- Construct flood barriers on one side to minimum elevation 12.8 NAVD88: $2.58 million to $5.16 million.

Figure 35 – Route 127 at Western Avenue (Stacy's Boulevard)

Route 128: At Causeway Street and Grant Circle

Route 128 is the main entrance and egress route into both Gloucester and Rockport, so flooding of this important roadway can lead to major public safety disruptions and inconvenience to the public. Route 128 is a four lane highway, owned and operated by the Massachusetts Department of Transportation. None of Route 128 appears to flood in the 2030 time frame, but approximately 2,600 ft. of roadway is below the 2070 1% flood elevation of 12.8 NAVD88 (Figure 36).

The only adaptation measure proposed for Route 128 is to introduce flood walls or green landscaped berms, where right-of-way permits, along one side of the highway. Although Causeway Street floods in both 2030 and 2070, the street itself is not a critical roadway, and as such no raising or flood barriers are proposed.

Using the above order-of-magnitude unit costs, the cost ranges to adapt route 128 are as follows:

- Construct flood barriers on one side to minimum elevation 12.8 NAVD88: $2.60 million to $5.20 million.

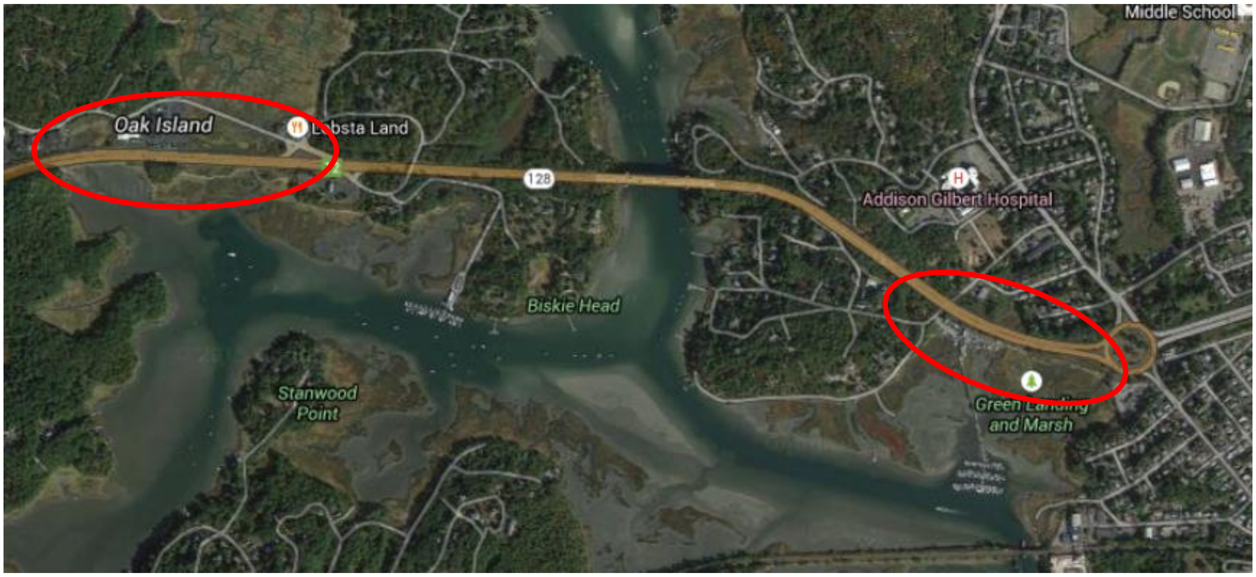


Figure 36 – Route 128 Portions Subject to Flooding in 2070

Route 133: Essex Street

Route 133 (Essex Street) is another major roadway leading to Gloucester's Inner Harbor commercial district. It is a two-lane roadway. Approximately 430 ft. of roadway is below the 2030 1% flood elevation of 9.5 NAVD88. Approximately 2,100 ft. of roadway is below the 2070 1% flood elevation of 12.8 NAVD88 (Figure 37).

As discussed above, this roadway serves a number of commercial establishments, marinas and the Gloucester Water Pollution Control Facility. It should be relatively easy to raise the roadway in the low area as there is generally room to make the transitions to adjacent properties. If this roadway is raised, adaption measures described above for the Water Pollution Control Facility would probably not need to be implemented.

Using the above order-of-magnitude unit costs, the cost ranges to adapt this roadway are as follows:

- Raise road to minimum elevation of 9.5 NAVD88: $3.15 million to $4.20 million.

- Construct flood barriers on one side to minimum elevation 12.8 NAVD88: $2.70 million to $5.40 million.

Figure 38 summarizes the costs described above for these roadways.

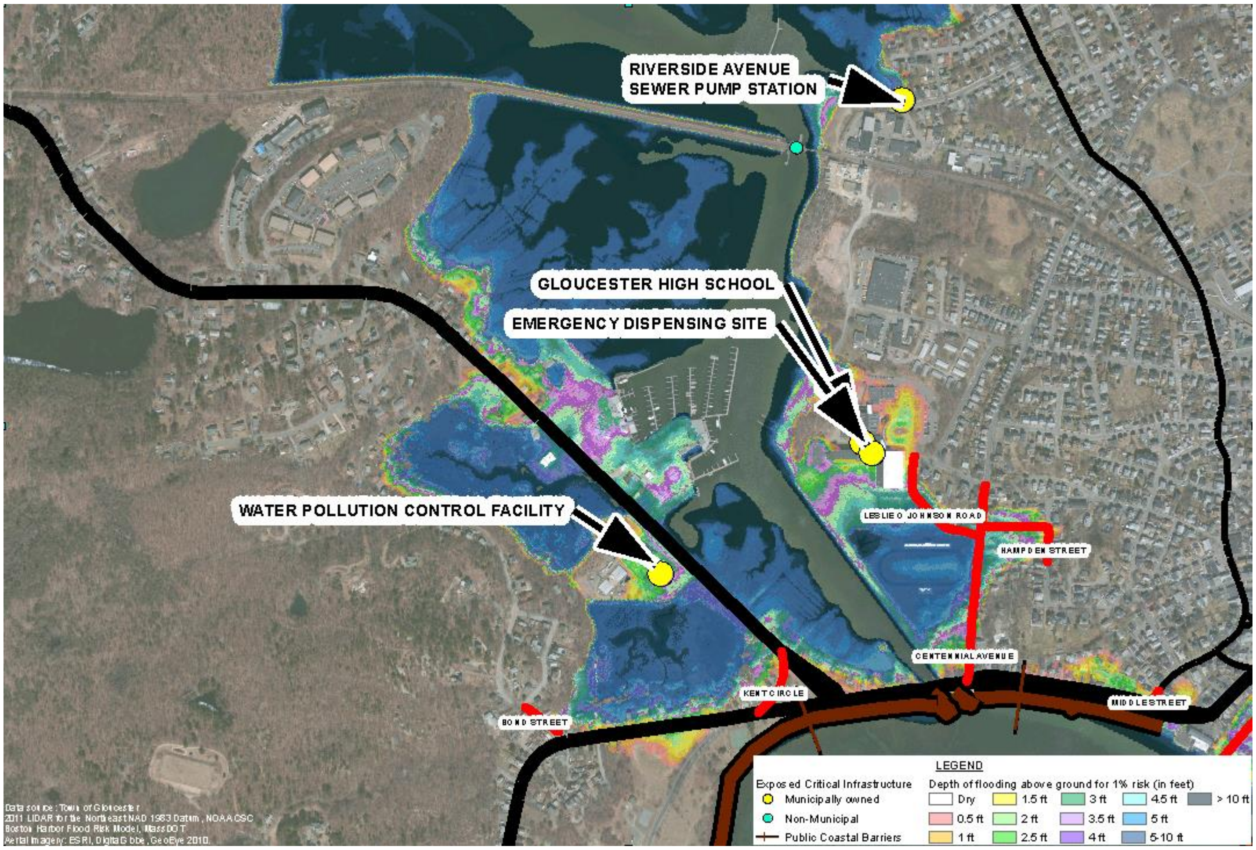


Figure 37 – Route 133 (Essex Street) flooding in 2070 (1% Flood Probability)

Roadway	Linear Ft. w/ El. < 9.5 ft. ± NAVD88 (2030 – 1%)	Linear Ft. w/ El. < 12.8 ft. ± NAVD88 (2070 – 1%)	Number of Traffic Lanes	Estimated Construction Cost (2030) Raise Road	Estimated Construction Cost (2070) Flood Barriers
Route 127: Goose Cove Causeway (Washington Street)	200	330	2	$300,000 to $400,000	$330,000 to $660,000
Route 127A: Thatcher Road, Hartz Street, Witham Street	4,250	7,930	2	$6.38 million to $8.50 million	$7.93 million to $15.86 million
Route 127: Washington Street at Mill Pond Dam	650	800	2	$975,000 to $1.30 million	$800,000 to $1.60 million
Route 127: Western Avenue (Stacy Boulevard)	430	2,580	2	$645,000 to $860,000	$2.58 million to $5.16 million
Route 128: At Causeway Street and Grant Circle	0	2,600	4	$0	$2.60 million to $5.20 million
Route 133: Essex Street at Cape Anne's Marina	2,100	2,700	2	$3.15 million to $4.20 million	$2.70 million to $5.40 million

Figure 38 – Estimated Roadway Adaptation Costs to Address Roadway Flooding Issues

Install a Tide Gauge in Gloucester Inner Harbor

Consider installing an automated tide gauge in Gloucester Inner Harbor to help monitor actual sea level rise locally. The nearest tide gauge is in Boston Harbor. Although it is very reliable, it does not provide localized data for Gloucester. Having a local tide gauge will provide important data for the design and implementation of future adaptation projects. (Approximate cost = $5,000 - $10,000)

Recommendations for Natural Resources

Annisquam River

Allow natural evolution to move forward, at least in the early to mid-term time frames. Much of the transition occurring here is expansion of low marsh, at least initially, which is not detrimental to overall ecological functioning of the broader marsh systems in Gloucester.

Good Harbor Barrier Beach

Although there does not appear to be an immediate threat to this area, it is recommended that a a more detailed coastal processes study of the beach and marsh complex be undertaken to better understand the local processes such as sediment transport, current, wave action, erosion rates, etc. Based on more accurate modeling, better long-term recommendations for green adaptations for resiliency can be developed. Potential adaptations for this area might include marsh deposition, dune and beach restoration, cobble or landscaped berms and living shoreline applications.

Eastern Edge of Essex Bay

Allow natural evolution to progress, at least in the early to mid-term time frames. Much of the transition occurring here is expansion of low marsh, at least initially, which is not detrimental to overall ecological functioning of the broader salt marsh and resource systems in Gloucester.

Recommendations for Potential Changes to Policies/Regulations

Potential Changes to Gloucester Wetlands Ordinance

- Amend Section 12-27 (Floodplain Management), as follows:
  - Subsection (g): Consider adding a subsection (6) requiring applicants to submit a discussion on how the effects of sea level rise are being addressed and mitigated for applications affecting lands in the flood plain. Consider establishing a performance standard for future sea level rise by adopting a specific sea level rise curve. Also consider that the applicant be required to submit a cost-benefit analysis of mitigation alternatives.
  - Consider clarifying the definitions of substantial improvements and relocation of existing buildings. These terms can often be contentious without clear definitions.
  - Consider allowing the ability to elevate existing structures to reduce flood hazards.
  - Consider adding performance standards for use of temporary flood barriers which might include things such as locating temporary barriers on wetland resources, provisions for pumping of flood water during or immediately after a flood, and cleaning of temporary barriers in located in a resource area.

- Consider amending Section 12-2.c.2 by increasing the width of the buffer zone within the flood plain. The current buffer zone is 100 ft. in accordance with the distance in 310 CMR 10.00. The Conservation Commission could increase its local jurisdictional area to review projects in the context of potential impacts to wetlands due to predicted sea level rise.

Potential Changes to the Gloucester Zoning Ordinance

- Consider establishing a Floodplain Overlay District By-Law, similar to one adopted by the Town of Oak Bluffs. The limits of the Floodplain Overlay District would be based on the FEMA FIRM map, at either the 1% or 0.2% flood level. The purposes of the Floodplain Overlay District include:
  - Limiting development in areas subject to flooding, particularly high hazard V zones and AO zones in order to minimize potential loss of life, destruction of property, and environmental damage inevitably resulting from storms, flooding, erosion and relative sea level rise.
  - Reducing or preventing public health emergencies resulting from surface and ground water contamination from inundation of or damage to sewage disposal systems and storage areas for typical household hazardous substances.
  - Enabling safe access to and from homes and structures for homeowners and emergency response personnel, such as police, fire, and rescue departments.
  - Minimizing monetary loss and public health threats resulting from storm damage to public facilities (water and gas mains; electric, telephone and sewer lines, streets, bridges, etc.).
  - Preventing loss or diminution of the beneficial functions of storm and flood damage prevention or reduction and pollution prevention provided by wetlands, beaches, dunes, barrier beaches, the floodplain, and coastal banks.
  - Protecting public access and ensure that areas of high public value remain open to the public.

The Floodplain Overlay District By-Law should include a list of clearly defined permitted uses, such as:

- Public access activities
- Repair of existing foundations, unless the work replaces the foundation in total or repairs the foundation so as to constitute new construction or a substantial repair of a foundation.
- Repair of existing structures, provided that the repair does not constitute a substantial improvement or a reconstruction.

The Floodplain Overlay District By-Law should also include a list of clearly prohibited uses, such as:

- The installation of a basement.
- New construction of residential structures.
- The construction of an addition or other alterations to an existing structure that results in an increase in floor area.
- Repairs to a substantially damaged structure or reconstruction of an existing structure that results in an increase in floor area.
- New construction of non-residential structures, with the exception of water dependent structures.
- Any increase in impervious surface on a residential lot. This may include, but is not limited to, swimming pools, tennis/basketball courts, pavers, concrete slabs at grade, curbing, and retaining walls. For water dependent projects allowed in the V, VE, and AO Zones, impervious surfaces accessory to the use could be allowed provided a registered professional engineer certifies in writing that the impervious surface will not cause an increase in wave runup, a deflection or channelization of flood waters, or an increase in the velocity of flow.
- The use of fill for structural support of buildings.

The Floodplain Overlay District By-Law should also include a list of uses that are permitted with approval of a Special Permit, such as:

- Substantial repair to a foundation or elevation of a structure.
- Restoration and construction of structures listed in the National Register of Historic Places or the official State Inventory of Historic Places.
- Construction of water dependent structures as determined by MassDEP Chapter 91 (Waterways) Regulations.
- Beach or dune nourishment and restoration of coastal resource areas as defined in the MA Wetlands Protection Act and Gloucester Wetlands Ordinance.
- The repair or replacement of an existing septic system.
- Replacement or repair of existing impervious surfaces, including, but not limited to, swimming pools, tennis/basketball courts, pavement, pavers, concrete slabs at grade, curbing, and retaining walls.
- Repair of existing or construction of new flood barriers, green infrastructure and stormwater management systems associated with prevention of flood inundation.
- Wet- or dry-floodproofing of existing structures.
- Deployment of temporary flood barrier protection. One issue that needs to be addressed is how means of egress is addressed. During a flood event, while the building is surrounded with a temporary flood protection barrier, egress routes may not be operational. Requiring that the building be unoccupied during a flood while temporary barriers are in place may help to address this building code issue.

- Consider amending the Zoning By-Law to provide incentives to residential and commercial property owners to raise/protect structures to improve resilience and flood protection of private properties.

    - Consider allowing higher maximum height restrictions by special permit in relief of the height restrictions in Sections 3.2.1, 3.2.2, 3.2.3, 3.2.4, 3.2.5 and 3.2.6 in the case of existing structures being elevated to improve flood protection.

    - Consider adopting a "freeboard incentive" for residential and commercial building projects, either for new construction or for existing structures being elevated to improve flood protection. As an example, the Town of Hull adopted a "freeboard incentive" that reduces building department application fees by $500 if an elevation certificate is provided to verify that the building is elevated a minimum of two feet above the highest federal or state requirement for the flood zone. Additional fee reductions could apply for additional freeboard.

- Consider amending Section 5.9 (Cluster Development) as follows:

    - Add a new subsection (h) under subsection 5.9.1: *To encourage preservation of land bordering salt marsh and other coastal resources to allow for natural growth and evolution of natural resources resulting from climate change and future sea level rise.*

    - Modify subsection 5.9.3.1 (b) as follows: *An evaluation of the open space within the cluster, with respect to size, shape, location, natural resource value and accessibility by residents of the city or of the cluster. <u>The evaluation shall include a discussion of how the proposed project will better allow for natural growth and evolution of lands bordering salt marsh and other coastal resources taking into account the long-term effects of climate change and future sea level rise than would occur under a by-right subdivision plan.</u>*

- Consider amending Section 5.15 (Open Space Residential Development) to add a new subsection under 5.15.1.1 as follows:

    - *(g) To encourage preservation of land bordering salt marsh and other coastal resources to allow for natural growth and evolution of natural resources resulting from climate change and future sea level rise.*

- Consider amending Section 5.18 (Marine Industrial District) to add a new subsection:

    - *(6) Will the proposed project negatively affect the flood resilience capabilities of the area taking into account the effects of climate change and future sea level rise as defined by a given performance standard (specify a sea level rise curve).*

Potential Changes to the City of Gloucester Rules and Regulations Governing the Subdivision of Land

- Consider amending Section 3.1.3 by adding a new subsection (w), as follows:
  - *(w): An evaluation of how the effects of climate change and future sea level rise are being addressed and mitigated for applications affecting lands in the coastal flood plain. The evaluation shall include cost-benefit analyses of mitigation measures being proposed.*
  - Consider establishing a performance standard for future sea level rise by adopting a specific sea level rise curve.
  - Alternatively, this evaluation could be added to the requirements for an Environmental Impact Evaluation described in Appendix A.
- Consider amending Section 3.2.1 by adding a new subsection (s), as follows:
  - *(s): An evaluation of how the effects of climate change and future sea level rise are being addressed and mitigated for applications affecting lands in the coastal flood plain. The evaluation shall include cost-benefit analyses of mitigation measures being proposed.*
  - Consider establishing a performance standard for future sea level rise by adopting a specific sea level rise curve.
  - Alternatively, this evaluation could be added to the requirements for an Environmental Impact Evaluation described in Appendix A.

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 City can purchase an easement from a property owner today in exchange for a promise to surrender the property to the City 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 City. Based on information provided in the latest Gloucester Hazard Mitigation Plan Update, there are twenty-four (24) properties in Gloucester that are classified as “repetitive loss” properties by the Community Rating System (CRS) of the National Flood Insurance Program. These 24 properties, having had

at least two or more flood claims of $1,000 or more in any given 10-year period since 1978, might be ideal candidates for such a program as they have already experience 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 climate change and sea level rise and promote more sustainable practices throughout the community.
  - Require that all City-funded projects take into account predicted impacts of climate change and sea level rise.
  - Update the City'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.

Develop a Coastal Flood Operations Plan

- Consider developing a Coastal Flood Operations Plan to prepare for and minimize flood damage due to coastal flooding as a result of extreme weather events. 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 recovery.
  - 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 City's overall emergency response planning documents.

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 included in this report illustrate 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. The BH-FRM model, from which these maps were developed, did not model the upland topography beyond the edge of water in the City of Gloucester. As such, the predicted water elevations, which were propagated landward of the model boundary using engineering judgment, do not include the true effects of land topography and friction and other factors which can affect calculated water surface elevations landward of the model boundary. The water surface elevations presented in this document, are a reasonable prediction of possible future conditions, given these limitations.

The authors of this study understand that the Massachusetts Department of Transportation is planning to further refine the upland topography contained in the BH-FRM model to include all coastal communities in Massachusetts, including the City of Gloucester, within the next few years. The readers of this study should understand that the water surface elevations generated by the refined model may be different than those presented in this study, and that the conclusions of this study may need to be revisited and updated once the new data is available.

These flood maps expressly do not include flooding attributed to wave run-up, overtopping of seawalls, backups within municipal drainage infrastructure or precipitation-driven overland flooding. Therefore, the extent and magnitude of flooding depicted on these flood maps strictly represent coastal flooding from sea level rise and storm surge. These flood maps shall not be used to represent the extent of flooding for which flood insurance is required. Projections depicted on these flood maps 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.

APPENDIX A – INUNDATION MAPS

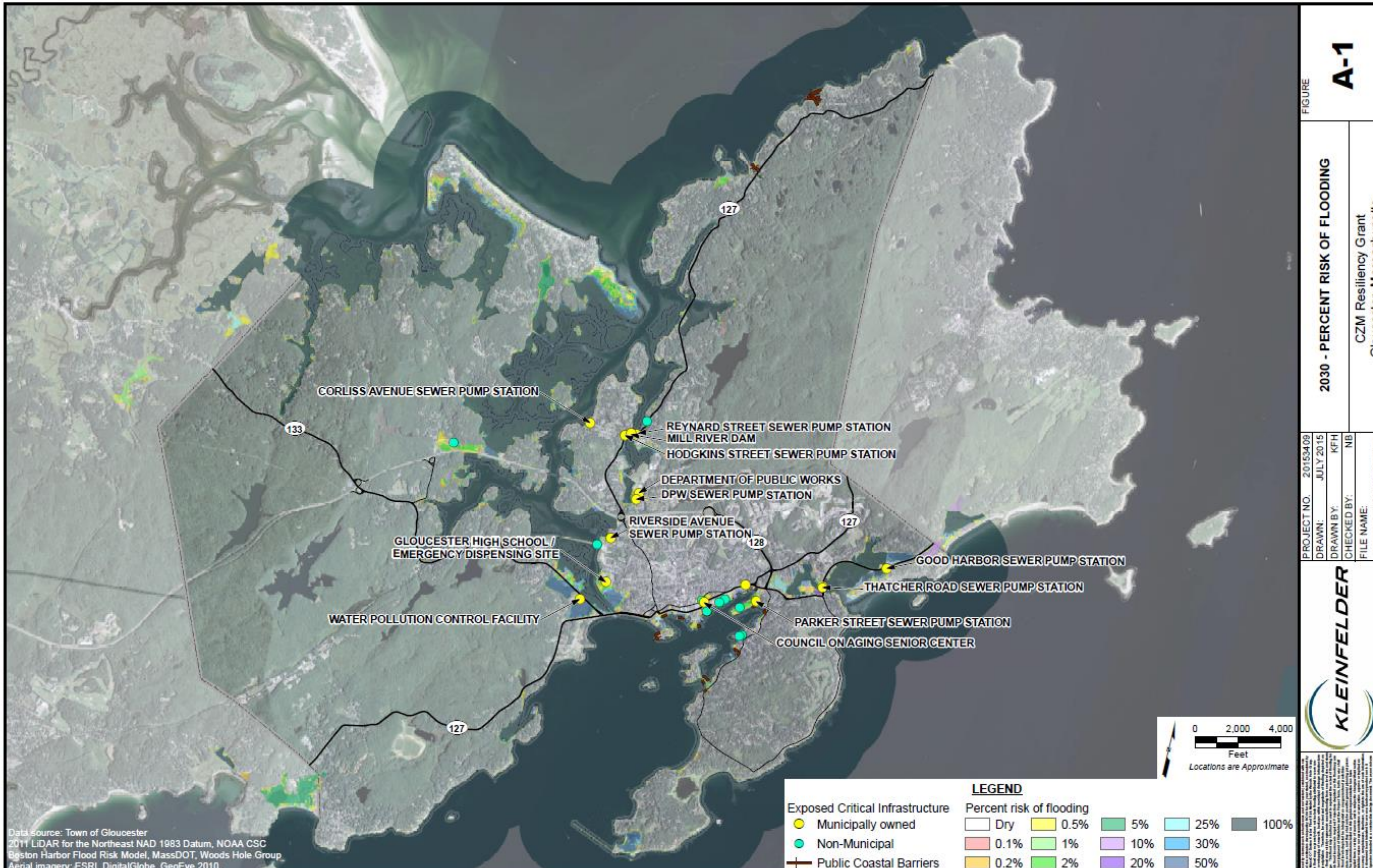


FIGURE
A-1
2030 - PERCENT RISK OF FLOODING
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME:
KLEINFELDER
CORLISS AVENUE SEWER PUMP STATION
REYNARD STREET SEWER PUMP STATION
MILL RIVER DAM
HODGKINS STREET SEWER PUMP STATION
DEPARTMENT OF PUBLIC WORKS
DPW SEWER PUMP STATION
RIVERSIDE AVENUE
SEWER PUMP STATION
GLOUCESTER HIGH SCHOOL /
EMERGENCY DISPENSING SITE
WATER POLLUTION CONTROL FACILITY
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
PARKER STREET SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
127
133
128
0 2,000 4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Percent risk of flooding
Dry
0.1%
0.2%
0.5%
1%
2%
5%
10%
20%
25%
30%
50%
100%
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.

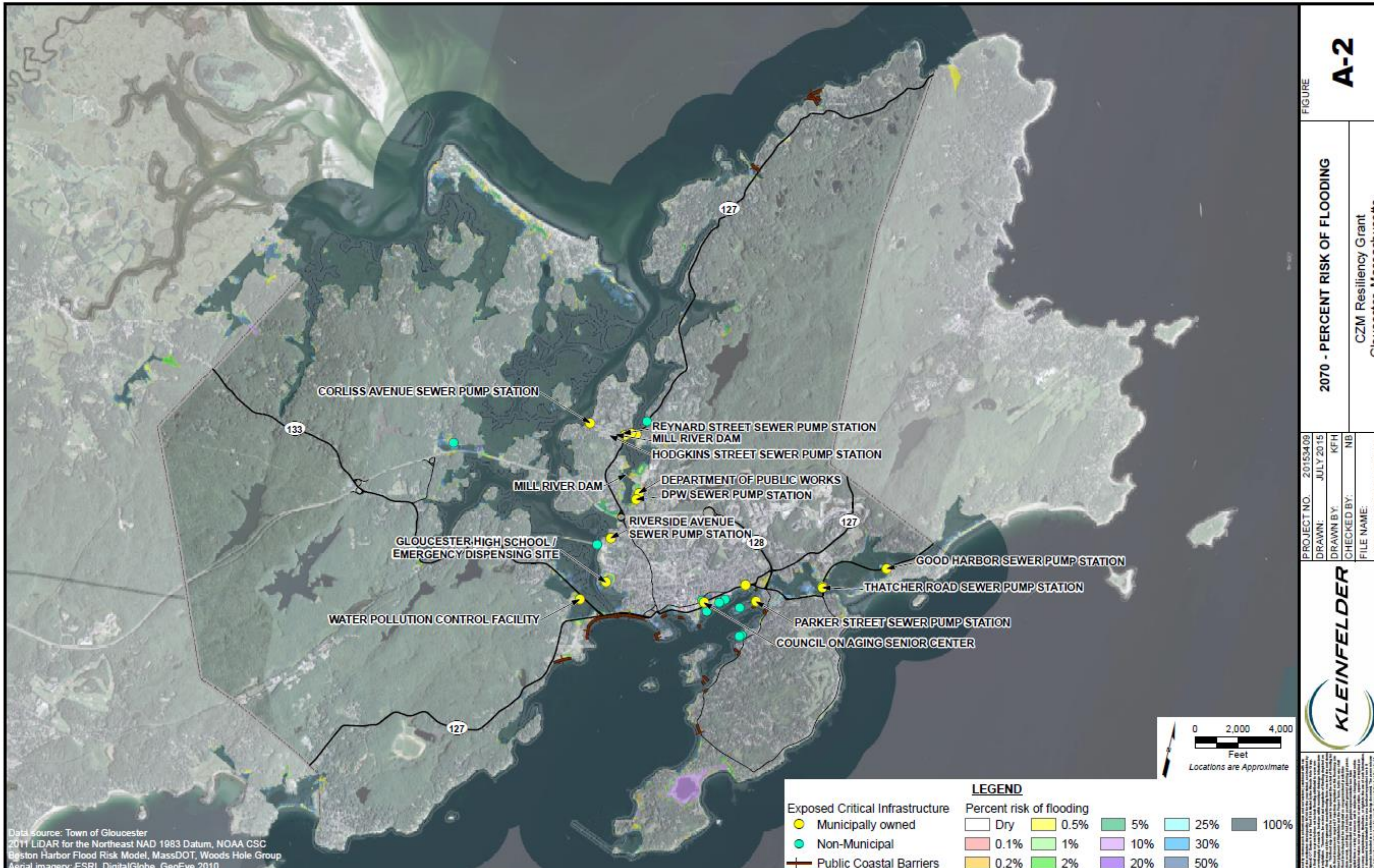
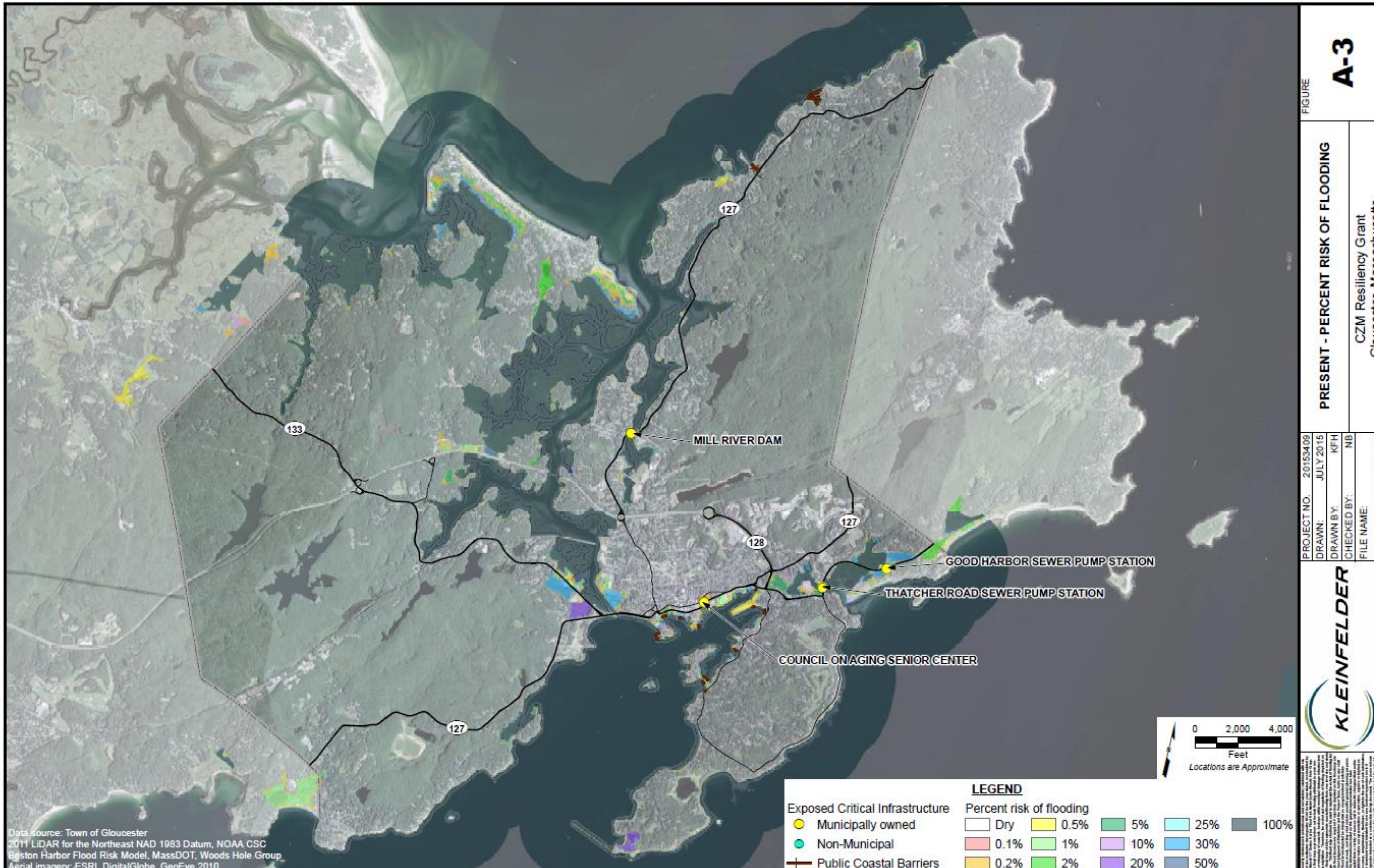


FIGURE
A-2
2070 - PERCENT RISK OF FLOODING
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME: Gloucester_2070_PercentRisk.mxd
KLEINFELDER
CORLISS AVENUE SEWER PUMP STATION
REYNARD STREET SEWER PUMP STATION
MILL RIVER DAM
HODGKINS STREET SEWER PUMP STATION
MILL RIVER DAM
DEPARTMENT OF PUBLIC WORKS
DPW SEWER PUMP STATION
RIVERSIDE AVENUE SEWER PUMP STATION
GLOUCESTER HIGH SCHOOL / EMERGENCY DISPENSING SITE
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
WATER POLLUTION CONTROL FACILITY
PARKER STREET SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
133
127
128
0 2,000 4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Percent risk of flooding
Dry
0.1%
0.2%
0.5%
1%
2%
5%
10%
20%
25%
30%
50%
100%
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.


MILL RIVER DAM
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
133
127
128
0 2,000 4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Percent risk of flooding
Dry
0.1%
0.2%
0.5%
1%
2%
5%
10%
20%
25%
30%
50%
100%
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.
FIGURE
A-3
PRESENT - PERCENT RISK OF FLOODING
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME:
KLEINFELDER

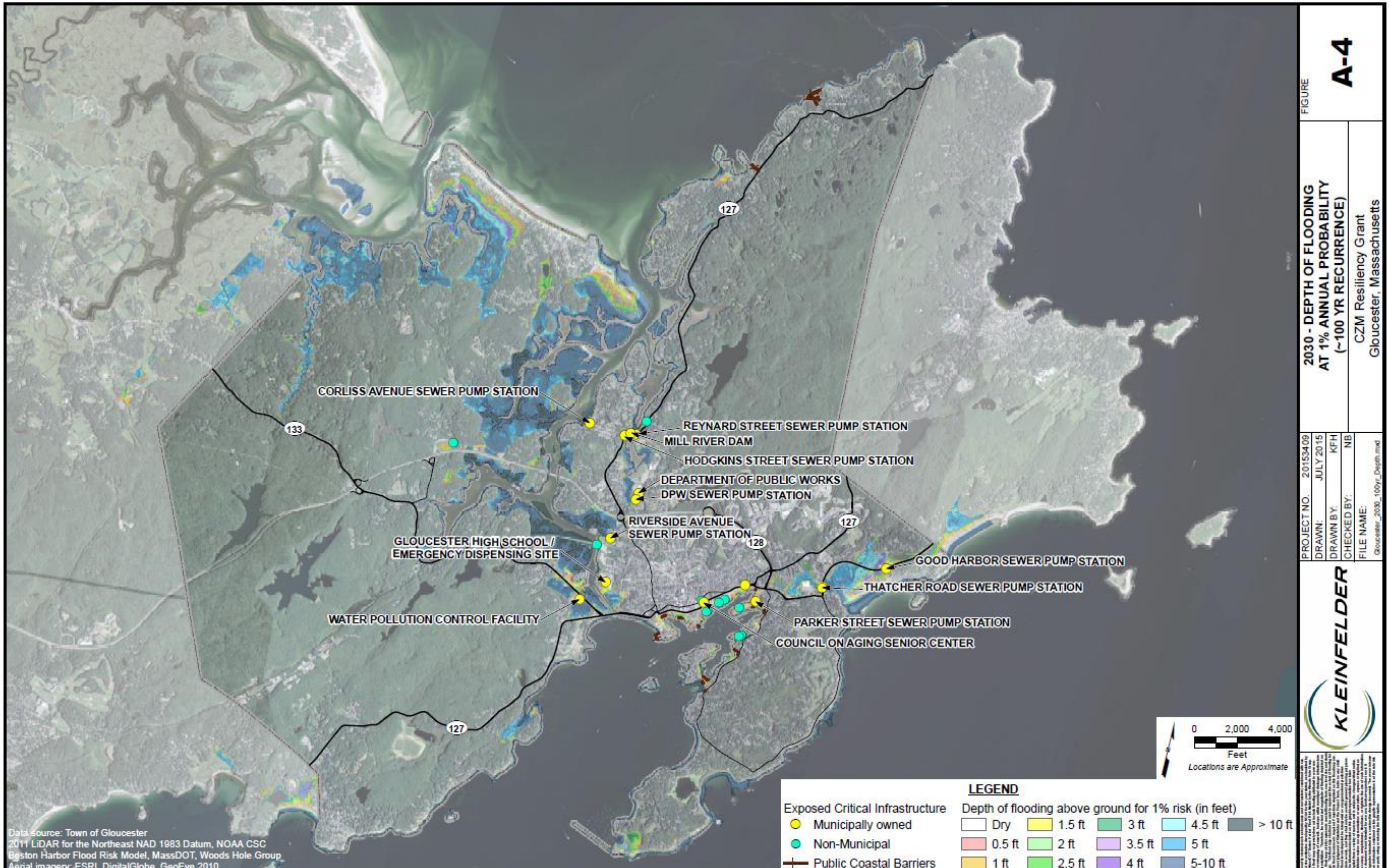
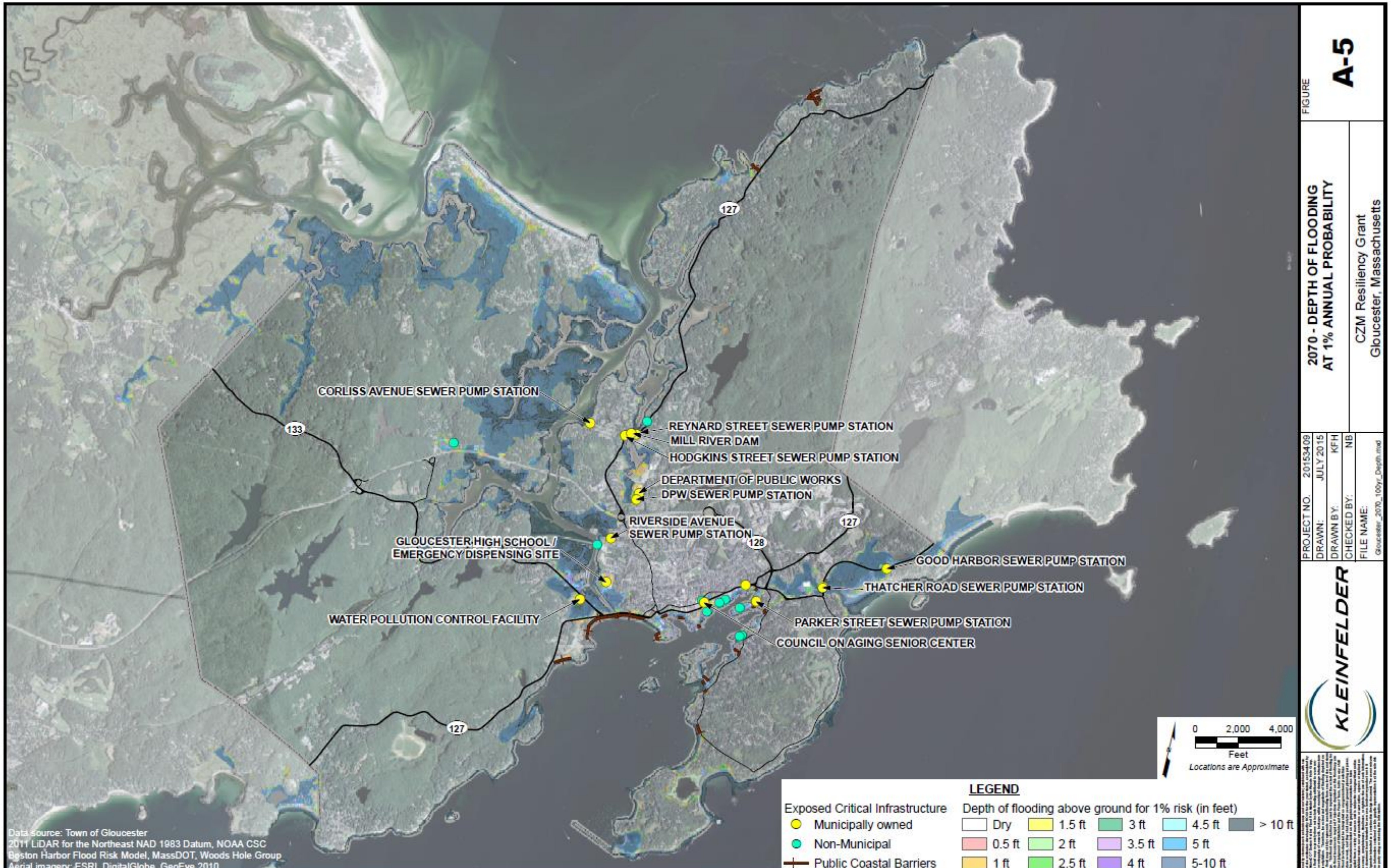


FIGURE
A-4
2030 - DEPTH OF FLOODING AT 1% ANNUAL PROBABILITY (~100 YR RECURRENCE)
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME:
KLEINFELDER
CORLISS AVENUE SEWER PUMP STATION
REYNARD STREET SEWER PUMP STATION
MILL RIVER DAM
HODGKINS STREET SEWER PUMP STATION
DEPARTMENT OF PUBLIC WORKS
DPW SEWER PUMP STATION
RIVERSIDE AVENUE SEWER PUMP STATION
GLOUCESTER HIGH SCHOOL / EMERGENCY DISPENSING SITE
WATER POLLUTION CONTROL FACILITY
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
PARKER STREET SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
127
133
128
0 2,000 4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Depth of flooding above ground for 1% risk (in feet)
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
5-10 ft
> 10 ft
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.


CORLISS AVENUE SEWER PUMP STATION
REYNARD STREET SEWER PUMP STATION
MILL RIVER DAM
HODGKINS STREET SEWER PUMP STATION
DEPARTMENT OF PUBLIC WORKS
DPW SEWER PUMP STATION
RIVERSIDE AVENUE SEWER PUMP STATION
GLOUCESTER HIGH SCHOOL / EMERGENCY DISPENSING SITE
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
WATER POLLUTION CONTROL FACILITY
PARKER STREET SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
133
127
128
0 2,000 4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Depth of flooding above ground for 1% risk (in feet)
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
5-10 ft
> 10 ft
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.
FIGURE
A-5
2070 - DEPTH OF FLOODING
AT 1% ANNUAL PROBABILITY
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME: Gloucester_2070_100yr_Depth.mxd
KLEINFELDER

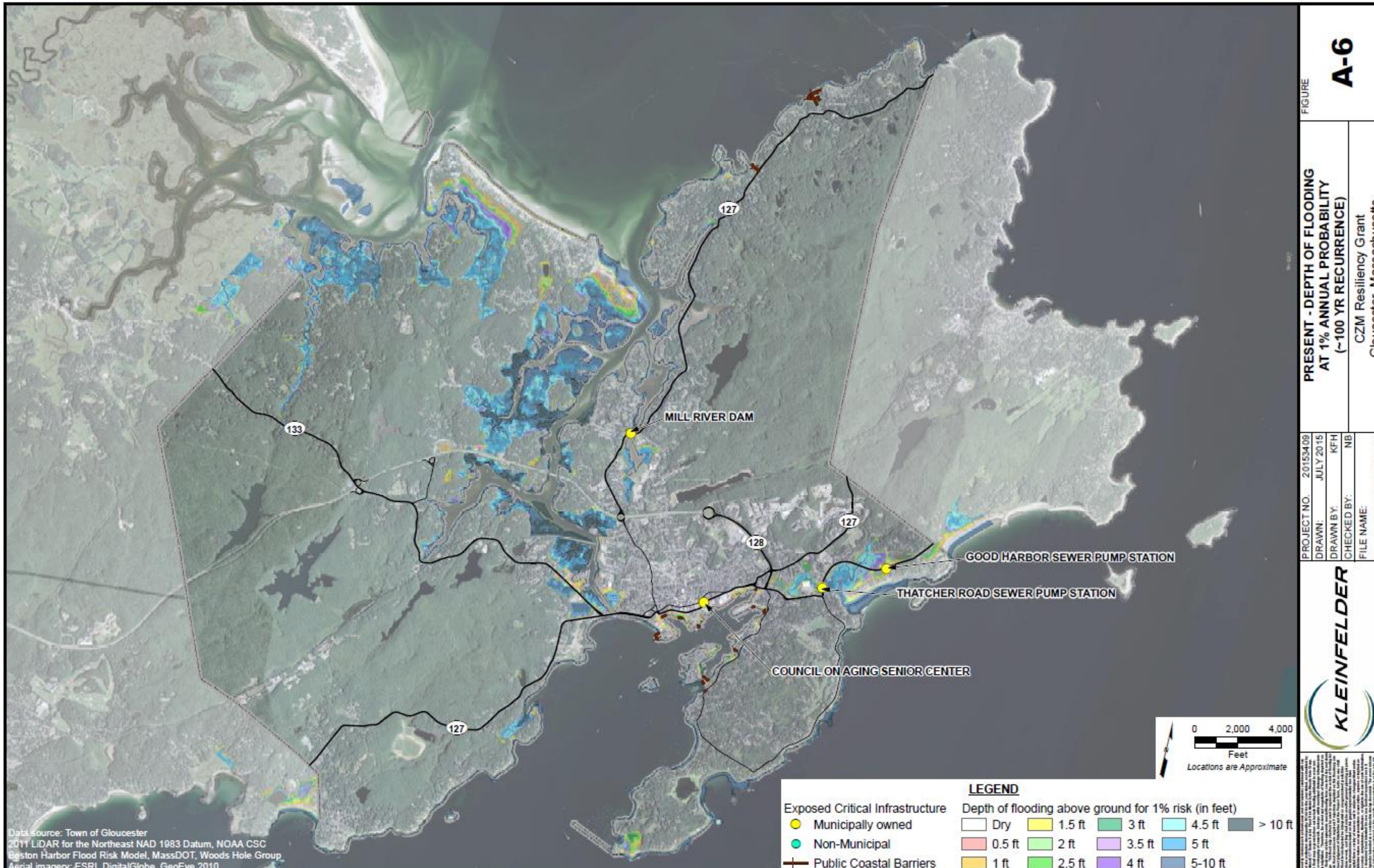


FIGURE
A-6
PRESENT - DEPTH OF FLOODING
AT 1% ANNUAL PROBABILITY
(~100 YR RECURRENCE)
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME:
KLEINFELDER
MILL RIVER DAM
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
127
133
128
0
2,000
4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Depth of flooding above ground for 1% risk (in feet)
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
5-10 ft
> 10 ft
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.

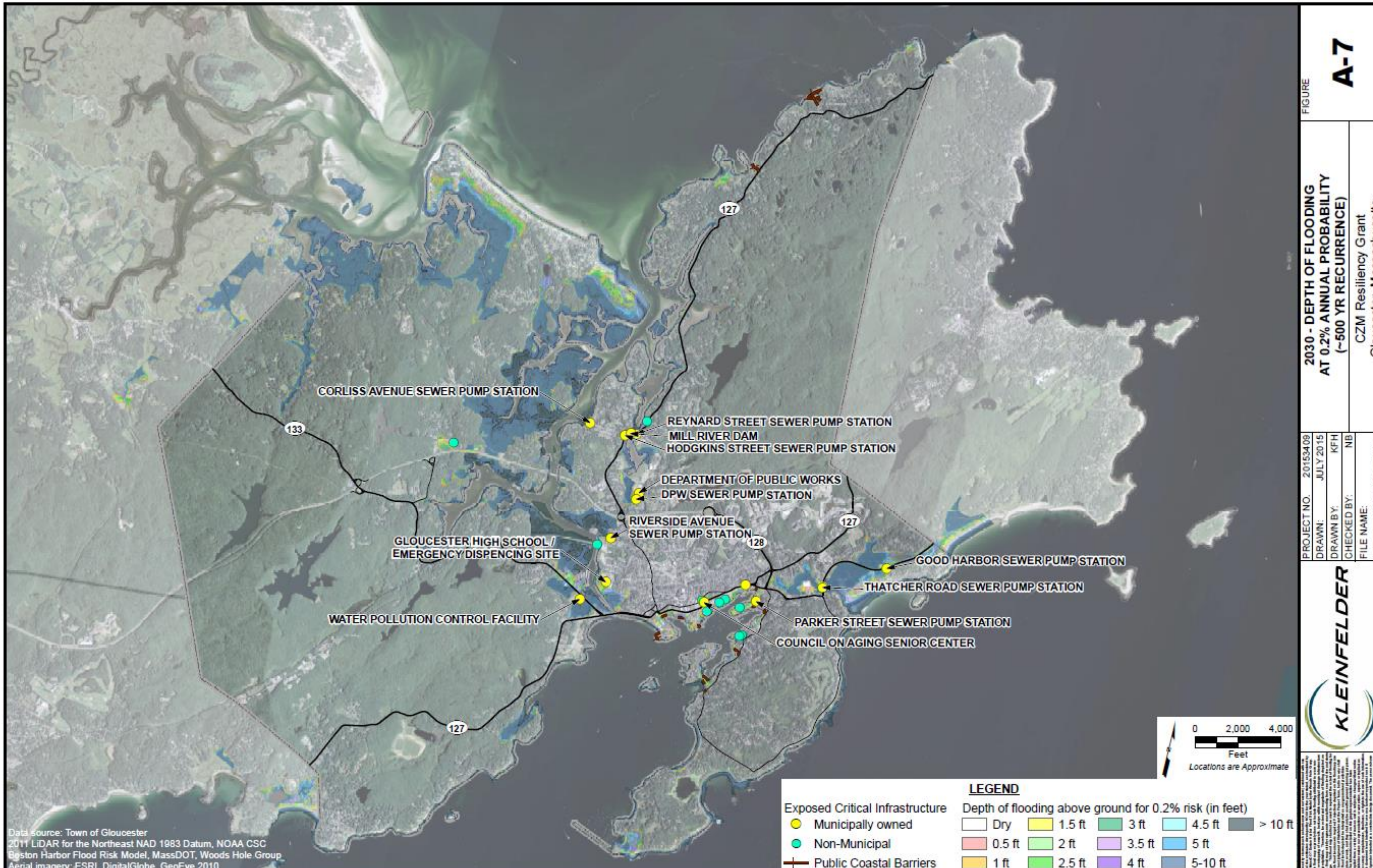
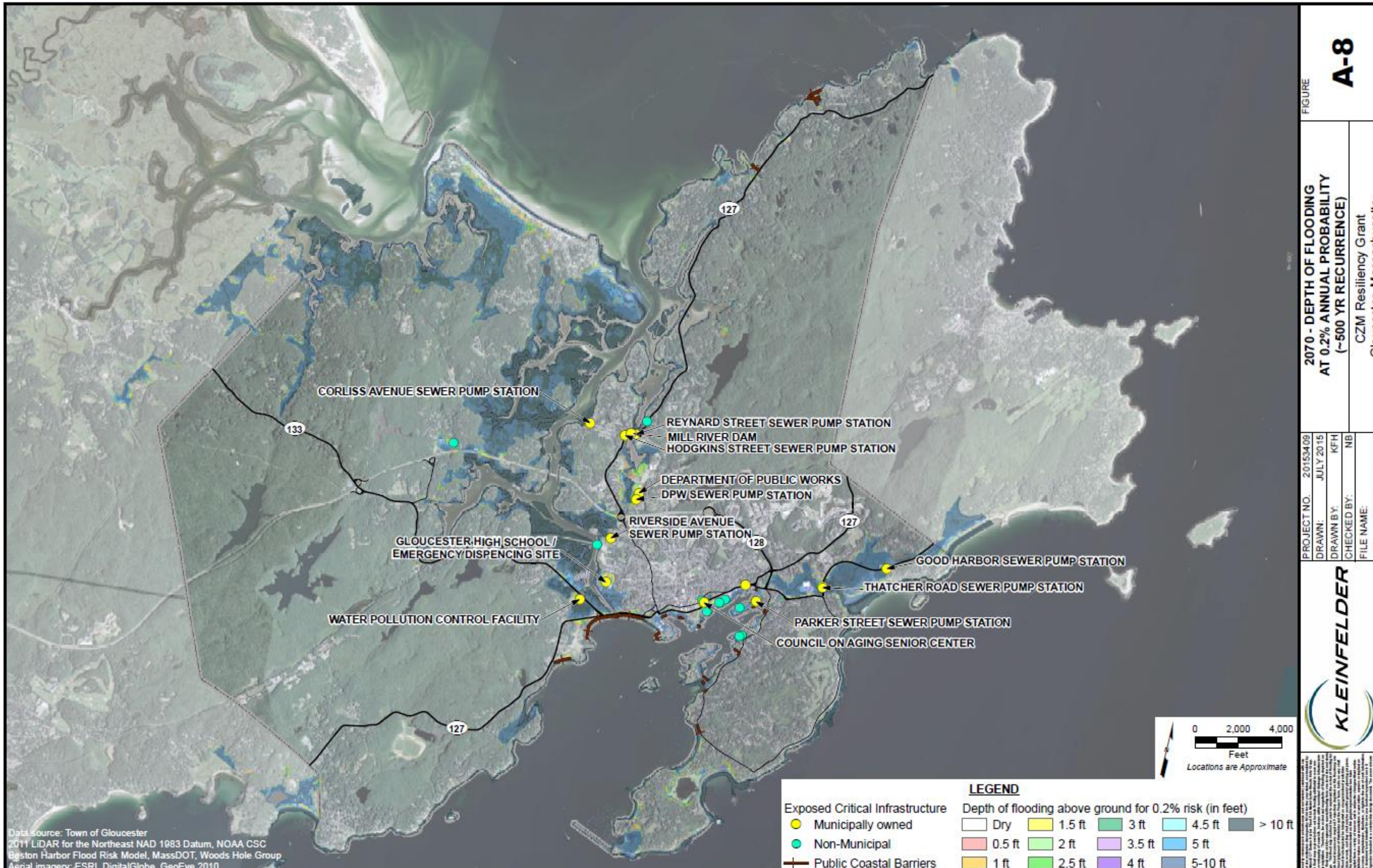


FIGURE
A-7
2030 - DEPTH OF FLOODING AT 0.2% ANNUAL PROBABILITY (~500 YR RECURRENCE)
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME:
KLEINFELDER
CORLISS AVENUE SEWER PUMP STATION
REYNARD STREET SEWER PUMP STATION
MILL RIVER DAM
HODGKINS STREET SEWER PUMP STATION
DEPARTMENT OF PUBLIC WORKS
DPW SEWER PUMP STATION
RIVERSIDE AVENUE SEWER PUMP STATION
GLOUCESTER HIGH SCHOOL / EMERGENCY DISPENCING SITE
WATER POLLUTION CONTROL FACILITY
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
PARKER STREET SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
133
127
128
0 2,000 4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Depth of flooding above ground for 0.2% risk (in feet)
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
5-10 ft
> 10 ft
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.


CORLISS AVENUE SEWER PUMP STATION
REYNARD STREET SEWER PUMP STATION
MILL RIVER DAM
HODGKINS STREET SEWER PUMP STATION
DEPARTMENT OF PUBLIC WORKS
DPW SEWER PUMP STATION
RIVERSIDE AVENUE SEWER PUMP STATION
GLOUCESTER HIGH SCHOOL / EMERGENCY DISPENCING SITE
WATER POLLUTION CONTROL FACILITY
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
PARKER STREET SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
127
133
128
0 2,000 4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Depth of flooding above ground for 0.2% risk (in feet)
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
5-10 ft
> 10 ft
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.
FIGURE
A-8
2070 - DEPTH OF FLOODING AT 0.2% ANNUAL PROBABILITY (~500 YR RECURRENCE)
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME:
KLEINFELDER

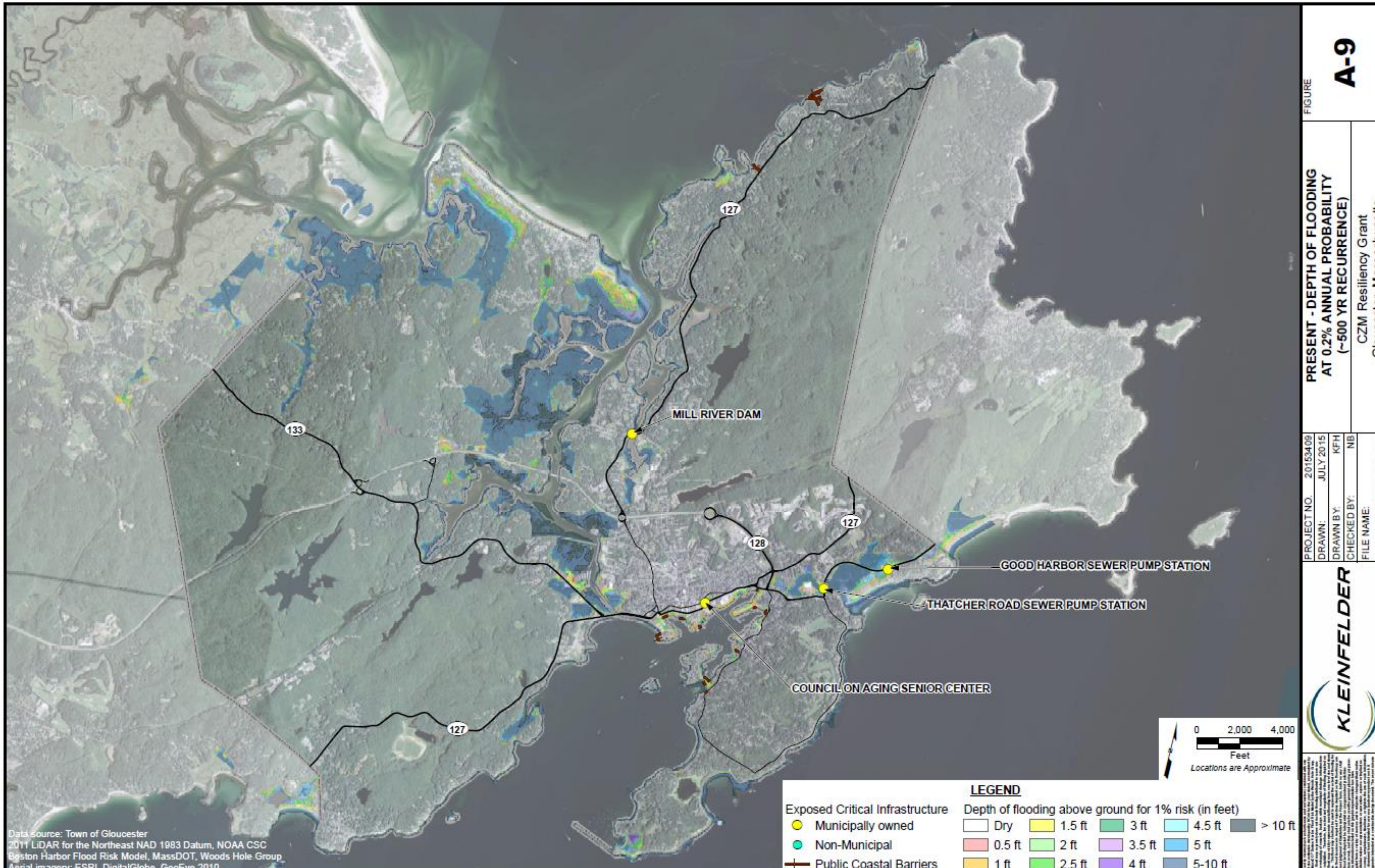
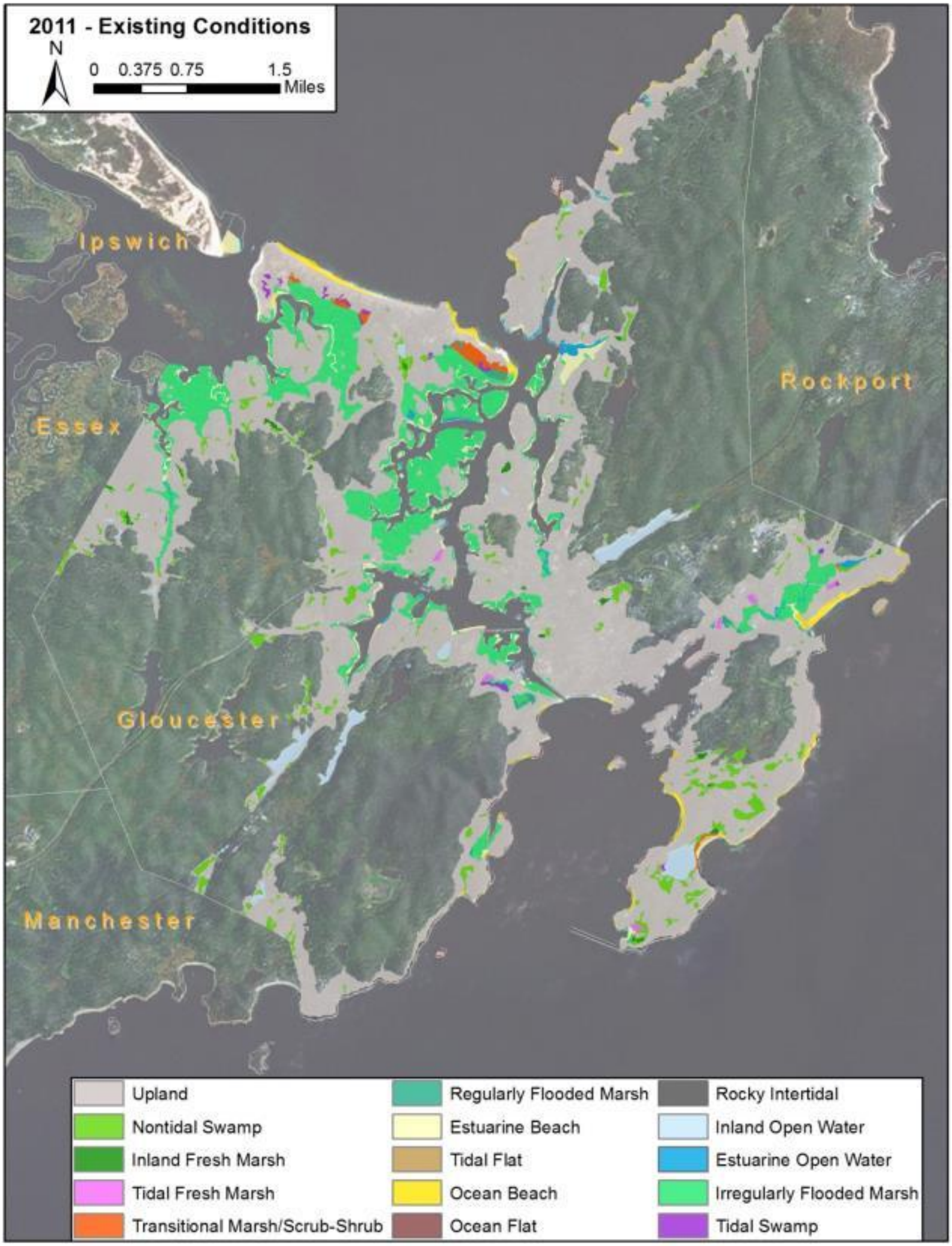
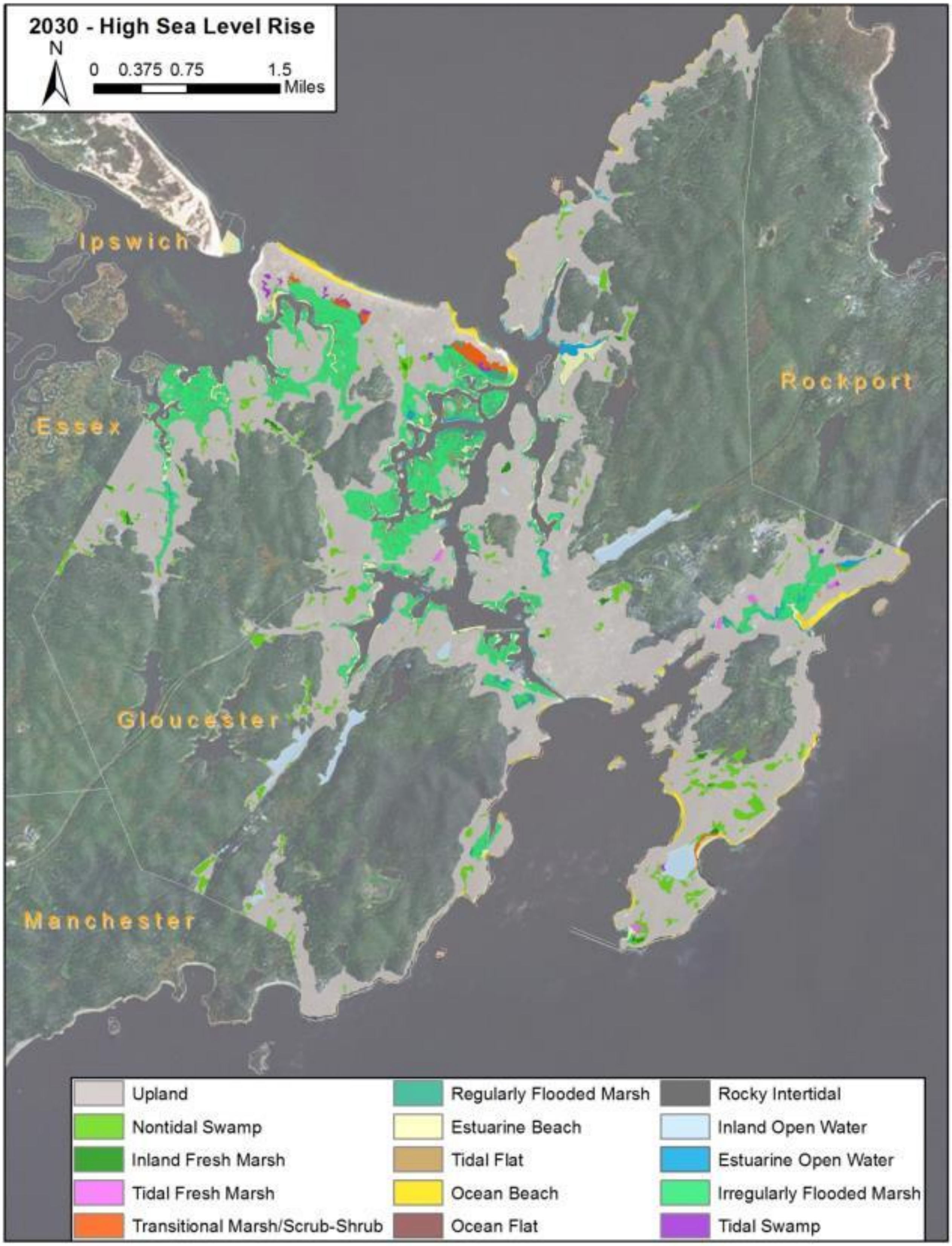
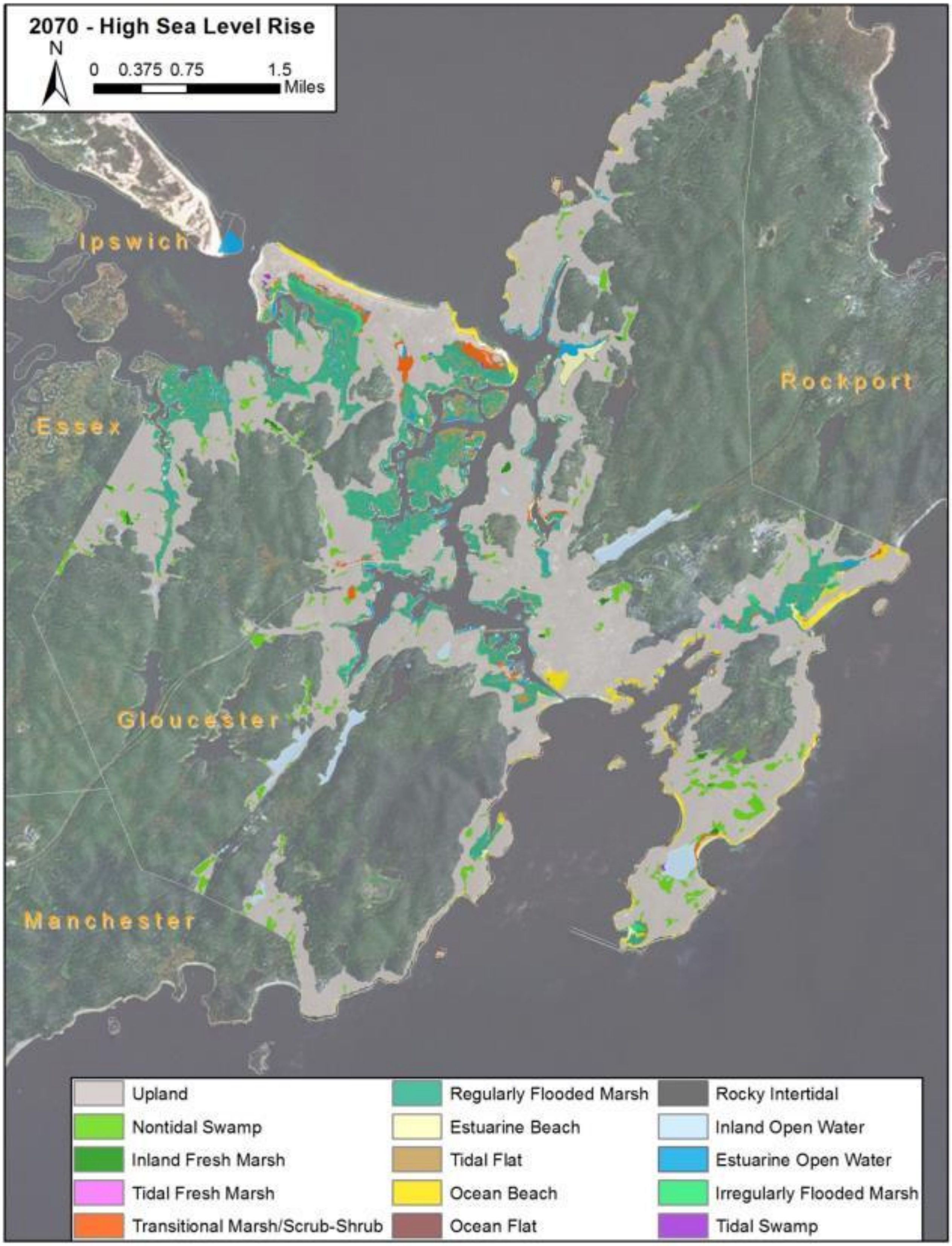


FIGURE
A-9
PRESENT - DEPTH OF FLOODING
AT 0.2% ANNUAL PROBABILITY
(~500 YR RECURRENCE)
CZM Resiliency Grant
Gloucester, Massachusetts
PROJECT NO. 20153409
DRAWN: JULY 2015
DRAWN BY: KFH
CHECKED BY: NB
FILE NAME:
KLEINFELDER
MILL RIVER DAM
GOOD HARBOR SEWER PUMP STATION
THATCHER ROAD SEWER PUMP STATION
COUNCIL ON AGING SENIOR CENTER
127
133
128
0 2,000 4,000
Feet
Locations are Approximate
LEGEND
Exposed Critical Infrastructure
Municipally owned
Non-Municipal
Public Coastal Barriers
Depth of flooding above ground for 1% risk (in feet)
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
5-10 ft
> 10 ft
Data source: Town of Gloucester
2011 LiDAR for the Northeast NAD 1983 Datum, NOAA CSC
Boston Harbor Flood Risk Model, MassDOT, Woods Hole Group
Aerial imagery: ESRI, DigitalGlobe, GeoEye 2010.

APPENDIX B – WETLAND CLASSIFICATION MAPS AND DATA


2011 - Existing Conditions
N
0 0.375 0.75 1.5
Miles
Ipswich
Essex
Rockport
Gloucester
Manchester
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp


2030 - High Sea Level Rise
N
0 0.375 0.75 1.5
Miles
Ipswich
Essex
Rockport
Gloucester
Manchester
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp


2070 - High Sea Level Rise
N
0 0.375 0.75 1.5
Miles
Ipswich
Essex
Rockport
Gloucester
Manchester
Upland
Nontidal Swamp
Inland Fresh Marsh
Tidal Fresh Marsh
Transitional Marsh/Scrub-Shrub
Regularly Flooded Marsh
Estuarine Beach
Tidal Flat
Ocean Beach
Ocean Flat
Rocky Intertidal
Inland Open Water
Estuarine Open Water
Irregularly Flooded Marsh
Tidal Swamp

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 ASSESSMENT DATA

Table C-1 Risk Assessment Summary Table for All Asset

Type	Name/Number	Address/ Location	Critical Elevation	Consequence Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score
Facility	Thatcher Road Pump Station	6a Thatcher Road	9.6	63	0.5	32	1	63	100	6333	41
Roadway	Rogers Street	From Flannigan Square to Washington Street	7.8	57	10	567	20	1133	100	5667	737
Roadway	Rocky Neck Avenue	Entire	6.3	53	50	2667	100	5333	100	5333	3467
Bulkhead/ Seawall	028-130-000-011-100	Rocky Neck Avenue	6.2	53	20	1067	100	5333	100	5333	2347
Roadway	Thatcher Road	From Bass Avenue to Rockport Town Line	7.9	53	10	533	20	1067	100	5333	693
Bulkhead/ Seawall	028-058-000-040-200	Cripple Cove Public	6.4	50	50	2500	100	5000	100	5000	3250
Facility	Good Harbor Sewer Pump Station	111 Thatcher Road	9.5	50	0.2	10	1	50	100	5000	22
Bulkhead/ Seawall	028-007-000-005-100	Harbor Cove Wharf	6.0	47	100	4667	100	4667	100	4667	4667
Revetment	028-130-000-011-200	Rocky Neck Avenue	6.0	47	100	4667	100	4667	100	4667	4667
Roadway	Commercial Street	From Washington St to Fort Square	7.3	47	20	933	100	4667	100	4667	2053
Bulkhead/ Seawall	028-007-000-016-200	Town Landing	8.6	47	2	93	5	233	100	4667	135
Bulkhead/ Seawall	028-054-000-108-200	State Fish Pier	8.8	47	2	93	5	233	100	4667	135
Roadway	Fort Square	Entire	8.7	47	1	47	5	233	100	4667	103
Revetment	028-053-000-016-100	Head of the Harbor	8.9	47	1	47	2	93	100	4667	61
Roadway	Main Street	From East Main St to Western Ave	9.0	47	0.5	23	2	93	100	4667	44
Roadway	Mansfield Way	From Main St to Rogers St	9.5	47	0.5	23	1	47	100	4667	30
Bulkhead/ Seawall	028-009-000-014-100	Solomon Jacobs Park	9.3	47	0.5	23	1	47	100	4667	30
Revetment	028-007-000-016-100	St. Peter's Marina	9.2	47	0.5	23	1	47	100	4667	30
Facility	Water Pollution Control Facility	50 Essex Avenue	10.2	93	0	0	0.5	47	50	4667	14
Roadway	Washington Street	At Hodgkins St	7.5	43	20	867	50	2167	100	4333	1257

Type	Name/Number	Address/ Location	Critical Elevation	Consequence Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score
Roadway	Washington Street	Bridge Approach	8.9	43	1	43	5	217	100	4333	95
Revetment	028-058-000-040-100	Cripple Cove Public Landing	7.1	40	25	1000	100	4000	100	4000	1900
Roadway	Parker Street	From East Main St to East Main St	7.4	40	20	800	100	4000	100	4000	1760
Roadway	Atlantic Street	From Atlantic Ave to Concord St	7.9	40	10	400	25	1000	100	4000	580
Roadway	East Main Street	From Bass Ave to Rocky Neck Ave	8.1	40	5	200	20	800	100	4000	380
Roadway	Eastern Point Road	At Rocky Neck Ave	8.4	40	2	80	5	200	100	4000	116
Roadway	Porter Street	From Rogers St to Main St	8.4	40	2	80	5	200	100	4000	116
Bulkhead/ Seawall	028-001-000-001-100	Fort Point	9.0	40	0.5	20	1	40	100	4000	26
Facility	Mill Pond Dam	Washington St at Hodgkins St	7.5	37	20	740	50	1850	100	3700	1073
Bulkhead/ Seawall	028-079-000-001-100	Robinson Landing	7.6	37	20	733	30	1100	100	3667	843
Roadway	Ye Olde County Road	East	8.0	37	10	367	25	917	100	3667	532
Roadway	River Road	From Bridgewater St to Leonard St	8.5	37	2	73	5	183	100	3667	106
Roadway	Ye Olde County Road	West	10.1	37	0	0	1	37	100	3667	11
Bulkhead/ Seawall	028-064-000-061-100	East Main Street	10.0	37	0	0	0.5	18	100	3667	6
Roadway	Beach Court	From Commercial St to Dead End	7.0	33	25	833	100	3333	100	3333	1583
Roadway	Witham Street	From Beachcroft Rd to Salt Island Rd	7.5	33	20	667	50	1667	100	3333	967
Breakwater	028-142-000-052-100	Lanes Cove	8.0	30	10	300	20	600	100	3000	390
Roadway	Concord Street	Near Landing Rd	9.1	30	0.5	15	2	60	100	3000	29
Bulkhead/ Seawall	028-142-000-038-200	Lanes Cove	7.0	27	25	667	100	2667	100	2667	1267
Bulkhead/ Seawall	028-142-000-038-100	Lanes Cove	8.0	27	10	267	20	533	100	2667	347

Type	Name/Number	Address/ Location	Critical Elevation	Consequence Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score
Bulkhead/ Seawall	028-131-000-018-100	Wonson Cove	8.3	27	5	133	5	133	100	2667	133
Facility	Council on Aging Senior Center	6 Manuel Lewis Street	9.6	53	0.2	11	0.5	27	50	2667	15
Roadway	Causeway Street	From Concord St to Yankee Division Highway (Rt 128)	6.3	23	50	1167	100	2333	100	2333	1517
Roadway	Leslie O Johnson Road	Entire	6.4	23	50	1167	100	2333	100	2333	1517
Bulkhead/ Seawall	028-139-000-010-100	Washington Street	9.1	23	0.5	12	1	23	100	2333	15
Roadway	Manuel F Lewis Street	From Rogers St to Main St	10.3	47	0	0	0.5	23	50	2333	7
Roadway	Centennial Avenue	From Washington St to Western Ave	6.4	20	50	1000	100	2000	100	2000	1300
Breakwater	028-142-000-038-400	Lanes Cove	6.9	20	30	600	100	2000	100	2000	1020
Revetment	028-142-000-038-300	Lanes Cove	7.0	20	25	500	100	2000	100	2000	950
Roadway	Gaffney Street	Entire	7.2	20	20	400	50	1000	100	2000	580
Roadway	Hodgkins Street	From Wesley St to Washington St	8.0	20	10	200	25	500	100	2000	290
Roadway	Hartz Street	From Bass Ave to Eastern Ave	8.0	20	10	200	20	400	100	2000	260
Roadway	Stevens Lane	From Rocky Neck Ave to Wonson St	8.1	20	10	200	20	400	100	2000	260
Roadway	Wonson Street	From Rocky Neck Ave to Clarendon St	8.8	20	1	20	5	100	100	2000	44
Roadway	Marina Drive	Entire	9.5	20	0.5	10	1	20	100	2000	13
Roadway	Nautilus Road	Entire	9.4	20	0.5	10	1	20	100	2000	13
Roadway	Veterans Way	Entire	9.9	20	0.5	10	1	20	100	2000	13
Roadway	Sumner Street	From Concord St to Essex Ave	10.0	20	0.2	4	1	20	100	2000	9
Facility	Parker Street Sewer Pump Station	20 Parker Street	10.4	63	0	0	0	0	25	1583	0
Roadway	Holly Street	From Washington St to Dennison St	10.4	30	0	0	0.5	15	50	1500	5
Facility	Hodgkins Street Sewer Pump Station	382a Washington Street	10.6	50	0	0	0.2	10	30	1500	3

Type	Name/Number	Address/ Location	Critical Elevation	Consequence Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score
Roadway	Bass Avenue	At Hartz Street	10.8	50	0	0	0	0	30	1500	0
Facility	Reynard Street Sewer Pump Station	Reynard Street at Washington Street	10.8	53	0	0	0.5	27	25	1333	8
Facility	Corliss Avenue Sewer Pump Station	Corliss Avenue	11.0	50	0	0	0.2	10	25	1250	3
Facility	DPW Sewer Pump Station	26 Poplar Street	11.0	50	0	0	0.1	5	20	1000	2
Roadway	Eastern Point Boulevard	Eastern Point Blvd to Dead End	10.9	40	0	0	0	0	25	1000	0
Bulkhead/ Seawall	028-003-000-072-200	Stacey Boulevard - West	11.0	50	0	0	0	0	20	1000	0
Bulkhead/ Seawall	028-003-000-072-100	Stacey Boulevard - West	11.0	50	0	0	0	0	20	1000	0
Bulkhead/ Seawall	028-003-000-072-400	Stacey Boulevard - East	11.0	50	0	0	0	0	20	1000	0
Bulkhead/ Seawall	028-003-000-072-300	Stacey Boulevard - East	11.0	50	0	0	0	0	20	1000	0
Roadway	Middle Street	From Western Ave to Pleasant St	10.7	30	0	0	0	0	30	900	0
Roadway	Concord Street	Near Cedarwood Rd	10.9	30	0	0	0.5	15	25	750	5
Roadway	Farrington Avenue	From Atlantic Rd to Eastern Pt Blvd	10.9	30	0	0	0	0	25	750	0
Roadway	Concord Street	Near Sumner St	10.7	23	0	0	0.5	12	30	700	4
Roadway	Kent Circle	From Western Ave to Essex Ave	11.2	33	0	0	0.2	7	20	667	2
Roadway	Poplar Street	From Washington St to Maplewood Ave	11.4	33	0	0	0	0	20	667	0
Roadway	Concord Street	Near Cabot Ln	11.3	30	0	0	0	0	20	600	0

Type	Name/Number	Address/ Location	Critical Elevation	Consequence Score	Present Probability (%)	Present Risk Score	2030 Probability (%)	2030 Risk Score	2070 Probability (%)	2070 Risk Score	Composite Risk Score
Facility	Department of Public Works	26 Poplar Street	11.2	57	0	0	0	0	10	567	0
Roadway	Hampden Street	From Hovey St to Granite St	10.9	20	0	0	0.5	10	25	500	3
Roadway	Mondello Square	From Bass Ave to Dead End	11.0	20	0	0	0	0	20	400	0
Roadway	Harbor Loop	From Rogers St to Rogers St	11.7	33	0	0	0	0	10	333	0
Roadway	Leonard Street	From Washington St	11.7	20	0	0	0	0	10	200	0
Roadway	Dennison Street	From Washington St to Dead End	12.3	33	0	0	0	0	5	167	0
Roadway	Sayward Street	From East Main St to Bass Ave	12.3	20	0	0	0	0	5	100	0
Facility	Gloucester High School	32 Leslie O Johnson Road	12.7	67	0	0	0	0	1	67	0
Roadway	Reynard Street	From Cherry St to Washington St	13.2	47	0	0	0	0	1	47	0
Facility	Emergency Dispensing Site	32 Leslie O Johnson Road	12.7	40	0	0	0	0	1	40	0
Bulkhead/ Seawall	028-133-000-017-100	Niles Beach	13.0	33	0	0	0	0	1	33	0
Roadway	Washington Street	At Lanes Cove	13.5	50	0	0	0	0	0.5	25	0
Roadway	Fremont Street	From Wonson St to Dead End	13.0	20	0	0	0	0	1	20	0
Roadway	Magnolia Avenue	From Essex Ave to Raymond St	13.3	20	0	0	0	0	1	20	0
Revetment	028-216-000-140-200	Crescent Beach	13.4	20	0	0	0	0	0.5	10	0
Facility	Riverside Avenue Sewer Pump Station	31 Riverside Avenue	13.0	50	0	0	0	0	0.2	10	0
Facility	Beacon Marine Sewer Pump Station	239 East Main Street	9.6	63	0	0	0	0	0	0	0
Facility	Commercial Street Sewer Pump Station	91 Commercial Street	15.0	63	0	0	0	0	0	0	0
Facility	Niles Beach Sewer Pump Station	Eastern Point Blvd	15.8	50	0	0	0	0	0	0	0