Feasibility of Harbor-wide Barrier Systems

Preliminary Analysis for Boston Harbor

UMASS BOSTON Sustainable Solutions Lab

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BOSTON Green Ribbon COMMISSION

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Preliminary Analysis for Boston Harbor

Sustainable Solutions Lab,
University of Massachusetts Boston

MAY 2018

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Sustainable Solutions Lab

The Sustainable Solutions Lab (SSL) is an interdisciplinary partnership among four schools within UMass Boston: The College of Liberal Arts, College of Management, McCormack Graduate School of Policy and Global Studies, and School for the Environment. SSL's mission is to work as an engine of research and action to ensure that all residents of Greater Boston, and cities across the world, are prepared equitably for the impacts of climate change.

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The University of Massachusetts Boston is a public research university with a dynamic culture of teaching and learning, and a special commitment to urban and global engagement. Our vibrant, multicultural educational environment encourages our broadly diverse campus community to thrive and succeed. Our distinguished scholarship, dedicated teaching, and engaged public service are mutually reinforcing, creating new knowledge while serving the public good of our city, our commonwealth, our nation and our world.

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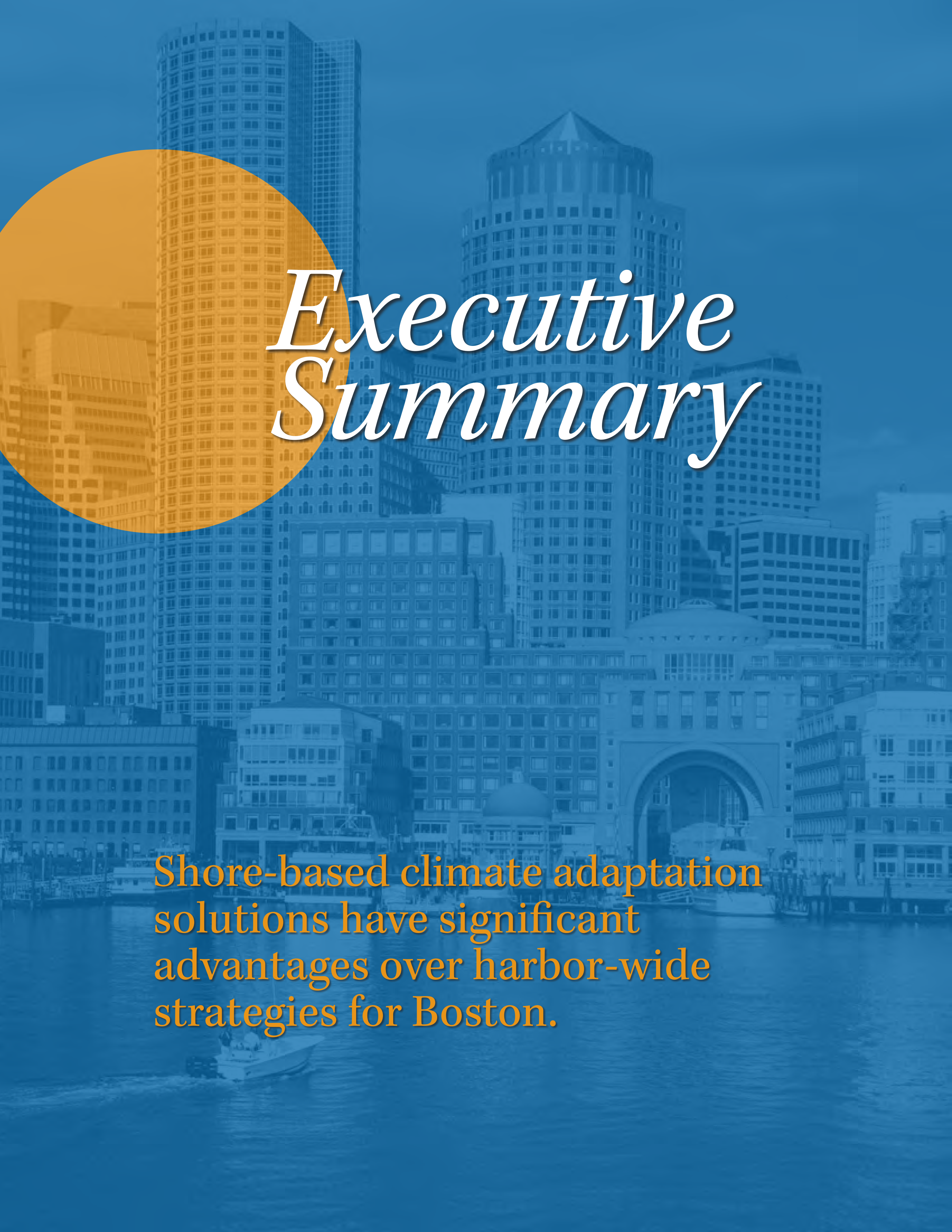


Executive Summary

Shore-based climate adaptation solutions have significant advantages over harbor-wide strategies for Boston.

As sea levels rise and climate change poses a growing threat, Boston and neighboring cities and towns along Boston Harbor and the Massachusetts coastline need to prepare. In 2016, the City of Boston began organizing a citywide response to climate change called Climate Ready Boston. This project included detailed climate change projections, a vulnerability assessment, and proposals for adapting to climate change and increasing the resilience of the city to sea level rise, heat stress, and increased precipitation. One of the recommendations from this project was to launch a feasibility study for a harbor-wide flood protection system (Strategy 5.4). This study on barriers, sponsored by the Green Ribbon Commission in support of its partnership with the City of Boston on Climate Ready Boston, responds to that recommendation. It was funded by the Barr Foundation.

The aim of this study is to provide the City of Boston with a preliminary assessment of the feasibilities and potential benefits, costs, and environmental impacts of three harbor-wide barrier configurations. The analysis was conducted by a multidisciplinary team of environmental scientists, engineers, economists, planners, and lawyers, drawing upon a wide range of data about engineered flood protection systems, climate change, coastal ecosystems, and economic impacts of flooding. We focused on barrier designs and configurations that would offer protection from coastal flooding while minimizing interference with Boston's main shipping channels and the gains that have been made in water quality over the last several decades. We also examined potential conflicts with various harbor uses, and conducted a preliminary comparison with shore-based adaptation solutions (which include district-level flood barriers as well as other structural and non-structural actions), such as those already being investigated by the City of Boston along the inner harbor waterfront in East Boston, Charlestown, and South Boston. The detailed technical report contains more analysis of the issues summarized below. Because many of the results of a section depend upon results from preceding sections, it is recommended that the sections be read sequentially.

This analysis yielded these key findings:

- The two most reasonable options for a barrier system are an Outer Harbor Barrier (OHB) from Winthrop to Hull and an Inner Harbor Barrier (IHB) between Logan Airport and the Seaport area of South Boston. Each would be a gated barrier system that would only be closed during flood conditions caused by storm surge exceeding shoreline levels of flood protection.
- Either barrier system with the gates open would not attenuate the tidal range in the harbor thus not decreasing tidal flooding ("nuisance flooding") and also not causing major environmental impacts compared to the expected changes due to climate change and sea level rise.

The aim of this study is to provide the City of Boston with a preliminary assessment of the feasibilities and potential benefits, costs, and environmental impacts of three harbor-wide barrier configurations.

- In the early years of operation, the frequency of closure of a barrier would be no more than a few times per year. Because of rising sea levels, and assuming the system was designed to be closed each time the water level is above the level of protection provided by shore-based measures, after 50–60 years the frequency of closure would likely increase so much that the barrier could no longer function as designed.
- Neither barrier system appears to be cost-effective. Depending upon assumptions made on levels of shore line protection and discount rates and assuming shore-based adaptation is effective against storm surges, the benefit:cost ratios range from 0.05 to 1.69 with most being well less than 1.0. This is very unfavorable compared to benefit:cost ratios of recently designed shore-based systems in Boston of 3.22 to 5.3.
- The anticipated increased water velocity in the barrier openings could cause navigational and safety issues for both recreational and commercial vessels near the barrier openings. The Outer Harbor Barrier could also impact the abundance, distribution, and behavior of fish populations, which would in turn impact both commercial and recreational fisheries.
- The percentage of socially vulnerable people who would remain vulnerable to flooding in the case of either an IHB or an OHB being built is the same as that of the total population in all of Boston. That is, socially vulnerable populations would not have disproportionate flooding after an IHB or an OHB was built.

- Shore-based systems, including a range of measures from zoning to various kinds of green and gray protective systems deployed along the waterfront of the inner harbor, offer many advantages over harbor-wide barrier systems. These include cost-effectiveness, community co-benefits, adaptability to changing conditions over time, and protection against tidal flooding as well as surge flooding. If over time the performance and implementation of shore-based systems lag, then decisions about barriers must be re-revaluated.

If the global community is able to dramatically decrease emissions of the greenhouse gases that cause climate change, the amount of SLR that Boston will experience can be constrained to the lower end of the future projections, thereby decreasing the number of adaptation measures that will be necessary over time.

KEY RECOMMENDATION

While this study is not comprehensive, and there are many ways that further research could refine and extend its findings, those findings were clear enough to justify making recommendations for next steps. The authors recommend that the City continue to focus its climate resilience strategy for the next several decades on the shore-based multi-layered approach described in Climate Ready Boston. Shore-based solutions would provide flood management more quickly at a lower cost, offer several key advantages over a harbor-wide barrier, and provide more flexibility in adapting and responding to changing conditions, technological innovations, and new information about global sea level rise. These shore-based solutions would be needed in any case over the next few decades to manage coastal flooding during the design and construction period of a harbor-wide barrier if a decision was made to build one in the future.

Climate Context

The climate projection consensus for Boston developed by the Boston Research Advisory Group in 2016 as part of Climate Ready Boston looked at extreme heat and cold, sea level rise (SLR), extreme precipitation, drought, and coastal storms for the region. Depending on how effectively the international community is able to curb global emissions, compared to 2013 the Boston area could experience 6 inches to 1.2 feet of relative SLR by 2050, and 1.8 to 7.3 feet by 2100. Changes in the future intensity and frequency of extratropical storms (nor'easters) are uncertain; there is more certainty, however, that the intensity of tropical storms (hurricanes) may increase. Even if the region does not see an increase in storm intensity, the storms that do occur will cause more flooding when combined with sea level rise. The biggest unknown in these projections—the reason why the ranges are so broad later on in the 21st century—is the amount of greenhouse gas reduction that will be achieved. If the global community is able to dramatically decrease emissions of the greenhouse gases that cause climate change, the amount of SLR that Boston will experience can be constrained to the lower end of the future projections, thereby decreasing the number of adaptation measures that will be necessary over time.

Given the preliminary nature of this analysis, only one scenario of sea level rise and associated flooding was analyzed compared to 2013. This is approximately 1 foot of relative SLR by 2030, 3 feet by 2070, and 5 feet by 2100. This is approximately equivalent to the IPCC RCP4.5 sea level rise scenario, a moderate scenario.

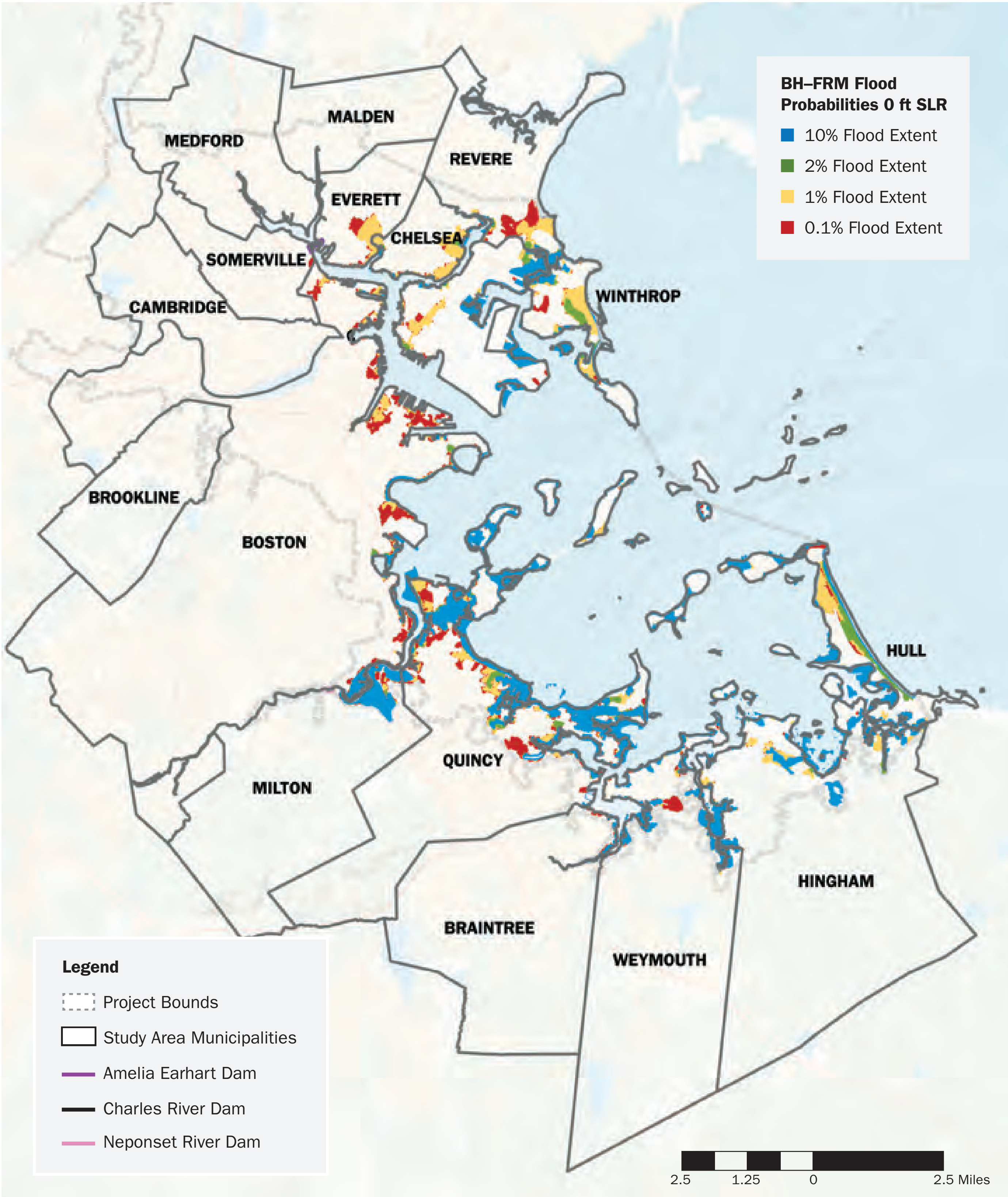
Figure ES.1 shows the present extent of storm surge coastal flooding in Boston Harbor. Figure ES.2 shows the extent of surge flooding with 5 feet of SLR.

Possible Barrier Configurations

This analysis assumes that the goal is not only to provide flood protection from storm surge to Boston and neighboring cities and towns along Boston Harbor, but also to maintain present and future commercial shipping and other navigation, and to preserve as much as possible the present ecological services of Boston Harbor in light of climate change. Commercial and recreational navigation is critical to Boston's historical identity as a maritime city and to its current economy. Likewise, hard-won environmental improvements in Boston Harbor over the past few decades have provided great benefits to the city and its natural resources. It is worth noting that the project team considered evaluating in detail a Metro Dike Barrier which would be an arc in deep water from Swampscott to Cohasset (see Figure ES.3). This system would have locks that would create a major impediment to traffic in and out of the

FIGURE ES.1

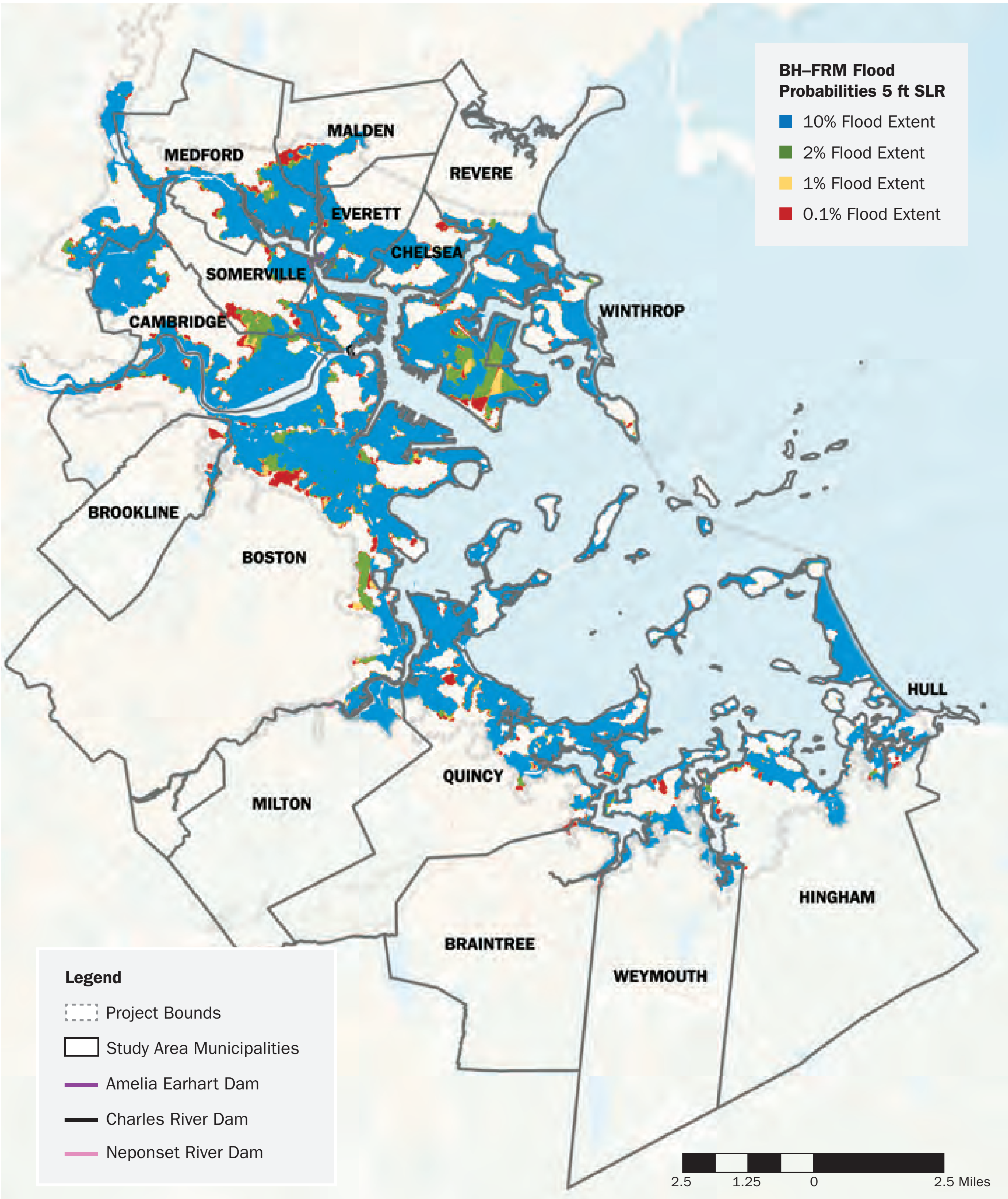
Boston Harbor Barrier—Probabilities of Flooding with 0 Feet SLR



Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

FIGURE ES.2

Boston Harbor Barrier—Probabilities of Flooding with 5 Feet SLR



Source: MassGIS, UMass Boston, Woods Hole Group, Esri harbor and hamper water exchange and, as a result, did not meet the criteria of minimally impacting shipping and navigation and ecological services. In addition, this system would be very expensive ($35–$85 billion) and difficult to construct. Therefore, this configuration was dismissed early in the project.

This analysis looked at two main options similar to those proposed by Climate Ready Boston (2106) (see Figure ES.3):

1. The Outer Harbor Barrier (OHB), a gated barrier system that would only be closed during flood conditions caused by storm surge; the OHB would cover 3.8 miles from Winthrop to Hull, with additional 9.3 miles of shore-based protection in Hull, Winthrop, and Revere to prevent floods from flanking the barrier from the ocean.
2. The Inner Harbor Barrier (IHB), a gated barrier system that would only be closed during flood conditions caused by storm surge; the IHB would be in the passage between Logan Airport and the Seaport area of South Boston. It would require approximately 18 miles of shore-based protection systems to its north and south. This configuration assumes that the barrier and shore-based system could be designed for compatibility with Logan Airport operations.

The largest of the two gates of the OHB considered for this study would be the largest built thus far and its in-water span length the longest in the world. Opening and closing gates of these types of barriers is a cumbersome process that takes several hours. The gates of these types of barriers are designed for a small number of closures over a year or more, and with SLR would be closed more frequently. For example, the gates discussed in this analysis are similar in scale to the Maeslant Barrier protecting Rotterdam. It was designed for a closure frequency of approximately once every 10 years. Studies suggest that rising sea levels could increase its closure frequency to once every 3.2 years in 2050 and once every 1.1 years in 2100.

Conceptual Designs and Costs

OUTER HARBOR BARRIER

We chose a configuration for the OHB that would make use of Lovells, Gallops, and Georges Islands and stretches of shallow water, minimizing materials needed for construction, and avoiding impacts to shipping channels. It would have two floating leaf sector gates; the northern one in the President Roads navigation channel with an average low tide depth of 35 feet (soon to be dredged to 45 to 51 feet), and the southern one in the Nantasket Roads channel with an average low tide depth of 32 feet. Each floating leaf sector gate consists of two leaves that are closed only during storms. The total width of the northern barrier would be 1500 feet—making it the largest gate system of this type yet constructed—and the width of the southern barrier would be 650 feet. This design is based on the minimum navigation size according to the US Army Corps of Engineers. Vertical lift gates (smaller, non-navigable openings that can be shut during storms but allow some tidal exchange when open) would also be built into the barrier to mitigate some of the localized negative water quality impacts. Since securing enough clean and compatible sediment to build a natural barrier would

FIGURE ES.3

Barrier Alternatives in Boston Harbor

Sources: Arcadis, Esri World Imagery

be a challenge, the barrier would be constructed of gray (e.g., concrete and steel) features and then could be “greened” (covered to form a core of an island or land mass) over time as additional funds and sediments were identified. It would be possible to increase the height of the barrier if necessary after it was constructed, but not the height of the sector gates. As a result, this solution is not fully adaptable to the uncertainties of sea level rise.

The modeling indicated that there would be no tidal attenuation caused by the gate openings in either the OHB or the IHB. Thus a barrier would not protect Boston Harbor from nuisance flooding associated with sea level rise and normal tidal cycles without closure of the gates.

Total design, engineering, permitting, and construction costs could range from $8.0–$11.8 billion (2017 dollars) with annual operation and maintenance costs estimated at approximately 1% of total construction costs. Over 60% of the costs are for the floating sector gates. Given the extensive time to design, permit, finance, and construct the project, including the several miles of structures and berms needed to prevent flanking of the barrier to the north and south, the earliest it could be functioning would likely be 2050.

INNER HARBOR BARRIER

The main channel at the location of the IHB is approximately 1,200 feet wide with depths of approximately 35 to 40 feet. This would be spanned by one large floating leaf sector gate and artificial islands to support the leaves when the gate is open. No vertical lift gates would be needed. Pumps would be needed at the IHB to adequately control upstream freshwater levels during times when the IHB is closed because of a storm surge, as the closed gate would block the egress of flood water from the inner harbor. The pumps would maintain the water elevation inside the barrier with the goal of allowing the Charles River and Amelia Earhart dams not to close or pump, or at least to pump less frequently.

Total design, engineering, permitting, and construction costs could range from $6.5–$8.7 billion (2017 dollars), including the many miles of structures and berms needed to prevent flanking. Approximately 60% of the cost is the floating sector gate. Annual operation and maintenance costs are estimated at approximately 1% of total construction costs. Given the proximity to Logan Airport, Massport and FAA regulations governing the air space around the airport must be considered as well. Preliminary analysis indicates that the height of the barrier is likely less than the air-space requirements at this location, but this aspect would require further investigation if more detailed planning and design for a barrier are ever pursued for this site.

Hydrodynamic Analysis

We applied the Boston Harbor Flood Risk Model (BH-FRM), used in both the Boston Central Artery/Tunnel project and Climate Ready Boston, to determine hydrodynamic conditions with and without harbor-wide barriers. Conditions were analyzed for relative SLR scenarios of 0, 1, 3, and 5 feet since 2013. The 1 and 3 feet scenarios are approximately the same as used in the vulnerability assessment conducted for Climate Ready Boston.

TIDAL ATTENUATION

One of the key questions this research sought to answer was whether building a barrier in the harbor would impact the tides, as well as provide protection from storm surge. Would it be possible to lower the high tide, and as a result, protect the waterfront from tidal flooding exacerbated by SLR and moderate storm surge flooding for the medium term without even closing the gates? Because the openings are so large, the modeling indicated that there would be no tidal attenuation caused by the gate openings in either the OHB or the IHB. Thus a barrier would not protect Boston Harbor from nuisance flooding associated with sea level rise and normal tidal cycles without closure of the gates.

Since there is no tidal attenuation, the quantity of water entering and leaving the harbor during tide conditions would not change significantly. The openings through which the water would flow, however, would be much smaller. As a result, significant changes in current velocities in the vicinities of the OHB gates openings would be expected. At normal flood tide, the peak velocity through the northern gate could increase from approximately 2 feet per second to 5 feet per second (1.2 knots to 3 knots). For the southern gate, the peak velocity could increase approximately 2 feet per second to

8 feet per second (1.2 knots to 4.8 knots). These high velocities would make navigation challenging for certain vessels. Therefore, it is unlikely that entry and exit into the harbor would be available throughout the entire tidal cycle, especially for recreational boats with limited power. At the same time, some new zones of stagnation in the harbor would be expected.

In our analysis, we found there were no differences in circulation dynamics outside of the OHB when the barrier was open under normal tidal conditions compared to present circulation. With the gates closed during storms, however, local circulation dynamics outside of the barrier would change. In particular, the flood tidal currents with the gates closed during storms could be perpendicular to the coast of Hull instead of generally parallel now—potentially increasing erosion on the Hull coastline.

The IHB would have minimal impact on the tides and currents in the harbor since the gate opening is not much less than the width of the current channel.

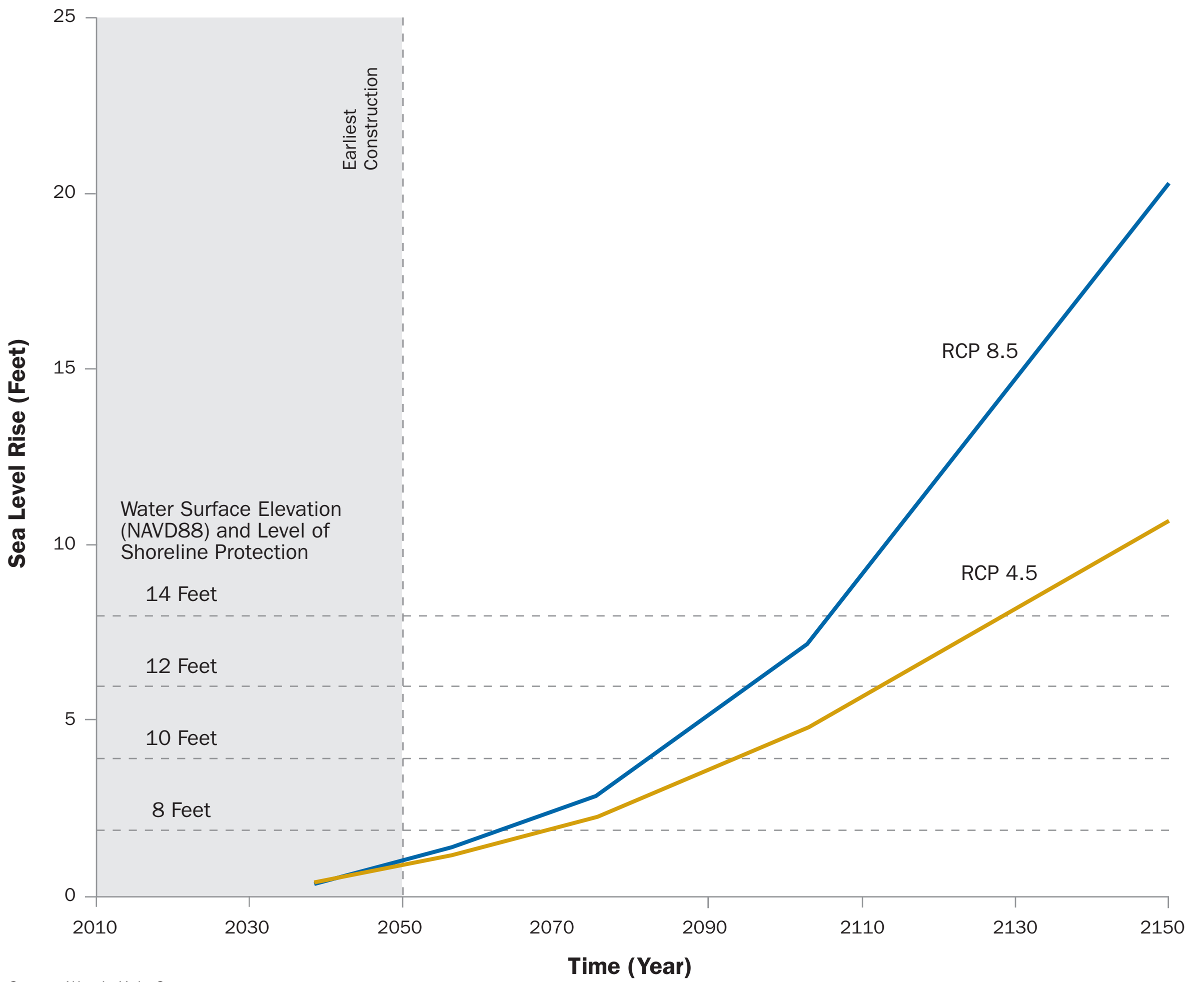
CLOSURE ANALYSIS

As described earlier, barriers of the size discussed in this project are not designed to open and close frequently. Any increase in closure frequency leads to higher risks of mechanical failure, environmental impacts, and shipping disruption, among other impacts. This analysis assumes that the maximum number of times the gates could be closed per year is fifty. This is a very high number (approximately once per week) compared to how often comparable systems worldwide are designed to close. We drew upon the historical record of tides and storms in Boston with projected sea level rise to forecast how many years after barrier construction the annual gate closure would exceed this number.

As shown in Figure ES.4, the closure analysis found that with no additional shore-based protection compared to the present (present protection is assumed to be 10 feet NAVD88—the approximate elevation of the present 1% storm), a barrier system under RCP 4.5 would be functional to approximately 2100 if it were able to close 50 times per year (the number of closures in earlier years would be considerably less, no more than a few times per year, if that). If fewer closures were permitted, the functional life decreases. At the end of this period, it would no longer be feasible to close the barrier gate sufficiently often to manage all storm surge events greater than 10 feet NAVD88. Similarly, if shore-based protection was at 12 feet NAVD88, the functional period would end in approximately 2110 (note in the subsequent economic analysis, this time was assumed to be

FIGURE ES.4

End of Functional Period of a Barrier System with Various Levels of Shoreline Protection



Source: Woods Hole Group

2100). With 14 feet NAVD88 shore-based protection, the functional period would end in 2130.

At the end of these periods, a barrier could still be used to lessen the impacts of the increasing number of storm surges, but not eliminate them as before.

Environmental Impacts

Environmental impacts of an inner and outer harbor barrier were considered under present and future (with 5 feet of SLR) conditions. Because of the tidal attenuation finding mentioned above, it was assumed that the presence of either barrier would not affect the tidal range in the harbor, and that the barriers would be closed for 46 to 84 hours during a nor'easter to reduce storm surge—less during a hurricane. This environmental assessment is based on an assumption of several (3-10) closures per year for major storms. Under future scenarios of up to weekly closures for regular tidal flooding, the environmental impacts are not discussed in detail in this report.

It should be noted that the environmental condition of Boston Harbor has undergone great change in its history with slow degradation before and rapid improvement after 1990 and the Boston Harbor Cleanup. Boston Harbor is currently undergoing, and will continue to undergo, great change with expected sea-level rise and a temperature increase of about 2.7 to 3.7 C by 2100. The future impacts of a harbor-wide barrier, then, must be considered in the context of other ongoing and anticipated changes in the harbor environment.

It does not appear that the construction of the OHB or the IHB would cause any irreversible negative transformations of the entire harbor environment in terms of water quality, habitat quality, or ecosystem services. While there are some foreseeable impacts, most of these are modest or limited spatially or temporally. For a great part of the harbor system, 5 feet of SLR and expected increases in sea surface temperature could cause more environmental impact than the construction of a harbor-wide barrier. In a separate analysis, these overall findings were confirmed. The team analyzed the change in the economic value of ecological services in Boston Harbor with and without a barrier assuming marshes could migrate inland as SLR occurred. This analysis showed some change in services due to the barrier, but it was not dramatic.

Economic Analysis

The economic feasibility of a harbor-wide barrier is based upon its benefits and costs. Damages avoided by the barrier system are the economic benefits. The benefit:cost analysis was done for several levels of shore-based protection implemented in different time periods with low and high estimates of project costs and discount rates.

The results are approximately the same for the IHB and the OHB. As in the case of the closure analysis, the benefits of a barrier system depend upon the elevation of shore-based adaptation. If the shore-based systems are effective in managing flooding, and a barrier is designed to manage all the events greater than the elevation of the shore-based protection, the benefit:cost ratios (BCR) of any barrier system are low—ranging from 0.05 to 0.33 for 7% discount rate and from 0.20 to 1.69 for 3% discount rate. If the shore-based measures are not effective, and a low discount rate of 3% is used, then in some cases, particularly if a barrier is built in 2050, the BCR may be more favorable (as high as in the range of 3.69–5.42). Under the higher discount rate of 7% and ineffective shore-based adaptation, most of the BCRs are less than 1.0. The results indicate a low cost-effectiveness of barrier systems if shore-based systems function as designed.

Since this analysis differs from Climate Ready Boston (2016) in both the approach and data used due to the size of the study area and project constraints, the expected benefits for some subareas of Boston in this analysis could be as much as 50% less than the benefit values using the methodology of CRB (2106). Even if this were the case in all subareas, if shore-based adaptation is effective, the BCRs are still less than 1.0 in most cases.

If the shore-based systems are effective in managing flooding, and a barrier is designed to manage all the events greater than the elevation of the shore-based protection, the benefit:cost ratios (BCR) of any barrier system are low.

The low BCRs for the barrier configurations we investigated in this study are likely to make eligibility for federal funding very challenging, if not impossible.

Shipping and Recreational Use Analysis

One of the guiding assumptions of this analysis was the importance of finding a solution that would minimize the disruption of the various uses of Boston Harbor. Many commercial and recreational activities occur within Boston Harbor. This analysis determined that the proposed inner and outer barriers could have both positive and negative impacts on these activities. Generally speaking, the proposed barriers would provide added protection to activities occurring within the harbor—including commercial shipping and fishing, and recreational boating and fishing—as they would protect shoreside infrastructure and vessels from storm turbulence and flooding.

The openings to the barriers would generally accommodate federal requirements for navigation channels, minimizing impacts to commercial vessels entering and exiting Boston Harbor (including the new post Panamax vessels for which Massport is enlarging its facilities at Conley Terminal). Vessels would not be able to enter or exit when the barriers are closed, and would have to plan travel in advance of closing.

The anticipated increased water velocity in the barrier openings could cause navigational and safety issues for both recreational and commercial vessels near the barrier openings. Additionally, there could be greater vessel congestion near the openings in the OHB, especially the northern barrier opening as its water velocity is expected to be more manageable than the southern barrier opening. The OHB could also impact the abundance, distribution, and behavior of fish populations, which would in turn impact both commercial and recreational fisheries.

Social Vulnerability Analysis

The social vulnerability analysis sought to determine the impact an IHB or an OHB would have on socially vulnerable populations as compared to the broader population. In particular, the analysis sought to understand if a barrier system would inadvertently disproportionately impact socially vulnerable populations.

Importantly, the analysis found that there is not a disproportionate negative impact on vulnerable populations from either the IHB or OHB. More specifically, the percentage of socially vulnerable people who would remain vulnerable to flooding if a barrier were to be constructed is not different from the percentage of socially vulnerable population in Boston as a whole. This analysis did not look at different factors that would allow socially vulnerable populations to recover from a storm or take into account the disparate challenges that different groups have after an emergency event. Instead, the focus was on exposure to flooding caused by storm events.

Comparison to Shore-Based Adaptation

While this study focused primarily on the feasibility of different harbor-wide barrier systems, a decision about whether or not to build a barrier should not be made in isolation but in comparison with other options. Our analysis identified several key advantages that shore-based solutions have over a single harbor-wide barrier.

MULTI-FACETED OPTIONS

Shore-based adaptations can fall under the general categories of protection, accomodation, and retreat. Within each of these categories, a mix of different strategies exists. These include policy-level actions such as flood insurance, zoning, or managed retreat from the coast. Shore-based protection systems can include "green" and/or "gray" approaches to flood walls, elevation of land using berms and other features, additions of transparent flood barriers, and temporary flood walls that can be deployed in advance of impending floods. They can be employed at the regional scale or the individual asset scale, and if designed correctly, can provide multiple layers of effectiveness and safety. In addition, they can provide management of high tide nuisance flooding, which harbor-wide barriers do not. Most of the shore-based solutions provide many co-benefits such as recreation, public access, open-space, and urban heat island cooling. These co-benefits might be particularly important in communities suffering from environmental and social injustice.

FLEXIBILITY AND ADAPTABILITY

Another advantage of shore-based solutions is that they provide a flexible, adaptive management approach to coastal protection. As a result, responses can be implemented over time as SLR and flooding increases, projections improve, and more is known about future socio-economic conditions.

RISK MANAGEMENT

The risk of singularly relying on a barrier, even if technology could be developed to ameliorate the concerns around closure frequency, is that if completion is delayed or the barrier is less effective than designed, then the City and the region may be left completely exposed, and in the words of Climate Ready Boston, having "catastrophic" results.

BETTER BENEFIT-COST RATIOS

The benefit-cost ratios at a 7% discount rate of harbor-wide barriers that effectively manage flooding above the level of shoreline protection range from 0.05 to 0.33.

For the same level of protection at the same discount rate (7%) and a shorter functional lifetime (20 years), Climate Ready Boston estimates a benefit-cost ratio of 3.22 to 5.3 for a shore-based flood protection system in the Greenway/Border Street area of East Boston, and a benefit-cost ratio of 4.3 to 7.9 for a shore-based protection project for Charlestown. Therefore, shore-based adaptation approaches, at least for these two districts, appear far more cost effective.

More evidence of the cost effectiveness of shore-based adaptation compared to harbor-wide barriers can be shown by examining a potential choice point the city of Boston could face in the future. If the city is protected to 14 feet NAVD by only shore-based protection, at a certain point that amount of protection will no longer be sufficient. Leaders will need to decide on additional protections.

Assuming shoreline protections can be built up, this would cost an estimated $508 million (2017 dollars based on $4,500 per linear foot for additional walls and $2,250 to expand existing walls) to provide protection equivalent to the Outer Barrier for Boston. Even assuming that the City of Boston would not pay for the entire cost "of building a barrier, the cost of shore-based protections is dwarfed by the potential cost of a barrier which could be $8–$12 billion.

Findings and Recommendations

Based upon the analyses conducted for this report, it is clear that shore-based adaptation strategies, if effective, have significant advantages over harbor-wide strategies for Boston, at least for the next few decades when a decision on a harbor-wide barrier could be re-examined if shore-based systems are not effective. The same finding likely applies to other municipalities in Boston Harbor.

KEY FINDINGS

The analysis has shown that while a harbor-wide barrier system could manage some coastal flooding with perhaps minimal environmental impacts and moderate impacts on harbor users, its cost-effectiveness is low and its operational life would be limited. With limited potential to adapt or adjust the barrier once it is in place, it could be challenging to respond to the uncertainties of climate change over time. The alternative of a wide spectrum of shore-based, district-level solutions located around the inner harbor waterfront, however, has the potential for high cost-effectiveness, and has several key advantages. With proper planning and design, these solutions have the potential to incorporate multiple levels of protection, manage coastal flooding, provide flexibility and adaptability, offer co-benefits that address social justice, endure for long operational lifetimes, and carry minimal impacts to the environment and harbor users.

KEY RECOMMENDATION

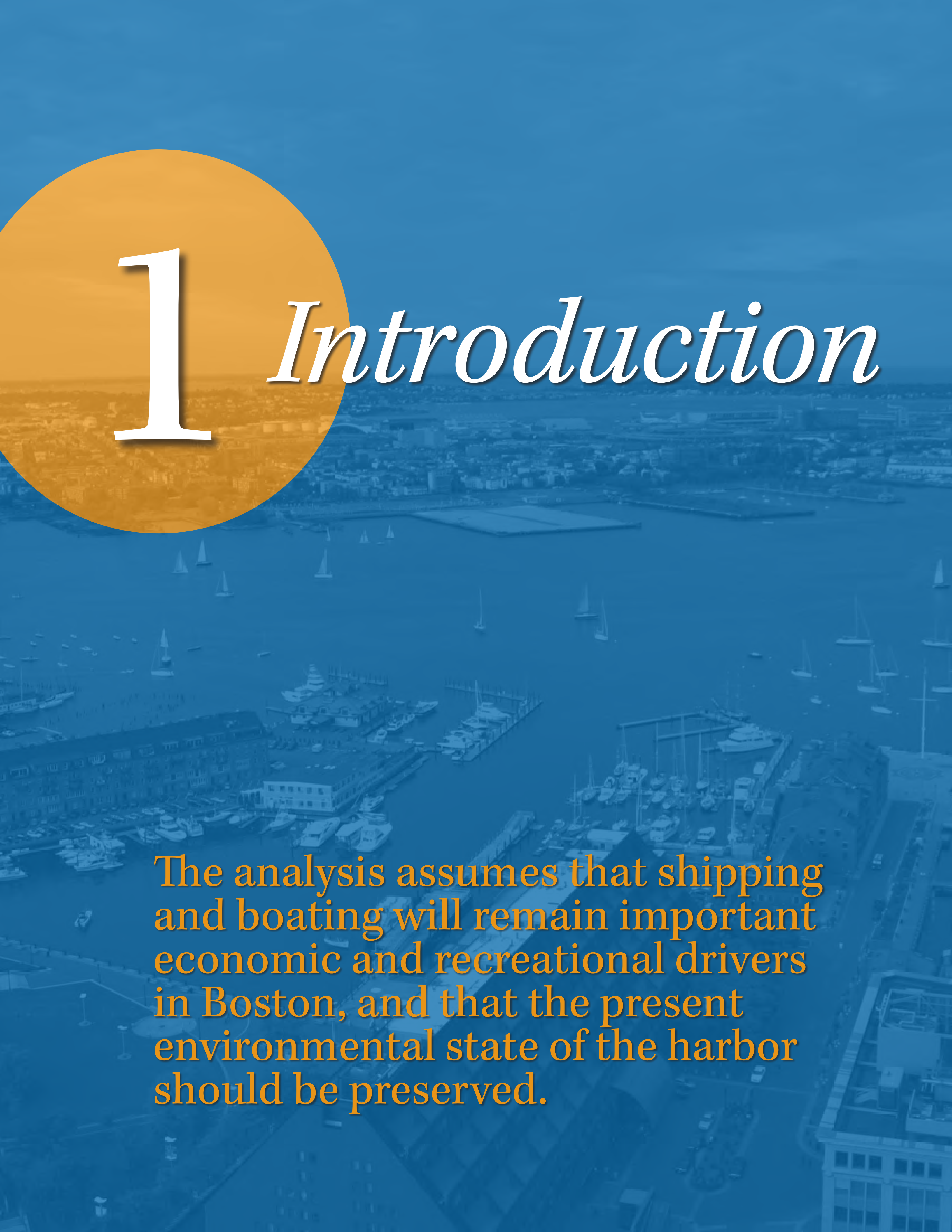
The authors recommend that the City continue to focus its climate adaptation strategy for the next several decades on the multi-layered, shore-based approach described in Climate Ready Boston (2016). Within a few decades, more will be known about the rate of sea level rise, the effectiveness of shore-based solutions, and technological advances that could improve the feasibility and cost of harbor-wide barrier systems. In the meantime, focusing on shore-based solutions will provide flood protection more quickly at less cost. These shore-based solutions would be needed in any case over the next few decades to manage coastal flooding during the design and construction period of any harbor-wide barrier if it is decided to build one in the future. Shore-based solutions are also more adaptive and can provide substantial co-benefits, while protecting the harbor's surrounding communities from sea level rise and storm surge. Any future barrier would probably best be used to complement shore-based systems by managing very large floods with the shore-based systems managing smaller events and helping to manage the very large events. This would limit the annual number of closures of a future barrier system. The decision regarding a barrier is very much dependent upon the future risk tolerance of the city and the performance of shore-based systems.

It will be especially important to monitor the actual and projected pace of sea level rise in Boston Harbor over the next several decades to determine whether shore-based solutions being implemented in Boston and adjacent cities will be adequate.

ADDITIONAL RECOMMENDATIONS

While moving forward with a harbor-wide barrier is not prudent, we recommend that the City continue to monitor climate, environmental, economic, and social changes, the risk tolerance of the city, the continuing evolution of the technology of harbor-wide barriers, and the global experience with existing storm surge barrier systems, to determine if the feasibility of a harbor-wide barrier should be re-examined at some point in the future. It will be especially important to monitor the actual and projected pace of sea level rise in Boston Harbor over the next several decades to determine whether shore-based solutions being implemented in Boston and adjacent cities will be adequate for the remainder of the century and beyond.

If the feasibility of a harbor-wide barrier is reexamined at some point, there are several engineering, hydrodynamic, environmental, climate, economic, and planning analsyes that would warrant more detailed examination than was conducted for this study. Regardless, the City should undertake strong greenhouse gas mitigation actions in concert with cities and nations globally to lessen the rate of climate change. Strong mitigation starting now could limit SLR by 2100 to 2 or 3 feet or less. This would greatly reduce the need for future consideration of harbor-wide barrier systems in this century and early next century.



1 *Introduction*

The analysis assumes that shipping and boating will remain important economic and recreational drivers in Boston, and that the present environmental state of the harbor should be preserved.

In 2016 the City of Boston released Climate Ready Boston (Climate Ready Boston, 2016). This major initiative to organize a citywide response to climate change included detailed climate change projections, a vulnerability assessment, and proposals for adapting to climate change. Effective policies can lessen the long-germ threat and ensure that the city, the Greater Boston area and the region are better prepared for the sea level rise (SLR) and extreme weather events we are already beginning to experience.

Climate Ready Boston recommended that the City of Boston implement five layers of climate readiness to prepare for climate change. These were:

- Updated Climate Projections
- Prepared and Connected Communities
- Protected Shores
- Resilient Infrastructure
- Adapted Buildings

Under "Protected Shores" is Strategy 5: "Create a Coastal Protection System," a set of initiatives to protect against coastal flooding. The details of this strategy are in Table 1.1.

This report addresses Initiative 5-4: "Launch a Feasibility Study of a Harbor-Wide Flood Protection System." Specific items recommended to be addressed by Climate Ready Boston (2016) include alignment options, sizes of gaps and gates, and project phasing. In addition, it describes several advantages the harbor has for such a strategy: its relatively shallow depth and the large availability of public land. Specific possible challenges include impacts on ecosystems and water quality, conflicts with shipping and boating, and risk of inducing flooding outside of a barrier.

Here we report upon the results a broad, preliminary study to investigate the practicality of several alternative configurations of harbor-wide protection systems (hereafter the harbor-wide study) and these issues. We investigate some of the options depicted in Figure 1.1 for engineering and cost considerations, and hydrodynamic, environmental, economic, social, and recreational and commercial shipping and boating impacts using a multi-criteria process. The implementation of any of the alternatives presented in this report would represent a significant alteration to a complex socio-ecological system. Few estuarine alterations of this magnitude have ever been attempted. The analysis assumes that shipping and boating will remain important economic and recreational opportunities in Boston, and that the present environmental state of the harbor should be preserved. Since this is a preliminary analysis, it does not employ evaluation or planning processes utilized by federal agencies such as the US Army Corps of Engineers and the US Environmental Protection Agency, or state agencies such the Executive Office of Energy and Environmental Affairs.

The implementation of any of the alternatives presented in this report would represent a significant alteration to a complex socio-ecological system.

TABLE 1.1

Summary of Initiatives to Create a Coastal Protection System

Number	Initiative	Summary
5–1	Establish Flood Protection Overlay Districts and require potential integration with flood protection	Based on preliminary hydrological analyses, establish new overlay districts in potential flood protection system locations and require that development proposals do not prevent the future creation of flood protection infrastructure.
5–2	Determine a consistent evaluation framework for flood protection system prioritization	Determine a framework through which alternative flood protection systems would be consistently evaluated, and which is compatible with the framework used by the U.S. Army Corps of Engineers, a key implementation and funding partner.
5–3	Prioritize and study the feasibility of district-scale flood protection	Using a consistent evaluation framework (Initiative 5–2), study the feasibility of district-scale flood protection in a number of locations, prioritizing those that face the greatest risk.
5–4	Launch a feasibility study of a harbor-wide flood protection system	Using a consistent evaluation framework (Initiative 5–2), study the feasibility of a harbor-wide flood protection system.

Source: Climate Ready Boston, 2016

We focus upon the outer and inner harbor configurations in Figure 1.1, subsequently referred to as the Outer Harbor Barrier (OHB) and Inner Harbor Barrier (IHB). These systems would have large gates that are open all the time except during floods. These types of gates are not designed to be opened and closed frequently—certainly less than 10 times per year. We do not analyze the Harbor Island configuration depicted in Figure 1.1 because, while it takes significant advantage of existing islands and relatively shallow water depths, compared to other options, it is similar in size to the outer configuration but provides less protection. We also address some of the issues of a proposed Metro Harbor Dike Barrier from Swampscott to Cohasset that would include a system of locks and fixed structures (see Figure 4.1). Since this lock system would permanently alter the present hydrodynamics and water quality of Boston Harbor and has major construction and cost challenges, it is not analyzed in detail.

The report initially summarizes the sea level rise (SLR) projections which could range from 1.8 feet to 7.3 feet or more by 2100 compared to 2013. A comparison with other existing barriers in the world indicates that the northern floating sector gate of the Outer Harbor Barrier would be the largest of its kind in the world. This is followed by conceptual designs and costs for the barrier options considered. The construction costs for the IHB range from $6.5–$8.7 billion, and for the OHB from $8.0–$11.8 billion. The subsequent detailed hydrodynamic analysis indicates that there would be no tidal attenuation caused by the gate openings in either the OHB or the IHB, but there would be changes in the velocity of tidal currents and circulation in some areas of the harbor. This analysis also estimates it would take at most 50–60 years under a moderate SLR

FIGURE 1.1
Recommended Possible Harbor-wide Protection Schemes

Source: Climate Ready Boston, 2016

scenario before the gates of a barrier would be closing more than 50 times per year—far exceeding design conditions. It examines this finding under various SLR scenarios and assumptions regarding surge elevations above which a barrier would be closed. This section is followed by an environmental analysis that finds, in spite of some unresolved issues, that a harbor-wide barrier system would have minimal environmental impacts compared to changes expected due to ongoing climate change and SLR.

The economic analysis of the IHB and the OHB system is then presented. Even though the methods are moderately aggregated and the results only representative of the actual benefits and costs, it is apparent that benefit:cost ratios under various assumptions regarding discount rates, costs, timing of implementation, and effectiveness of shore-based protection could be very low—in many cases well less than 1.0. This indicates low cost-effectiveness.

The recreational and commercial shipping section finds that there could be moderate impacts to these activities related to, for example, increased tidal velocities through the open gates.

The next section is a comparison of harbor-wide barriers to shore-based adaptation strategies that shows the relatively greater advantages of shore-based solutions given the reasonable assumptions in this analysis. The final section of the report contains a summary, key findings, and the major recommendation that the City implement shore-based strategies over the next several decades while monitoring conditions to determine if a barrier might be useful in the future. Appendices containing more details of the analysis and additional results are included.

> The report initially summarizes the sea level rise projections which could range from 1.8 feet to 7.3 feet or more by 2100 compared to 2013. A comparison with other existing barriers in the world indicates that the northern floating sector gate of the Outer Harbor Barrier would be the largest of its kind in the world.

REFERENCE

Climate Ready Boston, 2016. Final Report, City of Boston, December.

2 *Global Experience with Large Barriers*

To date only 15 storm surge barriers have been built worldwide, but interest in them is increasing as sea level rise accelerates and coastal development continues.

Accelerated coastal development and the prospect of increased SLR have generated serious interest worldwide in the building of large storm surge barriers to protect vulnerable coastal cities and populations. To date, however, only 15 such storm surge barrier projects have been undertaken, most as part of the Delta Works project in the Netherlands (Mooyaart, 2014). Other notable storm surge barriers have been built in the Thames River in the United Kingdom; St. Petersburg, Russia; the Ems and Eider Rivers in Germany; the MOSE project in Venice, Italy (not fully operational yet); and New Orleans, LA; New Bedford, MA; Stamford, CT; and Providence, RI in the United States. The completed projects generally fall into two types: either single barriers sited on tidally-influenced rivers (e.g., Thames, Ems, Eider, New Bedford), or river delta projects that span broad expanses of low-lying estuaries with multiple barriers (e.g., Netherlands Delta Works, New Orleans).

The storm surge barrier at St. Petersburg is the most similar to the Outer Harbor Barrier (OHB) considered for Boston Harbor, serving to close off an inner region of water (Neva Bay, Boston Harbor) during storms to prevent storm surges from an outer body of water (Gulf of Finland, Massachusetts Bay/Gulf of Maine) flooding a city and its surroundings (St. Petersburg, Boston). The Inner Harbor Barrier (IHB) proposed for Boston Harbor follows the more common river-mouth siting. Large-scale barrier systems do function successfully for protecting inland areas from coastal storm surge. For example, all five storm surge gates in the Netherlands were simultaneously closed in early January 2018 as a large storm impacted the nation, and the system prevented coastal flooding (Newmark, 2018). In addition to these barriers, four to five are in the planning stage. The research tends to agree that major gates or barriers at strategic locations of the mouths of large estuaries can reduce the overall number of ancillary interventions required around the perimeter of the estuary (Jonkman et al., 2013) to protect against storm events.

The gates of these types of barriers are designed for only a small number of closures over a year or more and with SLR will be closed more frequently. For example, the gates discussed in this analysis are similar in scale to the Maeslant Barrier protecting Rotterdam. It was designed for a closure frequency of approximately once every ten years. Studies suggest that rising sea levels could increase closure frequency to once every 3.2 years in 2050 and once every 1.1 years in 2100 (Zhong et al, 2012). The Thames Barrier in London was originally designed to be closed two to three times per year, and has recently experienced a closure rate of six to seven times per year (World Heritage Committee, 2006). Similarly, the MOSE barrier in Venice is intended to be closed, on average, ten times per year. With approximately 1.5 ft. of sea level rise, it would be closed once per day and with just over 2 feet of sea level rise, it will be closed more than it is open (Goodell, 2018). Increasing rates of usage for heavy mechanical equipment typically equate

Large-scale barrier systems do function successfully for protecting inland areas from coastal storm surge. For example, all five storm surge gates in the Netherlands were simultaneously closed in early January 2018 as a large storm impacted the nation, and the system prevented coastal flooding.

to increasing rates of failure and/or operational costs to repair or prevent failures. Furthermore, increasing rates of operation and closure will lead to increases in environmental impacts to the tidal prism and flushing regimes of the protected basins and estuaries behind any barrier.

Barrier Type Selection Based on System Considerations

The Gulf Coast Community Protection and Restoration District's (GCCPRD's) Phase I Storm Surge Suppression Study (2015) lists several key considerations when envisioning an applicable and adaptable barrier type: operations and maintenance, hydraulics, navigation and transport, reliability, durability for routine use and catastrophic events, constructability, morphological impact, and environmental impact (salinity and water quality impacts due to flushing and altered tidal prism). The GCCPRD Phase I report also details favorable and unfavorable aspects of all gate types for various conditions. An example is

TABLE 2.1

GCCPRD Barrier Considerations

Favorable	Unfavorable
Structural aspects, layout, and operation	
• Large gate span feasibility • No vertical clearance limitation • Not subjected to wind • Suitable for deep waters • Closing operation requires minimal time • Stable structure; no load concentration • Dry docks provides easy maintenance and protection from vessel collision	• Large space and deep excavation required for chambers • Silting may hamper operation • Load transfers to hinges and pintle which require regular maintenance against corrosion and underwater growth
Hydraulic and hydrodynamic aspects	
• Limited differential head and horizontal flow contraction in the last stage of closure • Suitable for reverse head and flow	• Susceptible to siltation inside chambers • Underwater pintle may jam due to debris hindering operation

Dircke et al., 2009

*Not sensitive to flow vibrations

TABLE 2.2

Barrier Gate Considerations

	Mitre	Vertical Lift	Flap	Horizontal	Vertical Rotate	Rubber
Span > 30 m	–	+	+	+	+	+
Span > 100 m	–	–	+	+	–	–
Water depth > 10 m	+	+	+	+	+	–
Impact Upon Landscape	+	–	+	+	–/+	+
Maintenance	+	+	–	0	+	0
Current and Waves	–	+	0	0/+	0/+	0
Closure Time	+	+	+	+	+	0/-
Space Required	+	+	+	–	+	+
Colliding Ships	0/–	+	+	0/–	+	0
Reliability	–/+	+	0/+	–/+	+	0
Clearance Height	+	–	+	+	–/+	+

Legend

– Not favorable up to not feasible

0/–: Below average/vulnerable

0: Average/possible

0/+: Above average

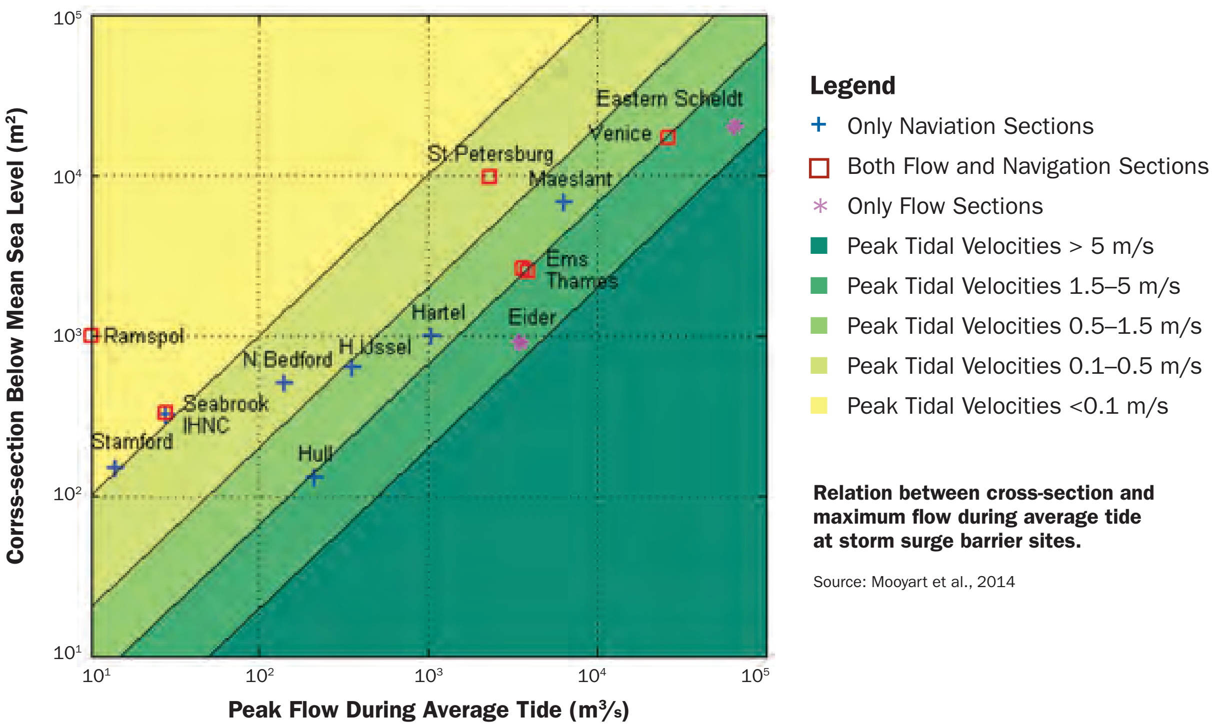
+: Favorable/proven technology

–/+: Score depends on design choices and conditions

Source: Dircke et al., 2009

FIGURE 2.1

Storm Surge Barrier Velocity Properties



Relation between cross-section and maximum flow during average tide at storm surge barrier sites.

Source: Mooyart et al., 2014

shown in Table 2.1. Similarly, Dircke et al. (2009) summarized general barrier considerations for only the parts of the barrier that are moveable (e.g., the gate portion), shown in the Table 2.2 matrix. "Horizontal" in this table is most similar to the type of gates in the IHB and the OHB. Figure 2.1 contains the velocity characteristics of several systems. Appendix A contains information on the costs of some of these systems.

Lessons Learned from Other Systems Applicable to Boston

Several proposed alignments exist for a future Boston Harbor barrier. Although common considerations such as tidal flushing and navigation would exist, each alignment poses unique challenges and would likely necessitate the selection of a different barrier and gate type combination. Based on historic efforts, the Inner Harbor and Outer Harbor Barrier alignments (Figure 4.1) are most representative of projects constructed to date around the world. The Metro Boston Dike Barrier alignment seems to pose the greatest amount of constructability and survivability challenges because of the water depths and exposure to severe wave energy.

Several proposed alignments exist for a future Boston Harbor barrier. Although common considerations such as tidal flushing and navigation would exist, each alignment poses unique challenges and would likely necessitate the selection of a different barrier and gate type combination.

Fetch and wave effects of the barrier design will be a significant consideration. Because of the open Atlantic Ocean waves, the Metro Boston Dike Barrier would require heavy armor materials, such as rock or concrete armor units, and would require gates which could withstand direct impacts from large offshore wave heights. Inside of the OHB, the remaining fetch of greater than 5 miles (8 km) prior to land could, in part, negate protective properties of the barrier at the inner harbor shoreline as waves would have enough fetch to regenerate. Jetties and rubble mound breakwaters

Wind and wave modeling capabilities have vastly improved since the 1970's and 1980's, and more detailed wind, wave, and bathymetry surveys will be required if a Boston Harbor-wide system is further investigated.

are regularly built in depths up to approximately 50 feet (15 meters). They are less common in greater depths, but have been constructed in depths up to 165 feet (50 meters), such as in Sines, Portugal. Bucharth (1987) catalogued costs of such immoveable barriers constructed at the time, which ranged up to $200,000 per meter length. He also discussed the ultimate failure of the original Sines breakwater, along with several other notable failures of deep water breakwaters due to extreme wave energy in exposed deep-water locations. Wind and wave modeling capabilities have vastly improved since the 1970's and 1980's, and more detailed wind, wave, and bathymetry surveys will be required if a Boston Harbor-wide system is further investigated.

Boston, United Kingdom Coastal Storm Surge Barrier

Coincidentally, the City of Boston in the United Kingdom, a small port located on an estuary on the North Sea in Lincolnshire, is constructing a storm surge barrier. The community of approximately 65,000 is building the barrier as a result of extensive damage from a storm surge in December 2013. The barrier and the raised banks downstream will protect against the present 0.3% flood, thus protecting 14,300 properties (Lincolnshire City Council, 2017). The barrier will cost 100 million pounds or $138 million.

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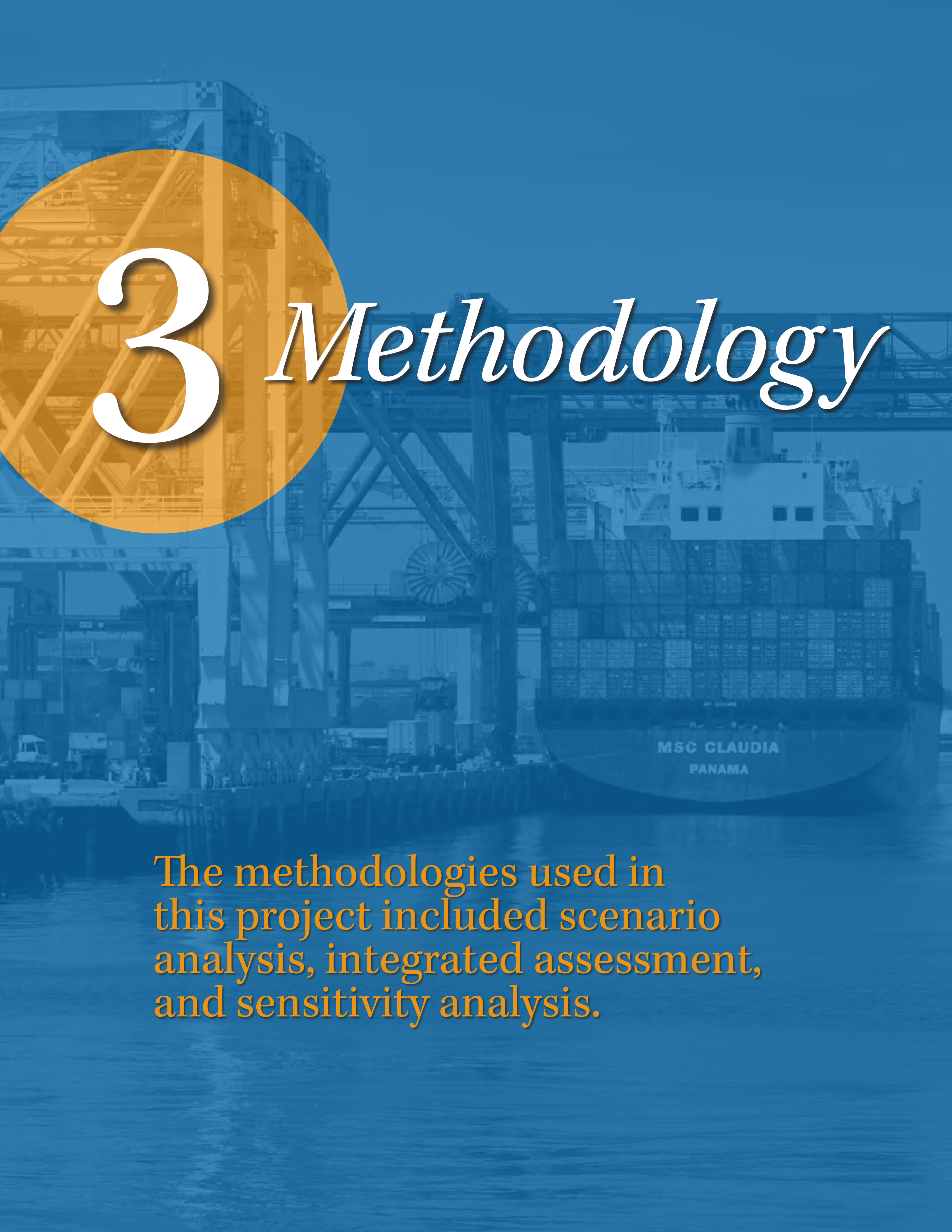


3 *Methodology*

The methodologies used in this project included scenario analysis, integrated assessment, and sensitivity analysis.

In assessing the feasibility and impacts of a Boston Harbor storm surge barrier, we employed three major methodologies, as described below: scenario analysis, integrated assessment, and sensitivity analysis.

Scenario Analysis

Scenario analysis is a method to assess the impacts of future events accounting for the uncertainties of different parameters. This is accomplished by assigning a range of values that are considered plausible to each parameter, determining the impacts upon the system for each scenario set, and then finding solutions that function reasonably well over all the scenarios. There are many uncertainties over the next 100 or so years that are relevant to a harbor-wide storm surge barrier. Some these include sea level rise, future storm climatology, other climate changes, demographics and human values, storm-related damages and societal responses to them, the costs of infrastructure, the spatial characteristics of cities, and the response of ecosystems to changing conditions. Given the broad goals of this project, we did not develop scenarios for all of these conditions. Rather, we used one set of moderate SLR conditions, storm conditions, and climate changes that may occur in the future; several interim strategies that Boston and the communities in Boston Harbor would employ until a barrier system was constructed; and the assumption that present development, land use, demographic conditions, and human values continue to exist over time. A more detailed study would include the use of more scenarios and more advanced approaches of decision-making under deep uncertainty.

SEA LEVEL RISE

We used the same global SLR scenarios for 2030 and 2070 as the Boston Central Artery Tunnel (CAT) vulnerability assessment and adaptation plan (Bosma et al., 2015) and City of Boston vulnerability assessment (CRB, 2016); these are in Table 3.1. Added to the global increase was the local increase of 1.1 mm/year. We added a scenario of 0 relative SLR to represent the present conditions (2013), and a relative SLR scenario of 5 feet; in the analysis, these are referred to as SLRs of 0, 1, 3, and 5 feet. Because of the complexity and time-consuming nature of the coastal flood modeling (described in Section 5), these were the only SLR conditions analyzed. Based upon the report used for developing the climate change scenarios for Climate Ready Boston (Douglas et al, 2016), where exceedance probabilities were developed for future SLR scenarios relative to 2000 for various IPCC greenhouse gas emission scenarios (IPCC, 2013, see Table 3.2), these SLR scenarios, once adjusted to 2013 conditions, are approximately equivalent to 1 foot of relative SLR by 2030, 3 feet by 2070, and 5 feet by 2100 under the high end of the likely range for IPCC GHG emission scenario RCP 4.5, a moderate emission scenario. If the low end of the likely range for the RCP 4.5 emission scenario is used, a relative SLR since 2013 of 1 foot would occur in approximately 2050 instead of 2030, 3 feet of SLR by 2100 instead of 2070, and 5 feet of SLR by approximately 2150.

> Scenario analysis is accomplished by assigning a range of values that are considered plausible to each parameter, determining the impacts upon the system for each scenario set, and then finding solutions that function reasonably well over all the scenarios.

The scenario of 5 feet of relative SLR by 2100 was used in all of the analyses except for the estimation of the height of the barrier, where 7 feet of relative SLR was used for the design. We assumed that if such a massive structure was built, it would be constructed to a high plausible condition, not a moderate one.

INTERIM BOSTON HARBOR PROTECTION STRATEGIES

The City of Boston and several other municipalities within Boston Harbor have already carried out coastal flooding vulnerability assessments. Boston has also conducted pilot projects to develop conceptual designs and costs for coastal adaptations

TABLE 3.1
Base SLR Scenarios from MassDOT

Assumed Time Period	2013 Global SLR (cm)*	Local SLR since 2013 (cm)	Total Relative (cm and feet)**
Present (2013)	0	0	0
2030	19 (0.6 ft)	2	21 (0.7 ft)
2070	98 (3.2 ft)	6	104 (3.4 ft)

* from DOT report ** used in CRB and Harbor-wide Analysis
Source: Bosma et al., 2015

TABLE 3.2

Probabilistic Analysis of SLR Scenarios

			Likely Range					Maximum
	0.99	0.95	0.833	0.5	0.167	0.05	0.01	0.001
RCP8.5								
2030	– 0.1	0.1	0.3	0.5	0.7	0.9	1.0	1.2
2050	0.1	0.4	0.7	1.1	1.5	1.8	2.1	2.4
2070	0.6	1.0	1.5	2.2	3.1	3.7	4.3	4.8
2100	1.6	2.4	3.2	4.9	7.4	8.6	9.5	10.5
2200	18.9	19.9	21.4	26.1	32.8	34.1	35.3	36.9
RCP4.5								
2030	– 0.1	0.1	0.3	0.5	0.7	0.9	1.0	1.2
2050	0.1	0.4	.07	1.0	1.4	1.7	2.0	2.3
2070	0.4	0.9	1.3	1.9	2.6	3.1	3.6	4.1
2100	0.9	1.7	2.4	3.6	5.1	6.1	7.0	8.0
2200	5.5	6.2	7.2	10.9	16.5	18.0	19.3	20.9
RCP2.6								
2030	– 0.1	0.1	0.3	0.5	0.7	0.9	1.0	1.2
2050	0.1	0.4	0.6	1.0	1.4	1.7	2.0	2.3
2070	0.3	0.7	1.1	1.7	2.3	2.7	3.1	3.6
2100	0.4	1.2	1.8	2.8	3.8	4.6	5.3	6.2
2200	3.6	4.4	5.2	6.4	7.7	8.8	9.9	11.8

RSL projections for Boston, MA (in ft, relative to 2000) categorized by exceedance probabilities.

Source: Douglas et al., 2016

at the entrance locations of flood pathways into Boston, such as the East Boston Greenway and the Schrafft Building area in Charlestown (Climate Ready Boston, 2017). These district-level solutions have been conceptually designed to elevations of aproximately14 feet NAVD88—approximately consistent with the 1% flood elevation in 2070 with one foot of freeboard under a moderate SLR scenario, with the potential to add on an additional 2 feet of extra protection. One scenario for our impact and benefit/cost analyses assumes Boston and the other communities in the harbor all develop shore-based systems capable of managing coastal water surface elevations to 14 feet NAVD88, and that these will be built over the next approximately 50 years as SLR occurs and coastal flooding increases and then a barrier would be built in 2070. The solutions would include whatever is most appropriate for a location be it gray or green protection, accommodation, or retreat. Another scenario was that the City and region would implement a barrier in 2050 and in the interim would have built up coastal protection to 12 feet NAVD88. Figure 3.1 shows the NAVD88 datum elevation compared to present tidal conditions in Boston. The elevation of the present 1% flood is approximately 9.5 feet NAVD88 (based upon Boston Harbor Flood Model simulations). The datum used by the City of Boston, Boston City Base (BCB), is the NAVD88 value plus 6.4 feet.

Integrated Assessment

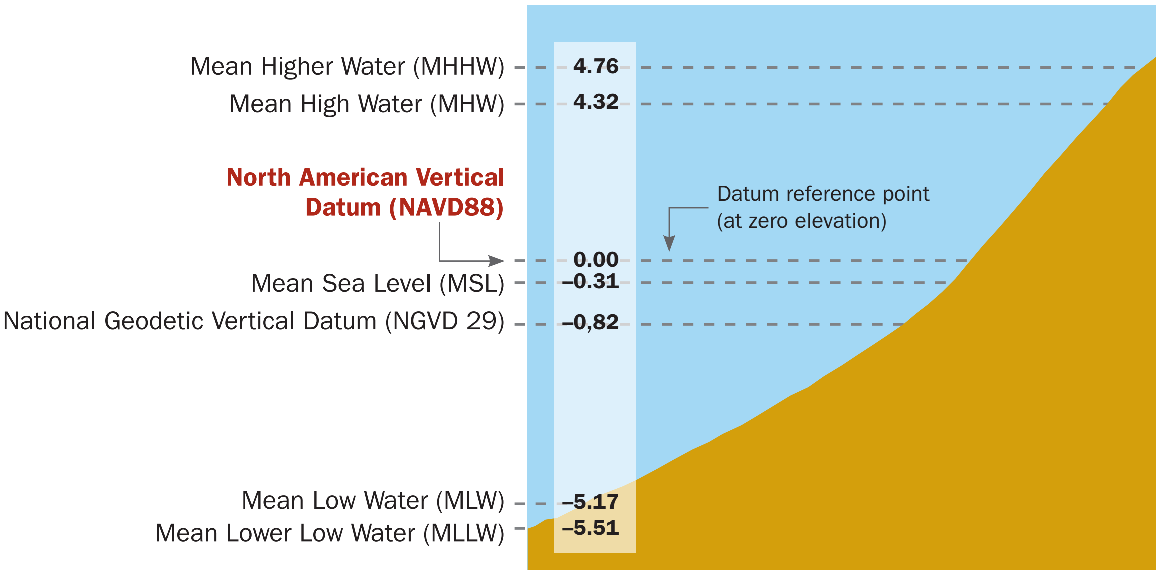
This analysis considers the economic, social, and environmental impacts of barrier systems, determined by quantitative or qualitative indicators. We compare indicators based on present conditions to those whose values evolve over time with and without a barrier system. Table 3.3 shows the indicators. We did not assess impacts of a harbor-wide system on cultural, tourist, recreational or historical values.

Sensitivity Analysis

We performed an economic analysis that considered two discount rates, several cost estimates for barriers, and two levels of effectiveness for shore-based systems built before barriers would be implemented.

FIGURE 3.1

North American Vertical Datum of 1988 (NAVD88)



Source: Massachusetts Office of Coastal Zone Management

TABLE 3.3

Indicators for Barrier Systems Impacts

Economic	Environmental	Social	Users
Discounted Expected Value Damages	Water Quality	Number of People Impacted by Flooding	Commercial
Barrier Cost	Habitat	Number of People Impacted by Flooding by Social Vulnerability Class	Fishing
Discounted Net Expected Value Benefits	Environmental Services		Recreational
Critical Infrastructure Flooded	Economic Environmental Services		

Source: UMass Boston

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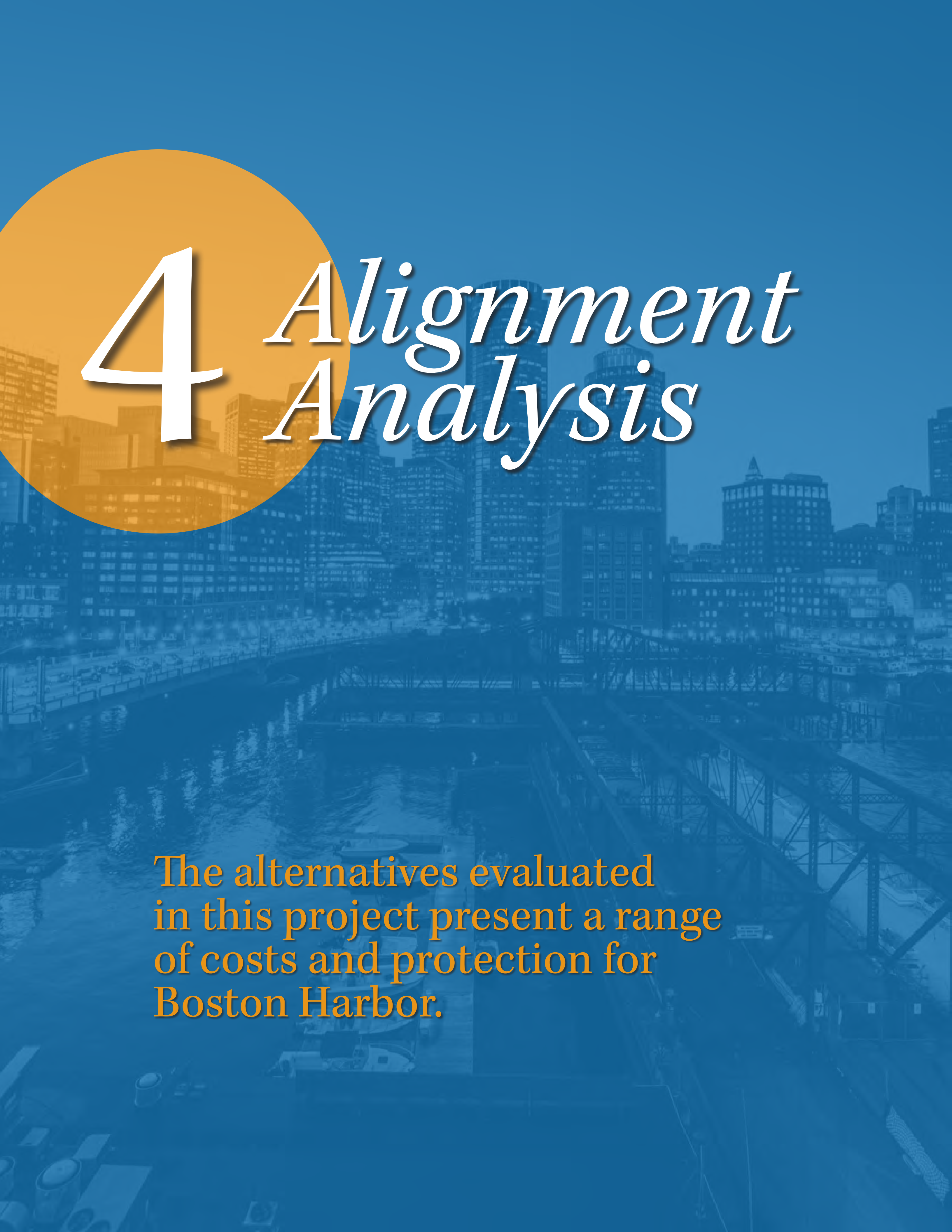
4 *Alignment Analysis*

The alternatives evaluated in this project present a range of costs and protection for Boston Harbor.



Several potential barrier options have been proposed for Boston Harbor as part of the effort to protect metro coastal Boston from future sea level rise and storm surge risks. These alternatives were assessed (Figure 4.1):

- **Metro Boston Dike Barrier**
  This alignment is a large, semi-circular barrier seaward of the main harbor and adjacent shorelines, presently envisioned to stretch approximately 18 miles from the shores of Cohasset north to Swampscott. This alignment would include locks rather than gates. A version of this was proposed by Peter Papesch of the Boston Society of Architects in 2017.

- **Outer Harbor Barrier**
  This alternative consists of approximately 3.8 miles of new barriers from Deer Island in Winthrop to Hull, including two new floating sector gates where the alignment crosses shipping channels. This alternative would also include approximately 9.3 miles of improvements to existing seawalls, riprap, and new levees along adjacent shorelines. The size of the largest gate would exceed the size of the largest existing floating sector gate in the world, and the in-water span would also be the largest in the world.

- **Inner Harbor Barrier**
  This alignment comprises approximately 18 miles of coastal barriers extending along the shoreline of Boston Harbor from Dorchester to Revere as well as a short section near Malden, along with one sector gate between South Boston and the Boston Logan International Airport.

This section presents the possible conceptual construction design and costs for each potential alignment.

Metro Boston Dike Barrier

NAVIGATION CONSIDERATIONS

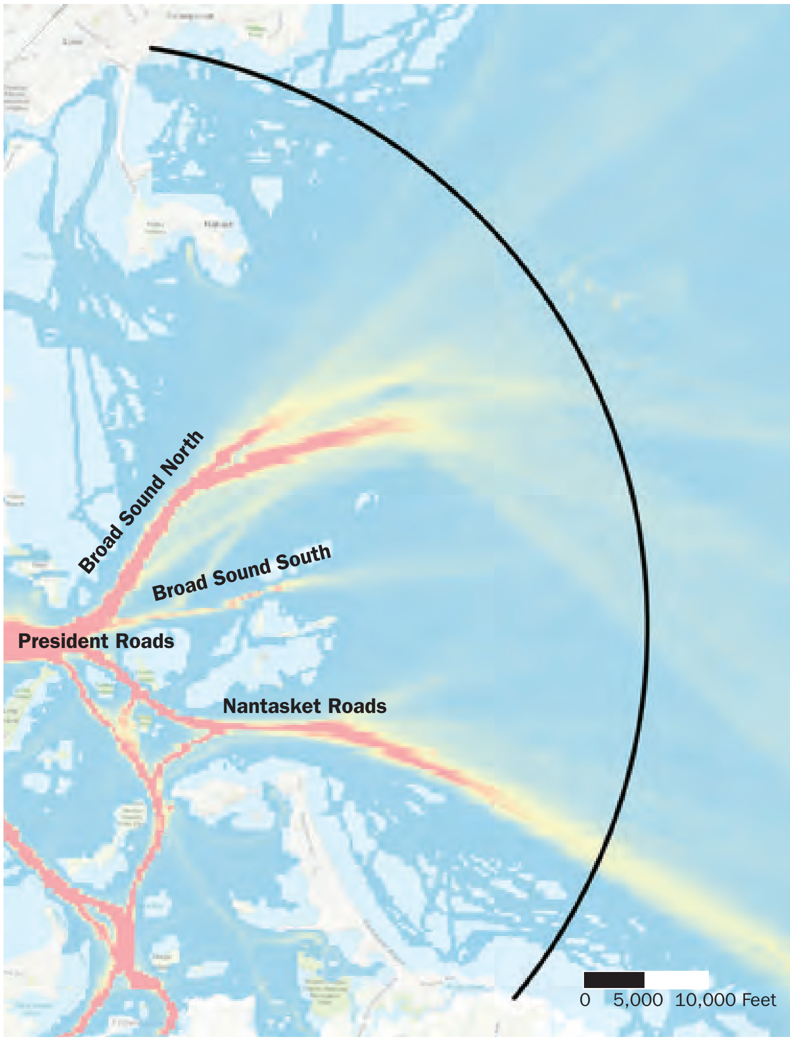
Boston Harbor is intersected by multiple federally authorized and maintained navigation channels. The primary deep-draft navigation channel is the President Roads channel and anchorage, which extends seaward from the harbor's dock facilities. This channel splits just east of Deer Island into the Broad Sound North and Broad Sound South channels, with the heaviest vessel traffic through the Broad Sound North channel, as shown in Figure 4.2. As can be seen in Figure 4.2, the vessel traffic density patterns diverge once in open ocean. Accommodating continued and uninterrupted navigation according to these patterns would likely require more gate or lock locations. For example, both heavy deep-draft commercial freighters and smaller shallow-draft vessels would be required to navigate several miles off a present-day straight-line course to transit the barrier. Lock or gate operations would also likely be hindered if ocean conditions limited the operation of the locks/gates before and after a storm event. These navigational concerns can be more easily managed with a barrier orientation closer to the harbor entrance.

FIGURE 4.1
Barrier Alternatives in Boston Harbor

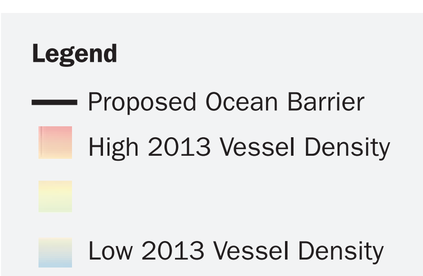
Sources: Arcadis, Esri World Imagery

FIGURE 4.2

Boston Harbor 2013 Automatic Identification System (AIS) Vessel Traffic Density



Source: National Ocean Service



WATER DEPTH, WAVES, AND HYDRODYNAMICS

The main hydrodynamic considerations for any alignment seaward of the harbor entrance would include:

- water depths and the associated impacts on design and constructability; and
- wave regeneration behind the barrier due to large fetch distances.

Jetties and rubble mound breakwaters are regularly built in depths of up to 50 feet, but are less common in greater depths. The alignment as proposed would span depths between 80 and 120 feet (Figure 4.3), and would require atypical and more expensive construction materials compared to other barrier concepts. The feature would also require advanced engineering to survive extreme events, such as the 0.1% annual exceedance probability wave event (1,000-year wave event), as has been required for similar structures, including the Costa Azul caisson breakwater in Baja California, Mexico. During Hurricane Sandy, the offshore significant wave height (the average of the top third of the recorded wave heights) at NOAA Buoy 44025, 33 miles south of Long Island, was determined to be over 30 feet. Any barrier proposed for the outer portions of Boston Harbor or seaward would likely be required to withstand such wave conditions.

In addition to design and cost challenges, constructability is a significant hurdle to advancing this concept, because of the depths along the proposed alignment. Notable delays would be expected due to inclement weather, logistical issues due to the remote worksite, and large material requirements for the feature itself.

Furthermore, the location of the Metro Boston Dike Barrier alignment would pose unique challenges. Constructability would be complicated due to the need to stage construction and deliver materials to offshore locations. Also, since the feature would be over six miles from shore for some reaches, it is likely that the fetch distance (the distance traveled by wind over open water) from the feature to the shore would be sufficient for wave regeneration between the barrier and the shore during high wind events. This alignment could require additional shore protection features in the harbor to reduce wave action, which would limit the potential benefits of a barrier concept.

Lastly, it should be noted that any large coastal flood barrier would likely redirect wave energy in localized areas, which could increase erosion and potentially induce flooding in those areas. In the case of the proposed Metro Boston Dike Barrier alignment, it is anticipated that areas to the south of Cohasset as well as areas to the north of Swampscott would be exposed to potential increased wave energy from the placement of the barrier itself. To mitigate for these areas of induced storm surge, risk reduction features such as improved seawalls, revetments, dunes, and levees were assumed to be necessary as part of the overall project cost.

The location of the alignment offshore poses unique challenges. Constructability would be complicated due to the need to stage construction and deliver materials to offshore locations.

FEATURE CONSIDERATIONS

Due to the alignment's open ocean location, a limited number of solutions would be available to construct the feature in a manner able to withstand the harsh conditions. The barrier would likely need to consist of over 18 miles of sinkable concrete caissons and/or a concrete rubble mound causeway. Three or more lock complexes and their associated support infrastructure would be spaced along the alignment. Few, if any, green features would be feasible due to the deep water and limitation on available fill material. The amount of stone and concrete required would be immense; the project would likely require a major market study to ensure material in such quantities is available in the region and to detail the transportation hurdles to moving such massive volumes of stone over long distances.

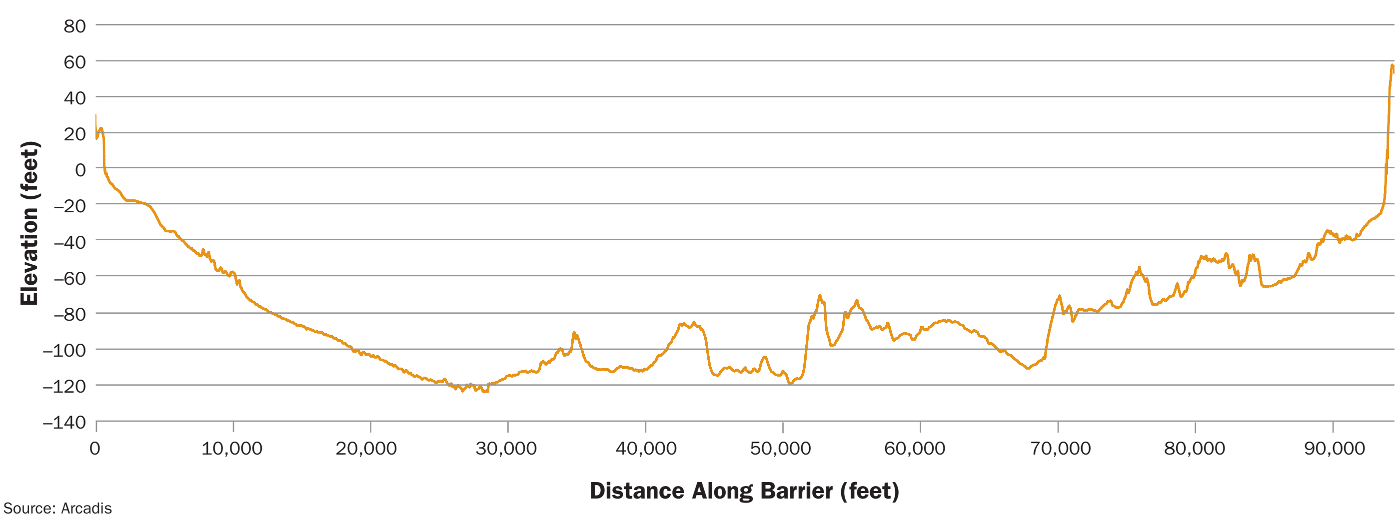
ENVIRONMENTAL CONSIDERATIONS

The barrier would have to be sited in consideration of possible interference with the 9.5-mile effluent outfall approximately due east from the MWRA Deer Island Wastewater Treatment Plant. In addition, many regulatory hurdles would exist and would contribute to a multi-year process culminating in an Environmental Impact Statement and Environmental Impact Report. Considerations for significant alterations to aquatic habitats, migratory routes, breeding patterns, and oceanic currents would likely require multi-year data collection and numeric modeling analysis to determine appropriate mitigation measures. Further, likely decreases in water quality due to increased residence times and diminished flushing rates, as well as impacts on lobster, striper, and shell fisheries would have to be considered. The Metro Boston Dike Barrier concept, in essence, would establish a new brackish or freshwater lagoon from a previously saline estuary. Few proxies exist to benchmark the cost and timeframe necessary to execute such a project.

COST

Few features like the proposed alignment have ever been attempted. The most relevant proxy

FIGURE 4.3
Depth Along Proposed Barrier Alignment



Source: Arcadis

> The Metro Boston Dike Barrier concept, in essence, would establish a new brackish or freshwater lagoon from a previously saline estuary. Few proxies exist to benchmark the cost and timeframe necessary to execute such a project.

would be the St. Petersburg Barrier in Russia, although it was constructed in a shallower protected estuary. Based on extrapolation of literature references such as Aerts et al. (2013), Jonkman et al. (2013), and Mooyart et al. (2014), it would not be inconceivable for such a barrier to exceed $80 billion in preliminary construction costs, with a likely range of $35–$85 billion, depending on the number and size of locks, the number and capacity of pump stations, and the material for the immovable portion of the barrier (e.g., caisson, earthen, aggregate fill). This imprecise cost would assume a high contingency to account for the vast array of uncertainties in the analysis concerning the location, number, and types of features required for this barrier, as well as future environmental mitigation and land rights uncertainties.

SUMMARY

This preliminary assessment of the Metro Boston Dike Barrier has identified several navigational, hydrodynamic, physical, and environmental challenges that would increase potential costs compared to other proposed alternatives and alignments. Though relocating the proposed alignment to only a few miles off the shoreline could significantly reduce the total construction cost many times over due to reduced water depths, it would still remain several times more expensive than the Outer or Inner Harbor Barrier alignments, likely without many notable additional benefits.

Boston Outer Harbor Barrier Cost Estimate

ALIGNMENT CONSIDERATIONS

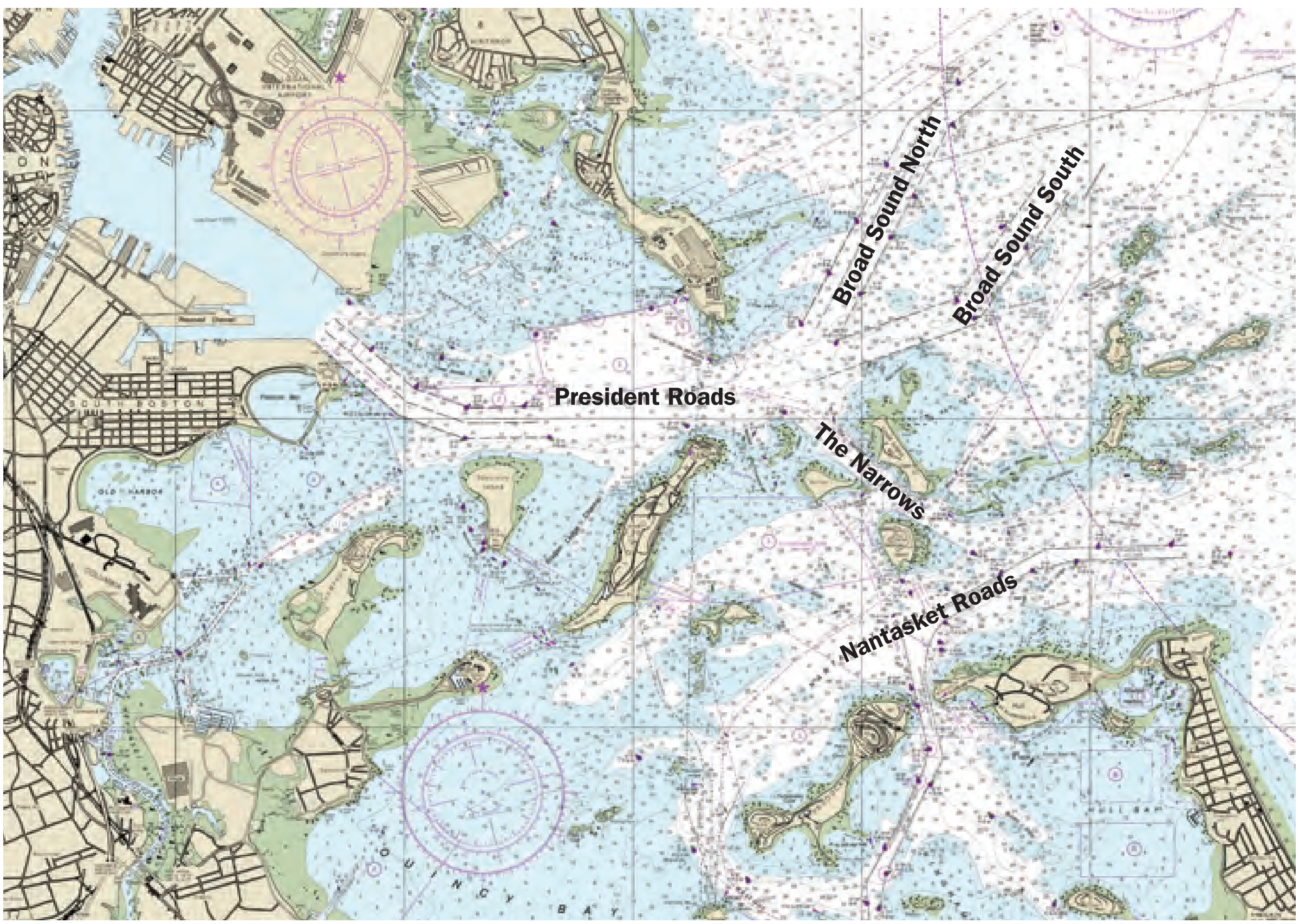
Any proposed alignment requires a basic examination of local hydrodynamics, water depth, and geotechnical conditions, as well as both commercial and recreational navigation. These primary considerations then lead to others, such as the types of moveable and immovable barrier components, availability of materials, constructability in prevailing sea conditions, induced impacts on surrounding areas, and survivability of features. This section should not be considered an exhaustive or comprehensive list of final considerations; rather, it focuses on some of the most fundamental ones. For example, in this preliminary evaluation, geotechnical conditions and environmental impacts were not considered to be major project drivers; however, this assumption should be revisited in future, more in-depth analyses.

NAVIGATION

Ports with larger capacities than Boston (such as New York, New Orleans, and Houston) have shipping channels ranging from 400 to 750 feet wide and 45 to 55 feet deep (USACE 2016a, 2016b, 2016c). An 800-foot gate would allow over 400 feet of seaway for two Panamax-sized ships passing with accompanying tugs. The widest navigable gates in North America are the 225-foot wide sector gate that comprises a portion of the West Closure Complex south of New Orleans, LA, and the 250-foot wide barge gate (the Bubba Dove Floodgate) south of Houma, LA. Both, however, have sill depths of less than 20 feet and are limited to shallow draft navigation.

The President Roads and Broad Sound North Channel (Figures 4.2 and 4.4) are presently approximately 1,000 to 1,500 feet in width with depths averaging 40 feet, and are slated to undergo expansion to depths of 47 to 51 feet in fiscal years 2018–2021 (USACE, 2013a). It is anticipated that over 11 million cubic yards of predominantly silt and clay material will be removed in the channel expansion process. To the south, the Nantasket Roads Channel varies from 500 to 1,200 feet in width, with a depth averaging 32 feet.

FIGURE 4.4
Present Navigation Channels



Source: National Oceanographic and Atmospheric Administration

This channel presently serves medium- to shallow-draft commercial vessels and recreational vessels. Connecting the Nantasket Roads to the President Roads is The Narrows, running roughly north to south between Lovells, Gallops, and Georges Islands, with depths ranging from 25 to 45 feet.

Should future dredging and deepening occur in the channels of the harbor, the material quantity in the channel and anchorage itself could be more than sufficient for most green features near Lovells, Gallops, or Georges Islands.

Gates in Boston Harbor would have to be situated to avoid proximity to the President Roads anchorage and turning basin, as well as the turn in the channel as it transitions from the President Roads to the Broad Sound North Channel near Deer Island. Presently, only a few gates in the world are of this magnitude, namely the 1,200-foot* Maeslant Barrier in Rotterdam, the Netherlands, and the 650-foot sector gate component of the larger St. Petersburg Barrier in St. Petersburg, Russia. Both are floating leaf sector gates. Several similarly sized gates are proposed for Galveston and New York but are in early feasibility stages.

WATER DEPTH AND HYDRODYNAMICS

As shown in Figure 4.4 and discussed above, the navigable entrances to the harbor (President Roads, Nantasket Roads) are deep; however, areas adjacent to The Narrows near Lovells, Gallops, and Georges Islands are quite shallow, with depths often less than 10 feet. Water depth will not only be a large cost driver for any barrier in Boston Harbor, but would also heavily factor into the survivability of the feature. The ability to locate large portions of the feature in protected shallow waters would prevent higher wave energies from reaching the barrier face.

SEDIMENT AVAILABILITY

To the extent deemed practicable, the team initially envisioned an alignment that would maximize opportunities for earthen and rock, or “green,” features, over concrete and steel, or “gray,” solutions. As previously stated, estimates for future channel enlargement predict that over 11 million cubic yards of material will require removal from the President Roads and Broad Sound North Channel. Offshore sand sources are available, though limited and distant from the project location. The timing of the upcoming harbor deepening and any future construction of this barrier do not align; thus, the team ultimately assumed that a gray wall and gate feature would be first constructed to establish flood defenses. Any future enhancement of that structure via establishment of green island and berm features around it would come in a later phase. This is reflected in the Cost Summary section below where costs for a completely gray feature are reported, while the costs for the optional green elements are reported separately in the discussion. Should future dredging and deepening occur in the channels of the harbor, the material quantity in the channel and anchorage itself could be more than sufficient for most green features near Lovells, Gallops, or Georges Islands. The proximal location would also likely reduce dredging and barge transport costs for disposal of the material compared to offshore sources.

ALIGNMENT AND TYPICAL FEATURE ASSUMPTIONS

Based on our deliberations, we chose a primary alignment stretching from Deer Island to Hull that would hug Gallops and Georges Islands. This alignment would enable shallow water placement for large reaches of the barrier on manmade island extensions of Georges and Gallops Islands, would avoid impacts as much as possible to The Narrows, and would benefit from the protection of shallow areas surrounding Lovells Island and off the northern shore of Hull and Telegraph Hill in Hull (Figure 4.7). To prevent surges from flanking the barrier, shoreline barrier systems as shown in Figure 4.1 would also be needed.

GATES

Based on a literature review, we assumed the two gates at President Roads and Nantasket Roads would both be floating leaf sector gates. The photo on page 36 shows an example of floating leave sector gates in the Netherlands. The gate leaves act as ballasted barges: they are stored in drydock-like housing cells when not in

* In all gate discussions, when a width is discussed herein (e.g., “650-foot”), the width measurement given references the total navigable opening of the gate when all leaves are in the opened position.

FIGURE 4.5
Outer Harbor Barrier Configuration

Sources: Arcadis, Esri World Imagery, USACE

Gates
- Vertical Lift Gate
- Floating Sector Gate
- Platform
- Coffer

Walls
- Caisson Wall
- Overland Levee
- Improvement to Existing Sea Wall

Other
- Disposal Islands
- USACE Dredged Areas

use. When the gate is to be closed, the housing cells are flooded, causing the gate leaves to float; the leaves are then rotated into the closed position, ballasted, and sunk into place. This type of feature requires costly construction of coffer cells and artificial islands to house the drydock-like cells for the sector gate leaves and ancillary operational features.

Acknowledging that smaller gate sizes could be plausible, our analysis team, through conversations with the U.S. Army Corps of Engineers (USACE) New England District planning and engineering department personnel, performed the cost analysis assuming that larger gate sizes (1,500-foot and 650-foot gates for President Roads and Nantasket Roads respectively) were necessary. This assumption was made in part due to the President Roads' gate location (its vicinity to a turn in the channel and the anchorage directly behind the proposed gate), velocity considerations, tidal flushing, and other qualitative environmental considerations. Further refinement of these assumptions could reduce costs in the design phase by narrowing gate sizes while retaining two-way traffic capabilities in the channels.

Although not accounted for in project modeling at this time, a number of environmental flow control gates or openings in the barrier would likely

Example of floating leaf sector gates.

be required for water quality and minor local velocity considerations. Future analysis would refine the number and net opening size required. However, inclusion of these environmental flow gates does not change the results of the hydrodynamic evaluation presented in Section 5, with the exception of local circulation enhancements. There is some flexibility in the sizing and style of these features, as is evidenced by the variation in similar constructed projects worldwide. Whether in the Netherlands (Deltaworks), Russia (St. Petersburg), or United States (Seabrook, Fox Point), general common attributes for this type of gate include either Tainter (radial) or vertical lift gates with associated monolith and equipment. For the purposes of this estimation, a vertical lift gate was assumed, similar to those found on the Seabrook barrier complex in New Orleans, LA. An example image depicting a vertical lift gate is shown in the photo on page 37.

While these gates are intended to protect against low-frequency events, they require regular operation to ensure functionality. However, frequent operation leads to higher maintenance costs as well as an increased risk of mechanical failure. For reference, the Maeslant flood barrier in Rotterdam was designed for an estimated closure frequency of once in ten years; however, it is operated for maintenance monthly (van den Brink and de Goederen, 2017). An analysis of predicted closure frequency can be found in Section 5 of this report.

BARRIERS

Reaches in deep water (a depth greater than five feet) were assumed to consist of concrete caisson sections which would either be constructed in place or floated to position, then sunk in place. This feature was chosen over solutions such as "combi-wall" or driven pile walls due to its ability to adapt to a variety of subsurface conditions and to better withstand harsh wave environments. Figure 4.6 provides a sketch of a concrete caisson's cross-section with various enhancement options. The cap or top of the caisson could be designed in such a way that it could be expanded vertically or enhanced with green elements to protect from rising seas in the future. Basic quantities of the caisson feature components were calculated (as discussed in greater detail in the following section), and the cost was converted to a loaded cost per unit length, then applied over the required total length. Caissons require less foundational support compared to other wall measures and can be placed in relatively deep water and energetic wave environments.

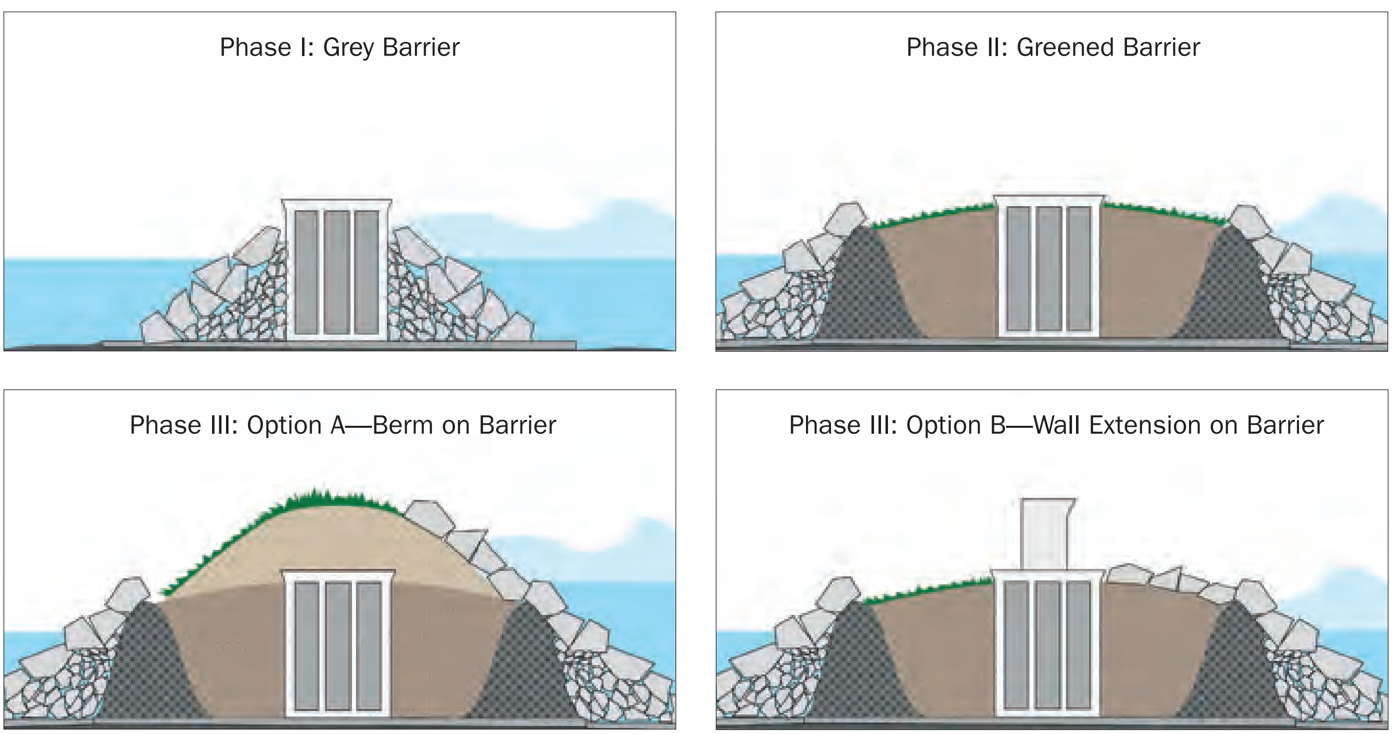
As previously discussed, due to sediment availability concerns, any barrier could be first constructed of gray features to provide flood risk attenuation and "greened" over time as additional funds and sediments are identified. These "greened" segments would consist of a caisson wall surrounded by man-made islands. The islands were assumed to be limited to areas with a maximum water depth of five feet and would have an elevation approximately five feet NAVD88. A smaller flood protection berm or levee could then be constructed on top of the island platform, with overtopping protection matting (Figure 4.6).

For both the green and gray immoveable portions of the barrier, it is conceivable that the features could be engineered to be built in stages or modified over time to rebuff increasing sea level and the associated increases in surge and wave heights. For earthen berms, additional lifts could be performed over time to increase the crown elevation. For the concrete walls and caissons, the design could be executed so that an additional lip or wall height could be added to the feature in a future modification. On the other hand, it would not be possible to increase the elevation of the navigable gates over time cost-effectively; that infrastructure should be initially built to account for any foreseeable additional SLR.

Example of vertical lift gate.

FIGURE 4.6

Enhancement of Grey Features of Caissons and Expansion Possibilities



Source: Arcadis

FLOODING ON SURROUNDING AREAS AND REQUIRED FEATURES

Shoreline district solutions in Winthrop, Revere, and Hull are required to ensure storm surge does not flank around the barrier. In addition, due to the possible marginal level of increased wave energy reflecting off the barrier, some enhancements may be necessary to these seawalls, revetments, dunes, and levees. As more information becomes available regarding predicted storm surge design elevations, future evaluations of these concepts could scale these features as necessary to form a continuous barrier from Winthrop to Nantasket.

> Cost estimations for the OHB were based primarily on collecting and evaluating existing data from plans for recently constructed or proposed projects.

ELEVATIONS

The elevation of the elements of the OHB are based on the following:

- Current elevation of Mean Higher High Water (MHHW).
- Present day 1% storm surge.
- 2100 SLR of seven feet, which falls in the high end of the range of likely probabilistic rates of SLR for RCP8.5 (Douglas et al., 2016).
- Attenuated wave height based upon 30-feet offshore wave heights associated with historic events of this magnitude. By the time waves reach the outer barrier, wave heights are approximately 15 feet; when they reach the inner barrier, they are approximately five feet.
- Two feet of freeboard.

The top of the crest of the structure would be at the top of the wave crest; manageable overtopping is allowed everywhere (both Inner and Outer Harbor Barriers). This means that some water will be allowed to overtop the barrier during larger storm events; however, the total volume of water over-topping the barrier would not be significant enough to increase the water level behind the barrier. As noted in the Scenario section, seven feet of SLR by 2100 was used for the design instead of the five feet described in the Scenario section. It was assumed that a massive structure such as this would be built to a more extreme condition, not a moderate one. The resultant elevations when the barrier is closed are in Table 4.1. When the barrier is open and the gate stowed to the side, the elevation of the gate is approximately equal to the elevation of the gate when closed.

COST ESTIMATION METHODOLOGY

Cost estimations for the OHB were based primarily on collecting and evaluating existing data from plans for recently constructed or proposed projects. A library of relevant structure and unit costs was compiled from the following sources:

- Cost Estimates for Flood Resilience and Protection Strategies in New York City, Aerts et al. (2013);
- Costs of Adapting Coastal Defenses to Sea-Level Rise—New Estimates and their Implications, Jonkman et al. (2013);
- Storm Surge Barrier: Overview and Design Considerations, Mooyart et al. (2014);
- The North Atlantic Coast Comprehensive Study (NACCS), U.S. Army Corps of Engineers (2015);
- The Gulf Coast Community Protection and Restoration District (GCCPRD) Storm Surge Suppression Study (2015);
- Louisiana's Comprehensive Master Plan for a Sustainable Coast (2017);
- Hurricane Storm Damage Risk Reduction (HSDRRS) projects constructed in the vicinity of New Orleans post-Katrina (2007-2014);
- Financing the Operation and Maintenance Costs of Hurricane Protection Infrastructure, RAND Gulf States Policy Institute (2012);
- East Rockaway Inlet to Rockaway Inlet and Jamaica Bay Reformulation Study (2016a); and
- Permanent Canal Closures and Pumps, U.S. Army Corps of Engineers (2013b).

TABLE 4.1

Elevations of Inner and Outer Harbor Barriers

Location	Design Level (ft, NAVD88)	Design Level (ft, MLW)
Outer Barrier	27	32
Inner Barrier	22	27
North Shoreline (Revere) and Hull	24	29
South Shoreline (South Boston, Moakley Park, etc.)	20	25
Inner Shoreline (Reserve Channel, Constitution Beach)	19	24

Source: Arcadis

Costs were updated to 2017 Massachusetts prices using the RS Means Historical Cost Indexes, along with the U.S. Army Corps of Engineers' Civil Works Construction Cost Index system (USACE, 2017) and the U.S. Bureau of Labor Statistics' CPI Inflation Calculator. For structures such as seawall improvements, revetments, berms, and dunes, unit costs derived from the NACCS and GCCPRD studies were applied per unit length to account for material quantity, installation, and finishing. These costs are applicable for a general range of design elevations between 10 and 20 feet NAVD88. Future storm surge analysis will refine design elevations for all features, at which point cost estimation methods can be refined to reflect updated values. Due to the amount of material required to construct the green and gray barrier features, it is not anticipated that small adjustments in design elevation (e.g., plus or minus 5 feet) will affect this preliminary estimation of cost.

Concrete caisson unit costs were estimated based on the required volumes of concrete and steel, as well as the labor and installation costs for a given monolith section 200 feet in length and 80 feet wide. The seafloor along the alignment was measured to an average depth of –20 feet NAVD88; this depth was added to the general protection elevation of +10–20 feet NAVD88 for a total structure height of 40 feet. The unit cost for a single monolith section was scaled for the total length of proposed caisson wall.

The 1,500-foot-wide gate at President Roads and the 650-foot-wide gate at Nantasket Roads were estimated based on recent work that Arcadis undertook for the East Rockaway Inlet and Jamaica Bay Reformulation Study (USACE, 2016a) and the Bolivar Roads channel serving Houston and Galveston as part of the GCCPRD Storm Surge Suppression Study (GCCPRD, 2015). The Bolivar Roads gate costs were estimated for an 840-foot and 1,200-foot opening width and a 50-foot depth. The sector gate costs for this study were scaled from those in the GCCPRD analysis based on the opening width for each of the gates in the alignment. Gate costs were treated as a lump sum and include a number of sub-features such as the gate housing islands and coffer cells, operational electronics and machinery, etc.

Additional barrier opening areas may be required to partially improve circulation and/or reduce local velocities. Specific hydrodynamic model simulations have not been completed to further test this idea. Though this portion of the analysis is presently undeveloped, the project team anticipates that the requirements for partial environmental flow exchange would be satisfied by the inclusion of a series of 70-foot-wide vertical lift gates, based on similar systems in other barrier structures. This style of gate is one solution among many potential styles, each with pros and cons in terms of aesthetics, operational considerations, and cost. A unit cost for each gate and associated monolith was based on recent work that Arcadis undertook for the Bolivar Roads channel (GCCPRD, 2015). The number of gates and opening area required for this barrier is likely the most uncertain aspect of this analysis. Future modeling would serve to refine the required features in this category.

For all costs reported, a contingency ranging from 50 to 100% was added to account for the vast array of uncertainties in the analysis concerning the location, number, and types of features required for this barrier, as well as future environmental mitigation and land rights uncertainties.

For all costs reported, a contingency ranging from 50 to 100% was added to account for the vast array of uncertainties in the analysis concerning the location, number, and types of features required for this barrier, as well as future environmental mitigation and land rights uncertainties. We believe a conservative range is appropriate for civil works projects such as the preliminary concepts in this report.

To estimate Operations and Maintenance (O&M) costs, maintenance activities were estimated for 50 years (the assumed minimum design life of a feature of this magnitude), including both annual activities and a mid-life major refurbishment of the gates. Annualized values were converted to a present-day lump sum using an inflation rate of 3%. For every project evaluated and considered, cost estimates were based on what is known today. Because the value of money increases over time, O&M costs associated with projects include an inflation rate of 3% annually over the project lifespan, based on when the project is chosen for implementation. This planning methodology is not unique. It is widely used by the U.S. Army Corps of Engineers in studies across the nation such as those related to the Everglades Restoration as well as local flood protection feasibility studies from Texas to California. This methodology makes it possible to equitably analyze projects over time despite uncertain revenue streams, environmental scenarios, and economic scenarios. With this methodology come certain caveats:

- For initial planning and project selection purposes, this analysis assumes future costs change at a rate equal to the rate of inflation.
- The analysis considers the possibility that in some years, potentially more money would be required than is possessed; solutions such as a bond issue would then be required. Similarly, in other years, all revenues received might not be spent and could potentially realize interest on holdings. These scenarios could result in interest paid to the owner or paid by the owner, depending on the situation; however, these possibilities are not accounted for in the planning methodology due to the high level of uncertainty associated with the future rates of revenue and inflation.

COST SUMMARY

A breakdown of estimated feature costs for the OHB is shown in Table 4.2. All values reported are in 2017 dollars. The values reflected in Table 4.2 summarize costs of multiple subcomponents for each feature. Due to the preliminary nature of this estimate, dollar values for land rights (for property takings and agreements) and mitigation acres (for damages to sensitive habitats) are not included, but these categories are reflected in the table as a reminder that such costs will require future estimates as project details are refined.

The high estimate applies a 100% contingency, whereas the low estimate adds a 50% contingency on all costs. As stated previously, the number and size of vertical lift gates would be refined via future analysis. For this exercise, a plausible range of vertical lift gates (6 to 12) was assumed across the low and high estimates. However, this makes up only a small portion of the total cost, which is therefore relatively insensitive to the inclusion and number of environmental lift gates.

It should be noted that the costs in Table 4.2 are shown in 2017 dollars, though construction would likely not be completed for either barrier alternative for decades. Large infrastructure projects like those proposed can take a decade or more to fully permit via the National Environmental Protection Act (NEPA) process and would require an Environmental Impact Statement (EIS) supported by a robust modeling and analysis effort. Construction, dependent on funding and material availability, could also take over a decade, although as previously stated it could

TABLE 4.2

Outer Harbor Barrier Estimated Range of Construction Costs

Item	Quantity	Units	Cost (Millions $, 2017)		Percent of Total
			Low Estimate	High Estimate	
Planning, Engineering, Design, Permitting, and Construction Management	—	Percent of Construction Cost	$890	$1,310	11%
Levee Construction on Land	14,700	Linear feet	$40	$60	1%
Floating Sector Gate (650 ft)	1	Each	$1,920	$2,560	22–24%
Floating Sector Gate (1,500 ft)	1	Each	$3,700	$4,930	42–46%
Vertical Lift Gates	6–12	Each	$720	$1,910	9–16%
Caisson Wall	14,100	Linear feet	$570	$760	6–7%
Improvements to Existing Seawall and Rip-Rap	34,500	Linear feet	$180	$240	2%
Right-of-Way	—	Acres	Not included	Not included	—
Mitigation Acreages	—	Acres	Not included	Not included	—
Total			**$8,020**	**$11,770**	

Note: The gate width listed only represents the actual opening of the gate, not the width of the artificial islands/arms/receiving structure on either side. The accompanying structures essentially double the width of the entire gate structure, adding approximately 2100 feet. We assumed a maximum of 12 vertical lift gates of 130 feet wide each for a total of 1560 feet. This adds up to approximately 3.8 miles total barrier length.

Source: Arcadis

be phased over time. Combining the expected timelines for design, permitting, and identifying funding, it is expected that a barrier concept like those discussed here would not be constructed until approximately 2050. Building artificial islands around the caissons to "green" the barrier at a future date could potentially add on the order of $400 million to the total construction cost.

The planned design life for infrastructure of this magnitude would likely be on the order of 50 to 100 years. Accordingly, the barriers might need to be designed for expected conditions at or near the year 2100, both in terms of initial construction (e.g., foundations to handle designs further out in time) and adaptation planning (e.g., design height changes and anticipated footprint/right of way needs). Beyond initial design and adaptive planning, O&M can be accounted for throughout the life of the project. The estimated 50-year O&M cost is shown in Table 4.3. Note that O&M costs are shown for 50 years rather than 100 years because of the broad range of uncertainty in projecting O&M needs and costs too far into the future. For example, sea spray would deteriorate concrete as well as metallic features such as gate joints or bearings, and there would be a snowball effect of increasing O&M regardless of what initial design standard the feature is constructed to. The average estimated annual value equates to approximately 0.8% of the construction cost. This value is in the range of 0.5% to 2% as discussed in Aerts et al. (2013).

TABLE 4.3

Outer Harbor Barrier Estimated Range of Operation and Maintenance Costs over 50 Years

Item	Total Cost (Millions $, 2017)		Percent of Total Construction Cost
	Low Estimate	High Estimate	
Operations and Maintenance	$1,613	$2,181	19–20%

Source: Arcadis

COST DISCUSSION

As discussed in Appendix A, Aerts et al. (2013) compiled a summary table of the geometric and monetary features of large existing floodgates worldwide. This table was used to compare the estimates detailed in this report to the general costs of similar features throughout the world. Mooyart et al. (2014) compared methods and found that in 2017 dollars, large flood barrier systems (for the landward seaward components), on average, cost $0.94 million per foot span across all gate types and gate/barrier combinations, with a $0.51 million per foot standard deviation (i.e., roughly a 50% standard deviation). These costs are generally corroborated in Aerts' New York City planning estimates for inner and outer harbor defense strategies. Using Mooyart's unit cost per meter length assumptions, the OHB cost from Hull to Deer Island would range from $8.6 to $29.5 billion; the costs outlined in this report for these components would fall within the lower half of this range. The estimates in this report are likely on the lower end of the scale based on Aerts' assumptions because large portions of this alignment would be static earthen features, which are relatively more cost effective, whereas the gate catalogue sampled for Aerts' estimate largely comprised moveable span-dominated features.

FIGURE 4.7

Inner Harbor Barrier Alignment

Sources: Arcadis, Esri World Imagery, USACE

Boston Inner Harbor Barrier Cost Estimate

ALIGNMENT CONSIDERATIONS

As mentioned in the OHB discussion above, this section should be read as a list of primary concerns rather than an exhaustive or comprehensive list of final considerations. Again, environmental impacts were not considered to be a major driver in these preliminary estimates, but they should be considered in future analyses. The analysis team is aware of other flood protection planning efforts, namely for South and East Boston. As the details of all efforts are refined, coordination will be required among the various project teams. In addition, given the proximity of the barrier to Logan Airport, Massport and FAA regulations must be considered as well. The Logan Airport Airspace Map (Appendix E) cites 25 feet NAVD88 as the maximum permissible elevation near the site. The proposed height of the barrier in Table 4.1 is 22 feet NAVD88, which falls within this stated maximum, but this must be confirmed. The proposed Inner Harbor Barrier (IHB) alignment stretches from Dorchester to Revere with a small section in Malden. There would be one floating sector gate between South Boston and Logan Airport (Figure 4.7). Appendix B contains more detail on the shore-based flood management systems that would also need to be part of the IHB project.

NAVIGATION

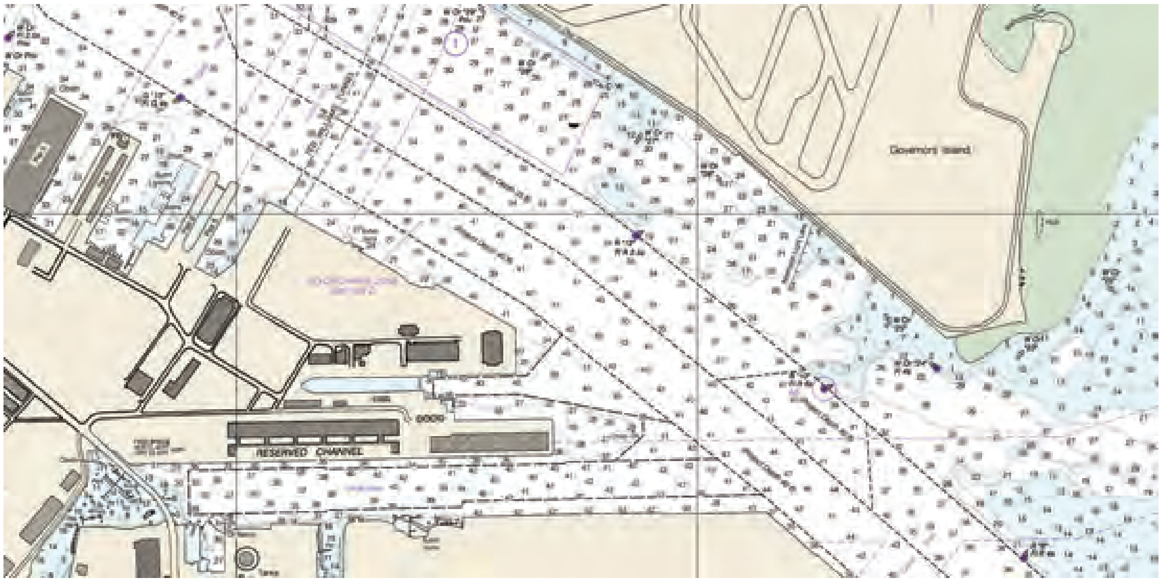
A major navigable crossing would be required across the President Roads Channel east of the Ted Williams Tunnel (Figure 4.8). The main channel is approximately 1,200 feet wide with depths of approximately 35 to 40 feet. The team assumed the gate across President Roads would be a floating leaf sector gate.* The IHB would likely require a moderate amount of dredging to realign the navigation channel with any proposed gate to minimize or avoid conflicts with land-based features on either channel bank.

WATER DEPTH AND HYDRODYNAMICS

Most of the Inner Harbor alignment is located onshore, and therefore would largely consist of dunes, levees, seawalls, and revetments, as opposed to larger caisson or gate structures. For this reason, hydrodynamic considerations on survivability are less important for the purposes of this study for the IHB than for the OHB.

* See the Outer Harbor Barrier *Alignment Considerations* discussion for more details regarding floating sector gates.

FIGURE 4.8
Inner Barrier Navigation Channel



Source: National Oceanographic and Atmospheric Administration

MATERIAL AVAILABILITY

Material for landward features proposed in this alignment would likely require transport to the jobsites via truck rather than dredge. There would be very limited, if any, options for green features associated with a channel barrier at this location.

INDUCED FLOODING ON SURROUNDING AREAS AND REQUIRED FEATURES

In the case of the proposed Inner Harbor Barrier alignment, it is unlikely that surrounding shorelines would be exposed to any significant level of increased flooding. However, future storm surge modeling and analysis should be conducted during the design phase of such a feature to ensure there are no increases in local flooding.

PUMPING SYSTEM

A barrier connecting South Boston and East Boston/Logan Airport would require additional engineering measures to adequately control upstream water levels during times when the barrier is closed. Specifically, during extreme weather events that bring heavy precipitation and storm surges, it would be necessary to manage discharge from the Mystic and Charles Rivers to ensure that freshwater discharge backup would not flood areas the IHB is intending to protect. With the IHB closed during a storm event, freshwater discharge propagating down the Charles and Mystic Rivers would be confined upstream of the IHB, resulting in a continuous increase in water levels behind the barrier. For example, a future nor'easter event consisting of projected sea level rise and storm surge could require the barrier to remain closed for up to 72 hours, with outer Boston Harbor water levels at elevations that would not allow the IHB to be opened. During this time frame, precipitation-based water arriving from the Mystic and Charles River watersheds would not be allowed to discharge into the ocean and would back up behind the Inner Harbor barrier. Therefore, the ability to pump this excess stormwater arriving from the river discharge is recommended as part of the barrier's overall adaptation design.

Ongoing studies evaluating climate change impacts on the Mystic and Charles Rivers (personal

> Most of the Inner Harbor Barrier alignment is located onshore, and therefore would largely consist of dunes, levees, seawalls, and revetments, as opposed to larger caisson or gate structures. For this reason, hydrodynamic considerations on survivability are less important for the purposes of this study for the IHB than for the OHB.

TABLE 4.4

Estimated Pumping Requirements for Inner Harbor Barrier

River	Peak Discharge (cfs)	Total Discharge (cf over 72 hours)	Average Discharge (cfs)
Charles River	23,450	932 Million	3,595
Mystic River	9,380	238 Million	920
TOTAL	**32,830**	**1.17 Billion**	**4,515**

Source: Arcadis

The two existing dams will likely keep their sluices and gates open to allow for freshwater discharge from the upper portions of the estuary/river down to the barrier.

communication with Ellen Douglas, 2017) are determining future discharge estimates for these two watersheds/rivers. These estimates use downscaled climate change precipitation data as input to watershed models, which in turn predict the overall stormwater contributions to the river discharges under changing climate conditions. Table 4.4 presents the results from the watershed modeling in terms of a peak and total discharge (over a 72-hour time frame) for a 2070, 24-hour, 100-year precipitation event. The total volume of water (over 1 billion cubic feet) would significantly increase the upstream water surface elevation behind the IHB by up to 20 feet; and therefore could not be stored behind the barrier during the passage of a coastal storm event. This stormwater would need to be pumped out behind the barrier. The peak discharge presented in Table 4.4 can be used to estimate the required need and sizing of a pump system as part of the IHB resiliency design.

When closed, the IHB would act similarly as the existing dams on the Charles and Mystic Rivers: the Charles River Dam (CRD) and Amelia Earhart Dam (AED). In that sense, during a storm surge event, the IHB would be another dam further downstream protecting a larger area. Operational management of the IHB, relative to the existing dams, is likely to function as follows:

The IHB would be closed with the potential approach of a significant coastal storm. When the Inner Harbor Barrier is closed, freshwater flow from the Mystic and Charles watersheds would be inhibited at the barrier (albeit further downstream of the existing dams). Stormwater would then be sequestered in the inner harbor area. During these early stages of the storm, there would be no need for the CRD and AED to close and/or operate pumps, as the Inner Harbor barrier would be protecting them from storm surge and outer harbor processes. The two existing dams would likely keep their sluices and gates open to allow for freshwater discharge from the upper portions of the estuary/river down to the barrier.

If the net freshwater discharge during the storm event is small enough, the sluice gates might never be closed and/or pumps never operated at the CRD and AED; however, it is more likely that during the course of the storm, the water surface elevation downstream of the two existing dams would become high enough (from freshwater discharge storage) that those dams would be closed and then pumping would begin to keep the upstream river water elevations at a level that would not induce flooding. However, since the stormwater would be sequestered by the IHB, eventually the water surface elevation in the inner harbor would get high enough to flank and overtop the existing dams, flooding areas both upstream and downstream of the AED and CRD.

To prevent this overflow, pumps at the IHB would likely be used when the water surface elevation in the inner harbor reached a certain elevation. This would maintain the water at a certain elevation such that the AED and CRD pumps might not be needed, or could operate less frequently. If pumps at the IHB keep the overall water surface elevation of the Inner Harbor down, then it is feasible that the CRD and AED might not need to close or activate pumps.

Inner-Harbor Alignment

GATES

As discussed in the previous section, only a single floating leaf sector gate across the President Roads channel would be required for the IHB. A large (1,500-foot) two-lane gate and its accompanying structures would span the entire distance between South Boston and Logan Airport, and would require some dredging to realign the channel through the gate (Figure 4.9).

BARRIERS

Much of the alignment was assumed to be constructed of green barriers on land (i.e., levees, dunes, or berms) built to an elevation of 22 feet

NAVD88, with the exception of a small portion of gray barrier along the South Boston harbor area and the gate across the President Roads channel. Unlike the OHB, the green reaches of the IHB could be built directly on land without first building a caisson wall, assuming sufficient sediment is available. Gray reaches along South Boston would not be built out of caissons, but rather would be concrete floodwalls. As with the OHB, both green and gray features in the IHB could be built in stages or modified over time to rebuff increasing sea level. Figure 4.10 shows example cross-sections of the overland green and gray structures.

PUMP STATIONS

These are assumed to consist of stations with multiple low-head, high-volume, shaft-driven pumps as are commonly found in largescale stormwater pumping facilities throughout the U.S. in locations such as New Orleans, and even locally in Boston. These types of facilities often require local electrical grid upgrades, significant backup power facilities, and overall significant O&M costs and requirements. Additional coordination with interior drainage systems and infrastructure would be required to generate operational plans that coordinate with the system goals during usage events.

COST ESTIMATION METHODOLOGY

The inner harbor alignment is simpler than the outer harbor alignment, with fewer gates, and a heavier emphasis on berms, dunes, and sea walls. Unit lengths for the gray reaches of the IHB along South Boston were derived from the NACCS and GCCPRD studies to account for material quantity, installation, and finishing. Pump station unit costs were derived from the USACE Permanent Canal Closures and Pumps project (2013b). The remaining aspects of the cost estimation methodology are the same as outlined in the OHB section.

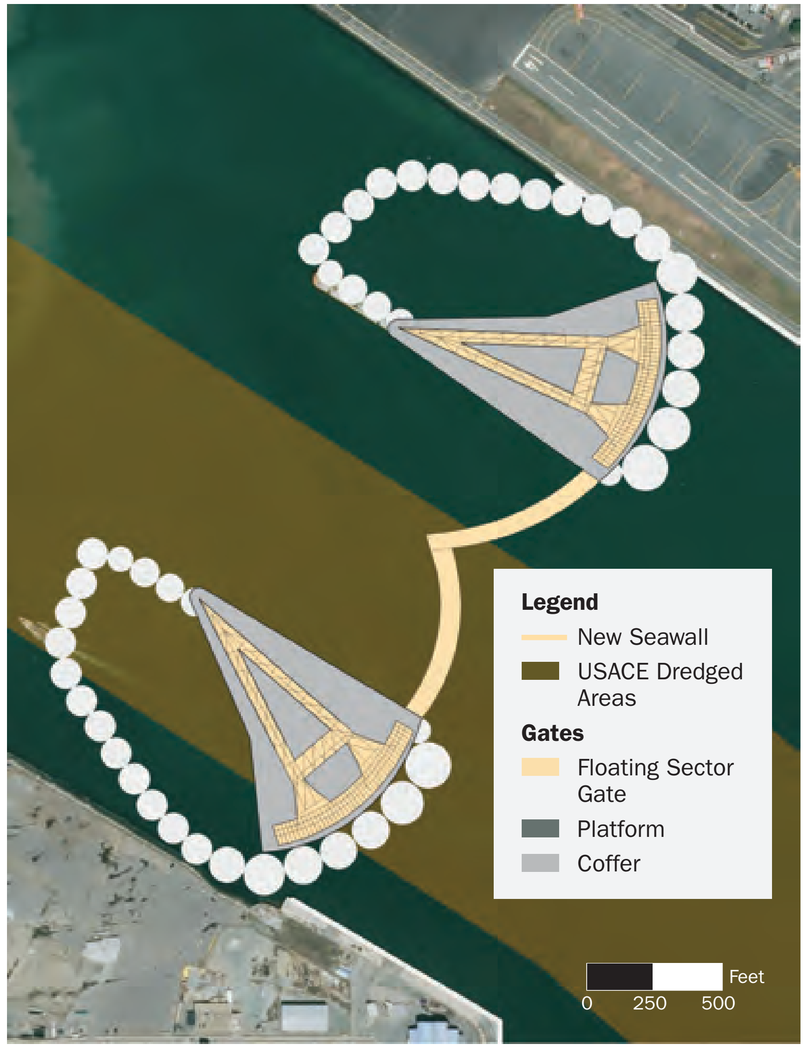
COST SUMMARY

A breakdown of estimated feature costs for the entire alignment is shown in Table 4.5. All values reported are in 2017 dollars. The estimated 50-year O&M cost is shown in Table 4.6. Like the OHB, the IHB would likely not begin construction for a decade or more and potentially have an intended design life as far out as 100 years (2130). No vertical lift gates would be needed.

Although the costs in Table 4.5 are shown in 2017 dollars, construction would likely not

FIGURE 4.9

Inner Harbor Barrier Floating Leaf Sector Gate



Sources: Arcadis, Esri World Imagery, USACE

be completed for either barrier alternative for decades. Large infrastructure projects like those proposed can take on the order of five to ten years to fully permit via NEPA and other permitting processes and would require an EIS. Construction, dependent on funding and material availability, would likely require on the order of five to ten years as well. Combining the expected timelines for design, permitting, and identifying funding, it is expected that the inner barrier concept would not be constructed until as early as approximately 2030.

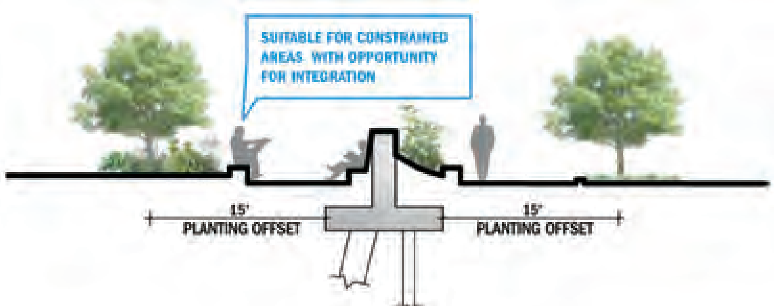
Once again, the planned design life for infrastructure of this magnitude would likely be on the order of 50 to 100 years. Accordingly, the barriers might ultimately need to be designed for approximately 2150 conditions, both in terms of initial construction (e.g., foundations to handle future

FIGURE 4.10

Example of Cross-section of the Overland Green and Grey Structures of Inner Harbor Barrier

Levee/Grading

When feasible, elevating the landscape can be the most cost-effective and integrated solution to flood protection.



Integrated Floodwall

There are many ways that a floodwall can be integrated into the design in a seamless way. This approach is suitable for areas that are spatially constrained, intervention height is relatively low, and opportunities exist for integrating a wall into the context.

Source: Proposal for South Battery Park City Resiliency Project, Arcadis

designs) and planning for adaptation (e.g., design height changes and anticipated footprint/right-of-way needs). Beyond initial design and adaptive planning, O&M should be accounted for throughout the life of the project. The estimated 50-year O&M cost is shown in Table 4.6. Note that O&M costs are shown for 50 years rather than 100 years because of the broad range of uncertainty in projecting O&M needs and costs too far into the future.

For the levee construction on land, low estimates assume it would consist primarily of relatively inexpensive earthen features and to a much lesser extent concrete seawalls. High estimates assume the features would consist of no earthen levees and entirely of more expensive concrete seawalls. There are some locations where only seawalls could fit, such as around certain areas of South Boston and the Seaport. As was done in the OHB analysis, the high estimate applies a 100% contingency, whereas the low estimate adds a 50% contingency on all costs.

Summary and Recommendations for a Feasible Barrier Option

Based on this analysis, the Outer Harbor Barrier, along with accompanying infrastructure improvements in outlying areas, would likely cost from \$8.0–\$11.8 billion, while the Inner Harbor Barrier would likely cost between \$6.5–\$8.7 billion to manage 2100 SLR and storm conditions. As with any planning-level cost estimate, there is wide latitude for cost estimate refinement and improvement. Loaded unit price and scaled cost features can be refined as alignment details, cross-section specifics, and more detailed design and data-gathering (e.g., surveys) leads to computer aided design sketches of the features. Unit price estimates will continue to be refined with information on quantities of materials and market research on local material availability. Immediate next steps could include continued research into defining the gate and its gray features, as these features comprise roughly 90 percent of the overall estimated cost for either the IHB or OHB.

Efforts such as the South and East Boston adaptation planning studies are already ongoing. The results of these studies and their outcomes—such as the features selected, their alignment, and the estimated costs for onshore concepts—will help inform offshore barrier estimates and should be incorporated into the overall project analysis as information becomes available.

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TABLE 4.5
Inner Harbor Barrier Capital Costs

Item	Quantity	Units	Cost (Millions $, 2017)		Percent of Total
			Low Estimate	High Estimate	
Planning, Engineering, Design, Permitting, and Construction Management	—	Percent of Construction Cost	$720	$970	11%
Levee Construction on Land	0–29,200	Linear feet	$90	$0	0–1%
Floating Sector Gate (1,500 ft)	1	Each	$3,700	$4,940	57%
Improvements to Existing Seawall and Construction of New Seawall	65,100–94,300	Linear feet	$290	$570	5–7%
Pump Stations	32,800	Cubic feet per second	$1,670	$2,230	26%
Right-of-Way	—	Acres	Not Included	Not Included	—
Mitigation Acreages	—	Acres	Not Included	Not Included	—
Total			**$6,470**	**$8,710**	

Note: Low Estimate = 29, 200 feet of levees and 65, 100 of seawalls. High Estimate = 0 feet of levees and 94,300 feet of seawalls.
Source: Arcadis

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TABLE 4.6
Inner Harbor Barrier Operation and Maintenance Costs

Item	Total Cost (Millions $, 2017)		Percent of Total Construction Cost
	Low Estimate	High Estimate	
Operations and Maintenance	$964	$1,286	15%

Source: Arcadis

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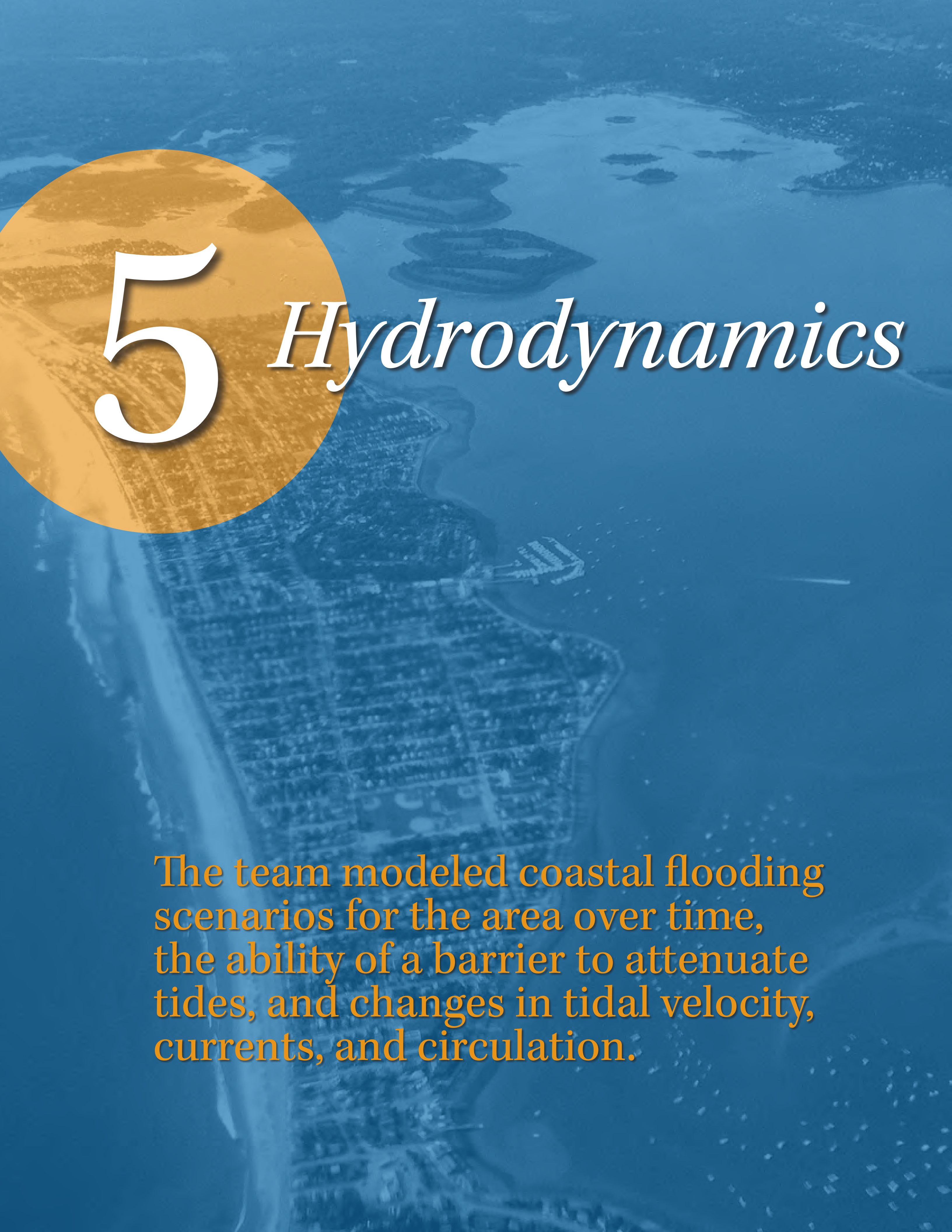


5 *Hydrodynamics*

The team modeled coastal flooding scenarios for the area over time, the ability of a barrier to attenuate tides, and changes in tidal velocity, currents, and circulation.

A Boston Harbor barrier would serve to protect the city from extreme coastal storm events, such as hurricanes and nor'easters, by inhibiting storm surge propagation into Boston Harbor.

Additionally, it has been suggested that a barrier would be able to reduce the impacts of sea level rise by lowering Boston Harbor's twice-daily high tide through restricting tidal flows. Therefore, a potential Boston Harbor barrier might also be able to delay chronic or nuisance coastal flooding due to sea level rise, as well as reduce the elevation of storm tides. Here we address the development of coastal flooding scenarios for the area over time, the efficacy of a storm surge barrier to attenuate the twice-daily tides inland of the barrier, and hydrodynamic concerns such as changes in tidal velocity, currents, and circulation.

Boston Harbor Flood Risk Model Summary

Following Hurricane Sandy, the Massachusetts Department of Transportation (MassDOT) and the Federal Highway Administration (FHWA) commissioned UMass Boston and Woods Hole Group to analyze the vulnerability of Boston's Central Artery/Tunnel project to sea level rise and extreme weather events. As part of that assessment, Woods Hole Group developed the Boston Harbor Flood Risk Model (BH-FRM). BH-FRM* is an integrated, probabilistic hydrodynamic model that includes the critical processes associated with storm-induced flooding (e.g., wind, waves, wave-setup, storm surge, river discharge, sea level rise, and future climate change scenarios) in Boston Harbor. It is calibrated to historical storm events using observed high-water data. BH-FRM has become the scientific standard in Boston and the region due to its ability to capture the net effect of varying storm types, magnitudes, and parameters, and to capture flood pathways within complex urban topographies (Bosma et al., 2015).

Floodplains without Barriers

We used the BH-FRM model and its associated Monte Carlo procedure to estimate flood depth probabilities at locations throughout the harbor for present sea level conditions, and for future conditions of 1, 3, and 5 feet of SLR relative to 2013. The flooding resulting from these scenarios throughout the harbor is shown in Figures 5.1 to 5.4. In addition, Figure 5.5 shows the approximate extent of flooding with a 1% exceedance frequency storm with 7 feet of SLR. This scenario was not developed using BH-FRM but instead by "bathtub" mapping the elevation of the 1% flood with 7 feet of SLR (16.7 feet NAVD88). Therefore, it should be considered as less accurate than the BH-FRM model.

We address the development of coastal flooding scenarios for the area over time, the efficacy of a storm surge barrier to attenuate the twice-daily tides inland of the barrier, and hydrodynamic concerns such as changes in tidal velocity, currents, and circulation.

Opening Size Considerations

As noted in Section 4, the Metro Boston Dike Barrier was eliminated from further analysis due to its extremely high cost with little additional benefits compared to the Outer Harbor Barrier (OHB). Therefore, evaluation of the efficacy of a potential harbor barrier to attenuate the tide in Boston Harbor, under normal tidal conditions, was limited to assessment of the Outer and Inner Harbor Barrier configurations.

The number, size, and configuration of the openings in the proposed barrier are the key parameters determining the barrier's ability to attenuate tidal exchange. Assuming the goals of continued, relatively unimpeded navigation into and out of Boston Harbor as well as some level of tidal flushing for water quality purposes are desired, then openings such as locks are not acceptable. As such, tidal gates, with the ability to close when needed (e.g., during storm events) are the most logical approach.

In order to potentially induce tidal attenuation in the harbor, small barrier openings would be needed; the smaller the total opening, the higher probability of creating tidal attenuation. However, the desire to maintain continued shipping requires openings large enough to accommodate vessels.

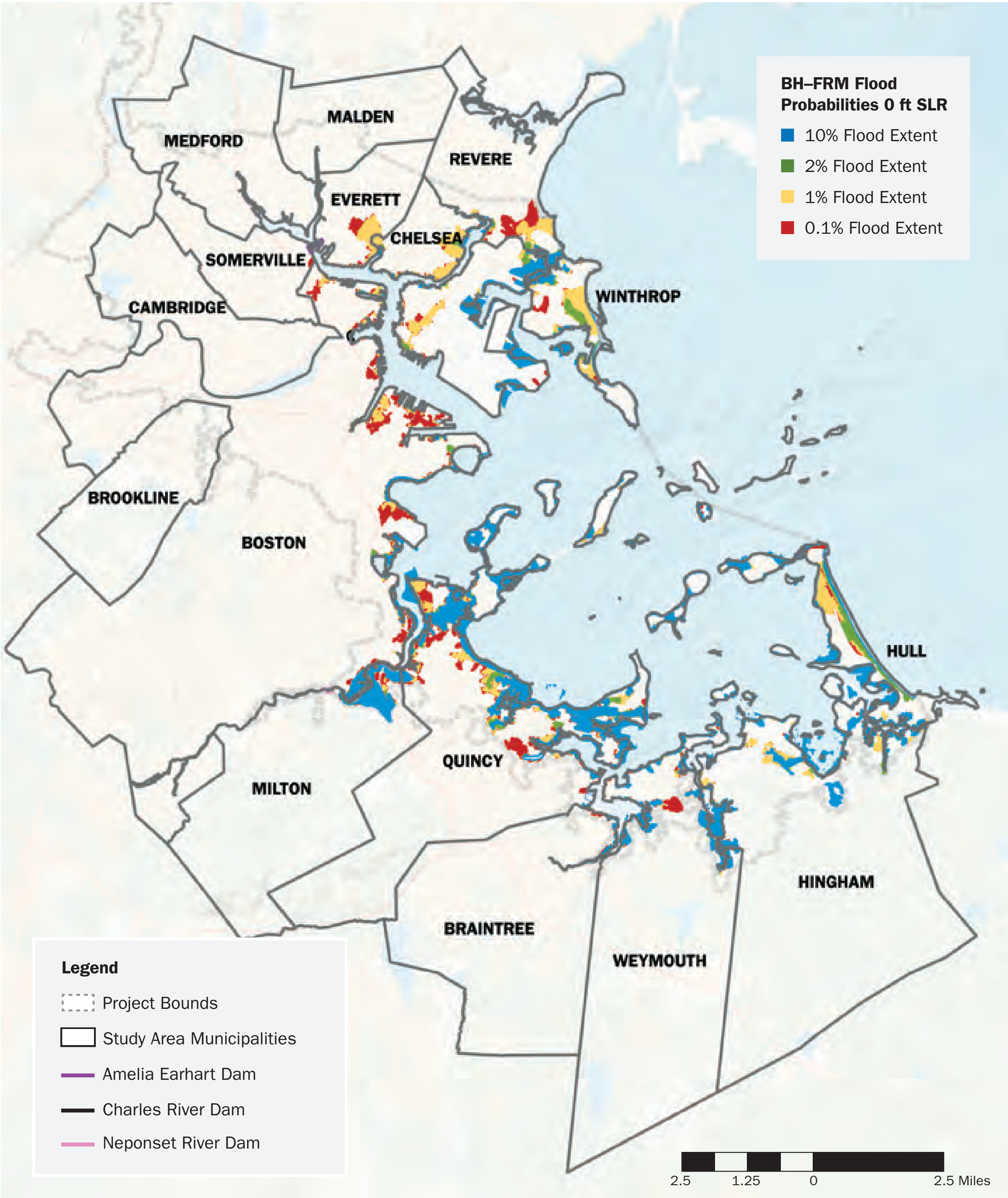
Outer Harbor Barrier

As described in Section 4, Woods Hole Group and UMass Boston worked with the United States

* For more information on the model, *https://www.massdot.state.ma.us/Portals/8/docs/environmental/SustainabilityEMS/Pilot_Project_Report_MassDOT_FHWA.pdf*.

FIGURE 5.1

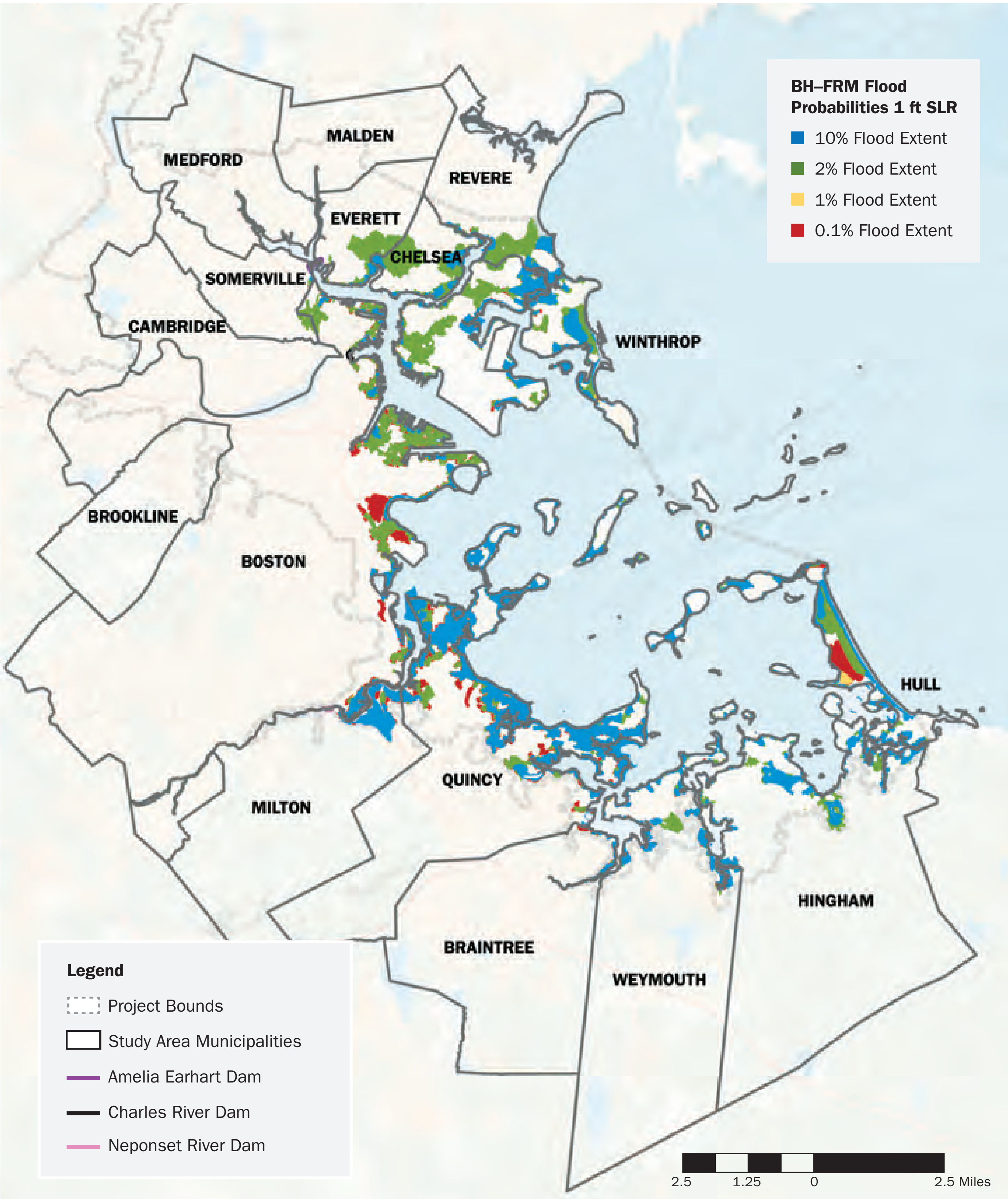
Boston Harbor—Probabilities of Flooding with 0 Feet SLR



Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

FIGURE 5.2

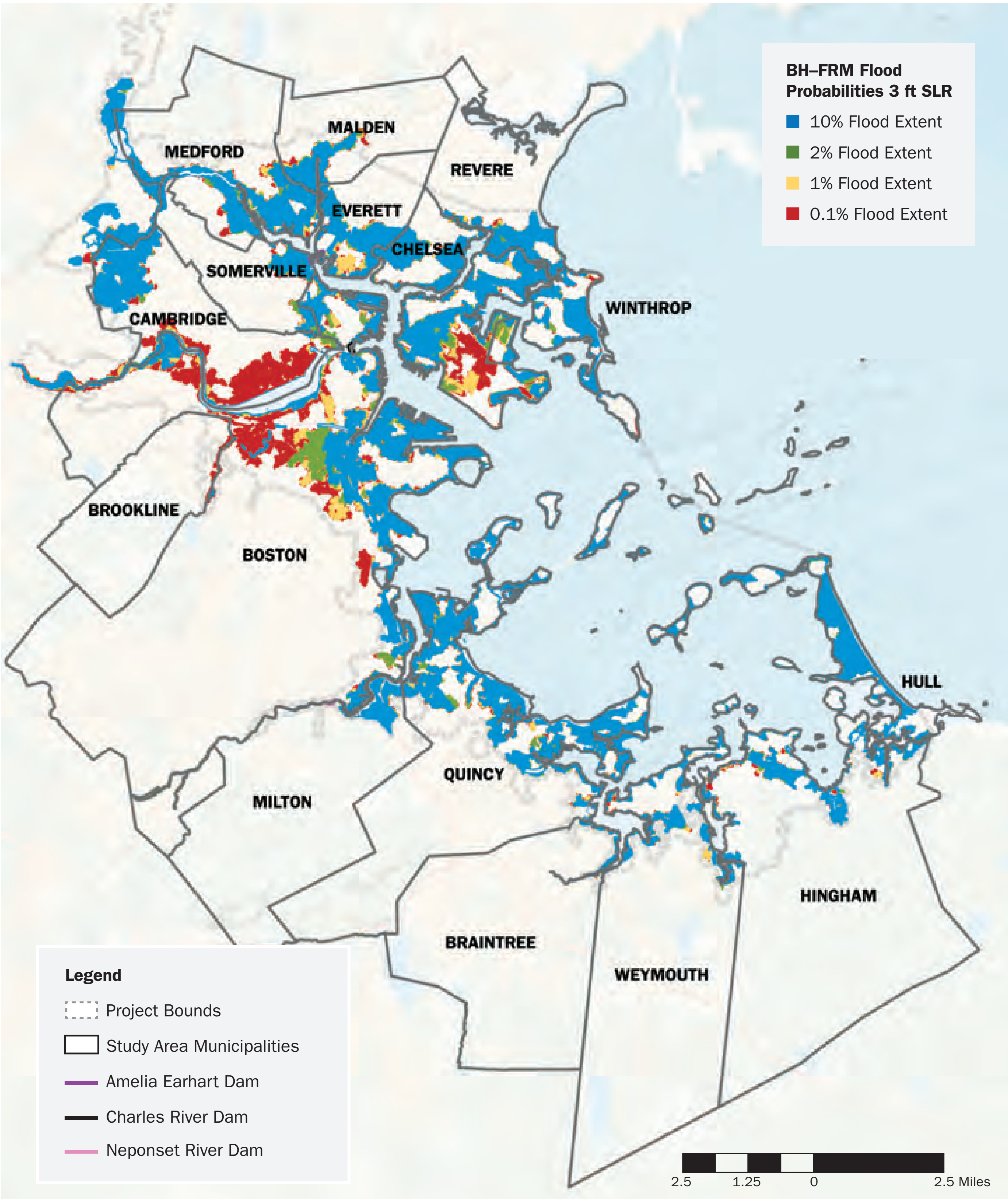
Boston Harbor—Probabilities of Flooding with 1 Foot SLR



Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

FIGURE 5.3

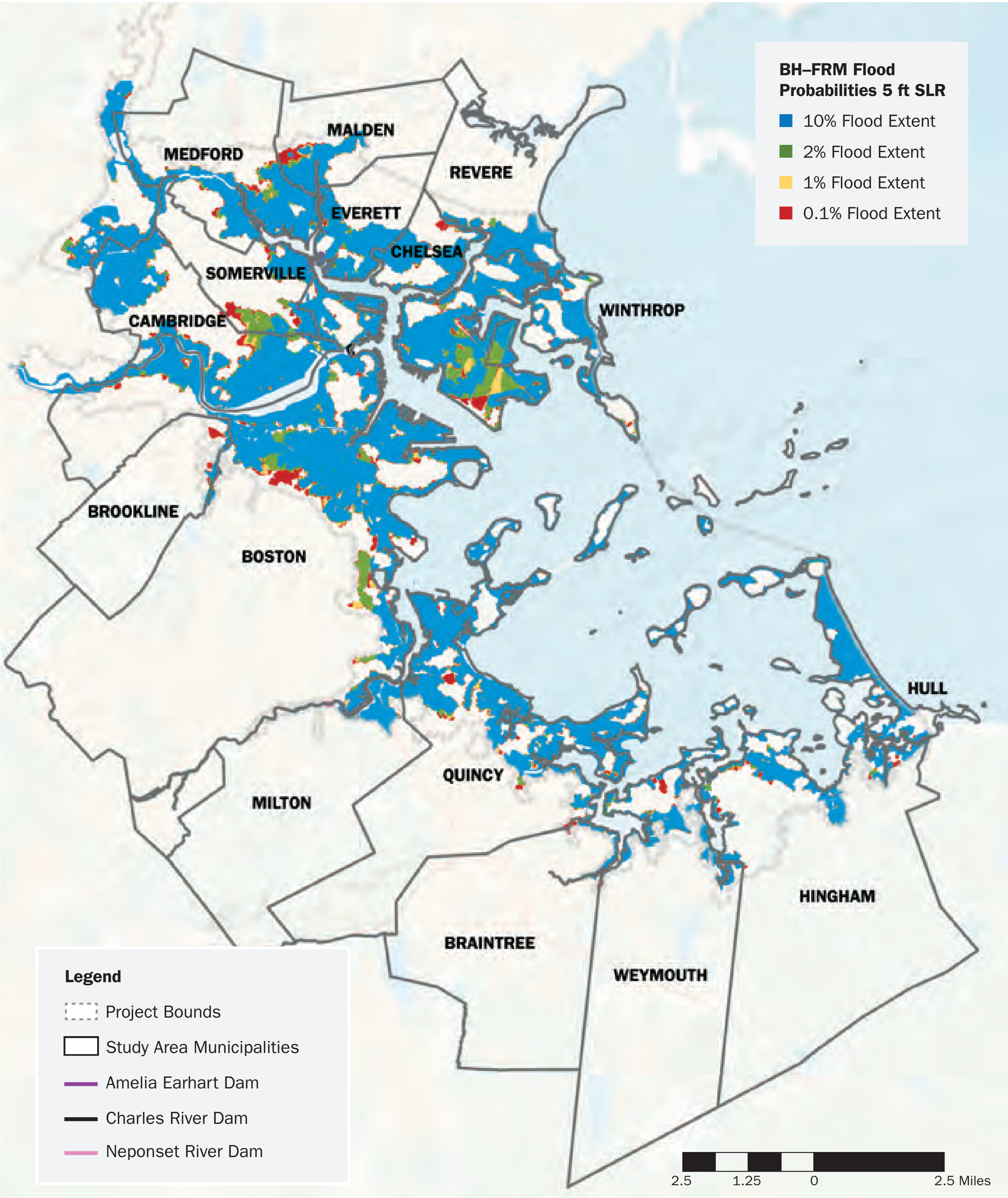
Boston Harbor—Probabilities of Flooding with 3 Feet SLR



Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

FIGURE 5.4

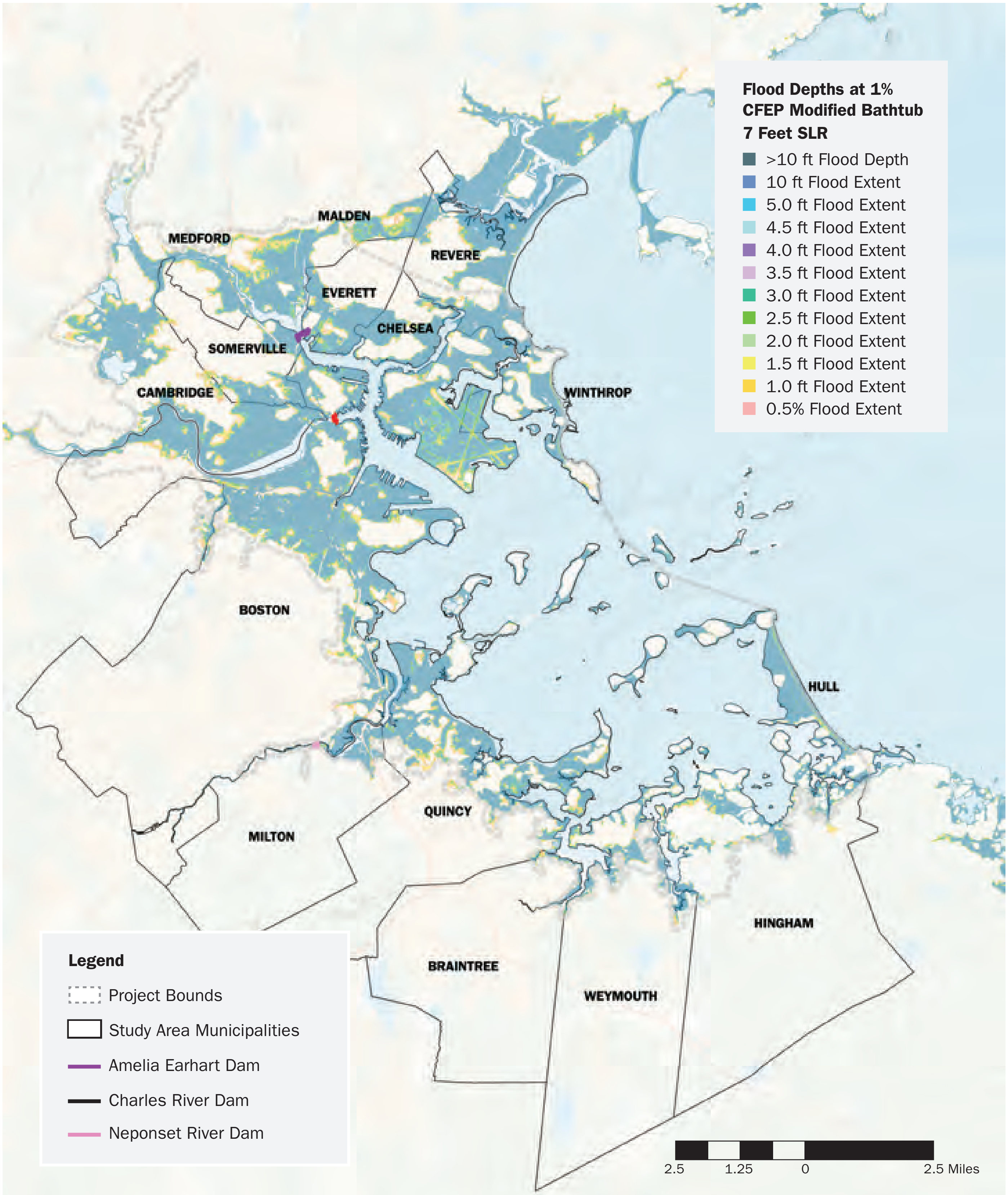
Boston Harbor—Probabilities of Flooding with 5 Feet SLR



Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

FIGURE 5.5

Boston Harbor Estimated Depths of Flooding with 7 Feet SLR



Sources: MassGIS, UMass Boston, NOAA, Woods Hole Group, Esri

Army Corps of Engineers, New England District to identify the smallest possible size, number and location of barrier openings that would maximize flood risk reduction while minimizing negative impacts on the environment and navigation. For the OHB, this consisted of two gated openings: a 1,500-foot opening between Deer and Gallops Islands and a 650-foot opening between Georges Island and Hull. The configuration modeled is shown in Figure 5.6. The presence of two gates allows for redundancy in the barrier design in case one tidal gate is under maintenance or non-functional. We aligned gate openings with the current federally-maintained navigational channels and they were considered the smallest possible gate openings that would still allow for large commercial and military vessels to enter the harbor. This configuration assumes that the barrier was aligned perpendicular to the authorized navigational channels and at least 10,000 feet away from any navigational turning basin. Even then, these small gate openings would likely require navigational supports and not allow for completely uninhibited vessel movement. Ultimately, with these minimum opening sizes, ship simulations would be required to ensure navigational safety.* The impacts of open vertical lift gates on tidal and circulation impacts were not modeled; the openings are not large enough to make a significant change in the results.

We conducted simulations to determine the potential impacts over a full lunar tidal cycle (30-day tidal simulation) with and without the barrier in place.** Gates were left open for tidal conditions with the barrier in place. Effects on water surface elevations were evaluated at five points located inside and just outside Boston Harbor to assess potential changes to hydrodynamics due to the barrier and gates. These approximate locations included:

- East of Deer Island (outside the barrier);
- Southwest of Deer Island (inside the barrier);
- Boston's inner harbor, mid-channel between Logan Airport and the Seaport District;
- Fort Point Channel (at the NOAA tidal station); and
- Hingham Bay.

Each of these water elevation points is shown in red in Figure 5.7.

Changes in tidal velocity magnitudes were also evaluated at six locations in and around the barrier openings and key locations within the harbor. These included:

- Inside the northern barrier opening;
- Inland of Lovells Island but seaward of the barrier;
- Inside the southern barrier opening;
- Inland of Gallops and Georges Islands landward of the barrier island;
- Between Moon and Long Islands; and
- Between Peddocks Island and Houghs Neck.

Each of these velocity points is shown in orange in Figure 5.7.

Changes in tidal velocity magnitudes were evaluated at six locations in and around the barrier openings and key locations within the harbor.

TIDAL ATTENUATION RESULTS FOR OUTER HARBOR BARRIER

Figure 5.8 summarizes the impacts of the OHB on tidal attenuation at the four water surface elevation observation points located inland of the barrier as simulated by the Boston Harbor Flood Risk Model. The solid line represents a snapshot of the time series of existing water surface elevations in Boston Harbor, while the dashed green line represents the time series of water surface elevations with the Boston Harbor barrier in place. The vertical axis represents the water surface elevation in feet relative to the NAVD88 datum (where 0 NAVD88 is approximately mean tide level). The horizontal axis of each sub-figure is model time in days. At all four locations, the barrier had no discernable impact on the height of Boston Harbor's tides, as indicated by the fact that the solid and dashed lines are identical.*** These

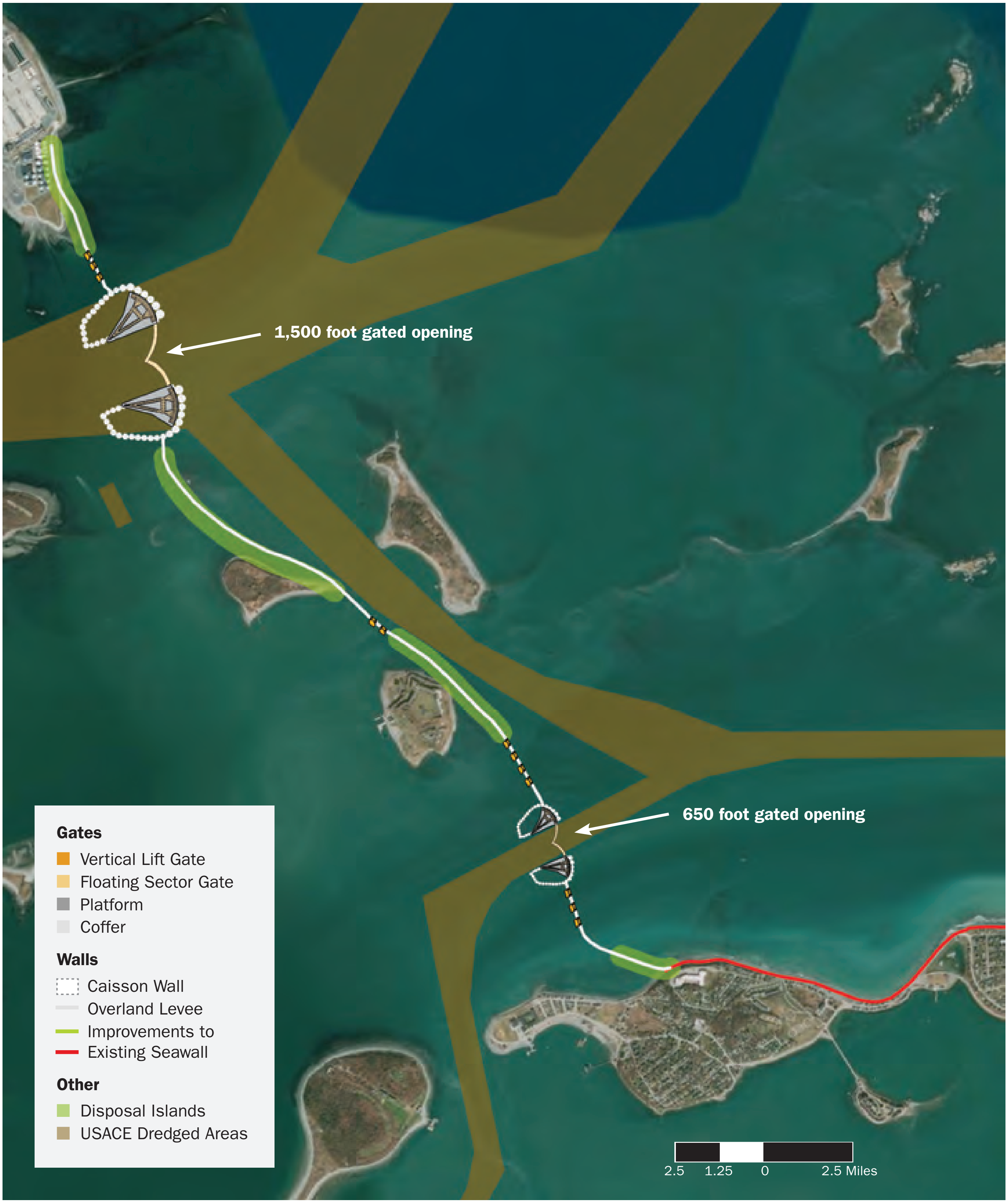
* Paradoxically, the smaller the barrier openings, the greater the need for use of tugboats due to higher tide current velocities, which means larger barrier openings may be required.

** There is no need to simulate storms in this analysis, as storm surge barriers would close in extreme weather if necessary.

*** As sea level rises, the impact of the OHB on tidal attenuation, which has shown to be non-existent under present sea level, would only lessen, not increase. As sea level rises, the range of the tide cycle remains the same, but the mean water surface elevation increases. This means the average cross-sectional area of the opening gets larger, which would only ease the volumetric transfer of ocean water. For example, with two feet of sea level rise, a barrier opening of 45 feet deep by 1,500 feet wide would expand to 47 feet deep by 1,500 feet wide, increasing the area of the opening by just over 4%.

FIGURE 5.6

Hypothetical Boston Harbor Barrier Modeled for Tidal Attenuation



Sources: Arcadis, Woods Hole Group

results indicate that the barrier openings do not inhibit tidal exchange into the harbor at any significant level as the volumetric flux into the harbor remains the same. The volume of water entering and exiting the harbor over a tidal cycle is the same with or without the barrier (with gates open) in place.

Since tidal range is not attenuated by the proposed OHB, the tidal benchmarks presently occurring within the harbor will not be impacted by the presence of the barrier structure. As such, Mean High Water (MHW), Mean Higher High Water (MHHW), Mean Low Water (MLW), tidal range, and any other deterministic benchmarks would not change due to the barrier.

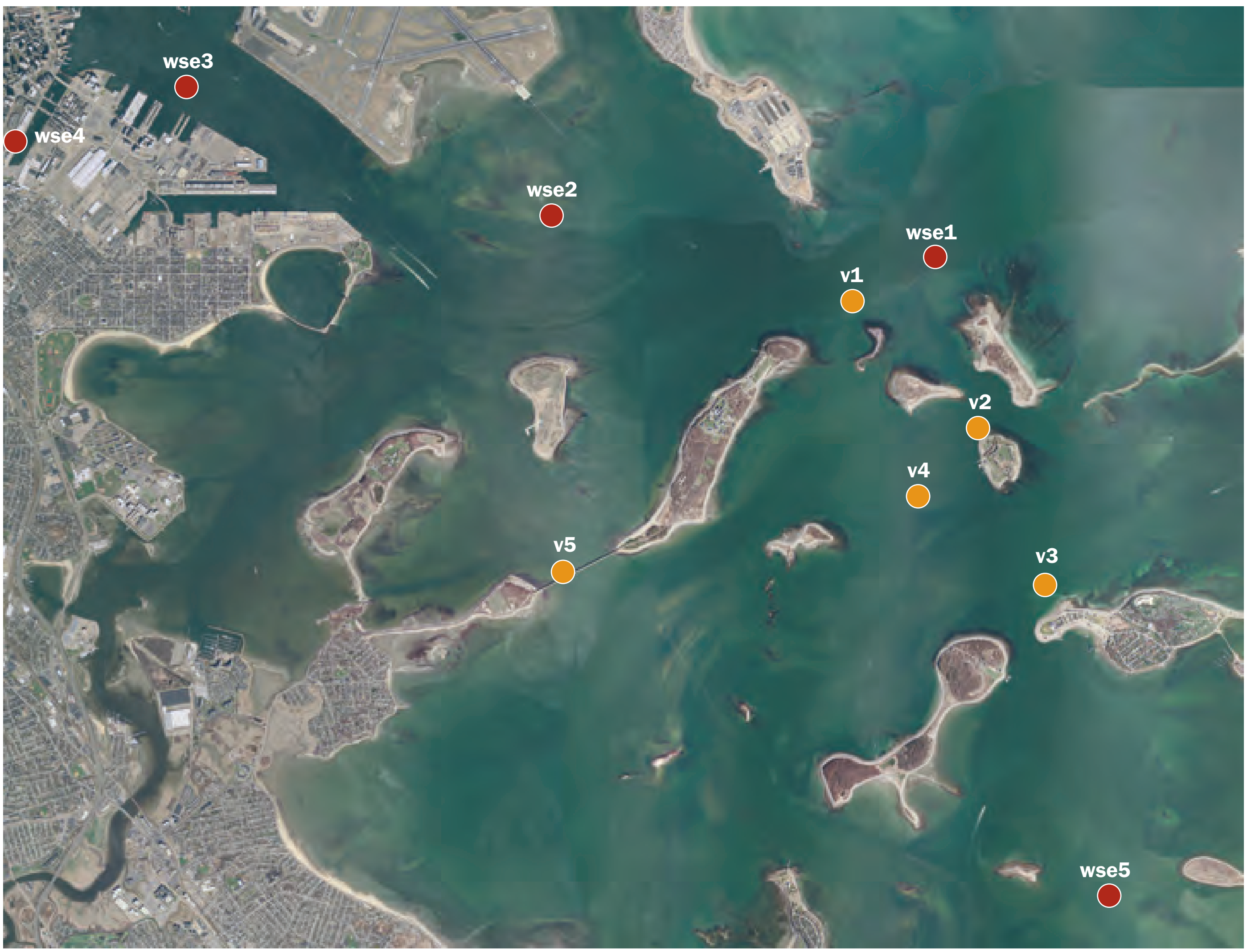
Without attenuating the tide, these tidal benchmarks will continue to rise in concert with sea level rise unless there is a change in the tidal constituents that make up the net tidal signal on a regional scale. Therefore, the barrier (with gates open) would not protect the city from future nuisance flooding that would be caused by increased mean sea levels. The barrier could only serve as a storm protection structure that can effectively protect the city from a storm surge.

TIDAL CIRCULATION AND VELOCITY FOR OUTER HARBOR BARRIER

Since the tides would remain the same in the harbor with the outer barrier in place, approximately the

FIGURE 5.7

Model Observation Locations



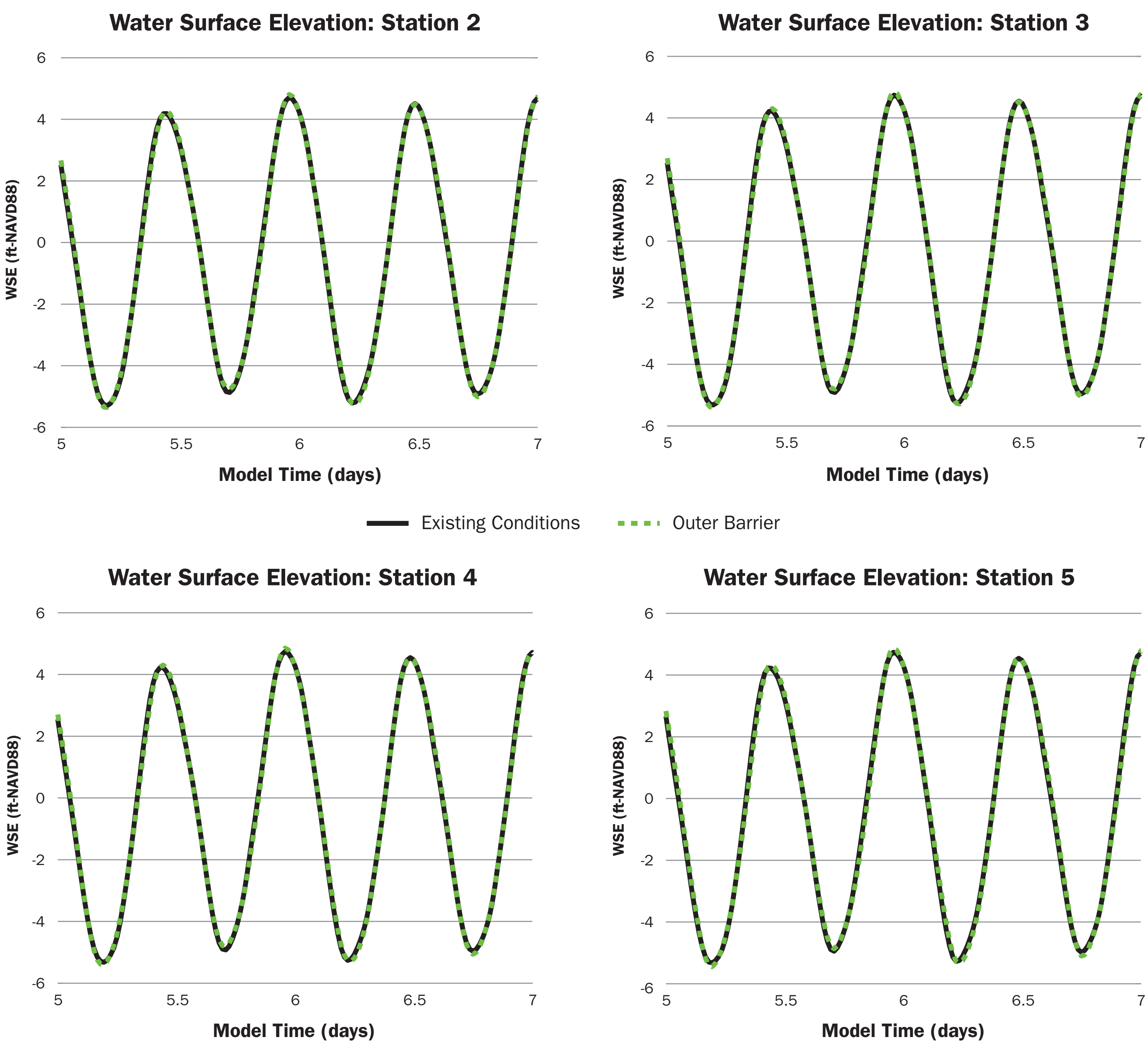
Water Surface Elevation (wse) stations are indicated in red. Velocity (v) stations are indicated in orange.

Source: Woods Hole Group

same volume of water would enter and exit the harbor on each tidal cycle. However, since the net opening size would be much smaller with the barrier in place, a significant change in current velocities would be expected, especially in the vicinity of the barrier gate openings. Figures 5.9 and 5.10 show a snapshot of currents within Boston Harbor during approximately peak flood tide for existing conditions, and with the OHB in place, respectively. The figures depict only changes in velocity and circulation near the proposed barrier; no significant changes in overall circulation (throughout the tidal cycle) were observed inland of Long Island. Color contours on the figures

FIGURE 5.8

Simulated Effect of Boston Harbor Barrier on Boston Harbor's Tides

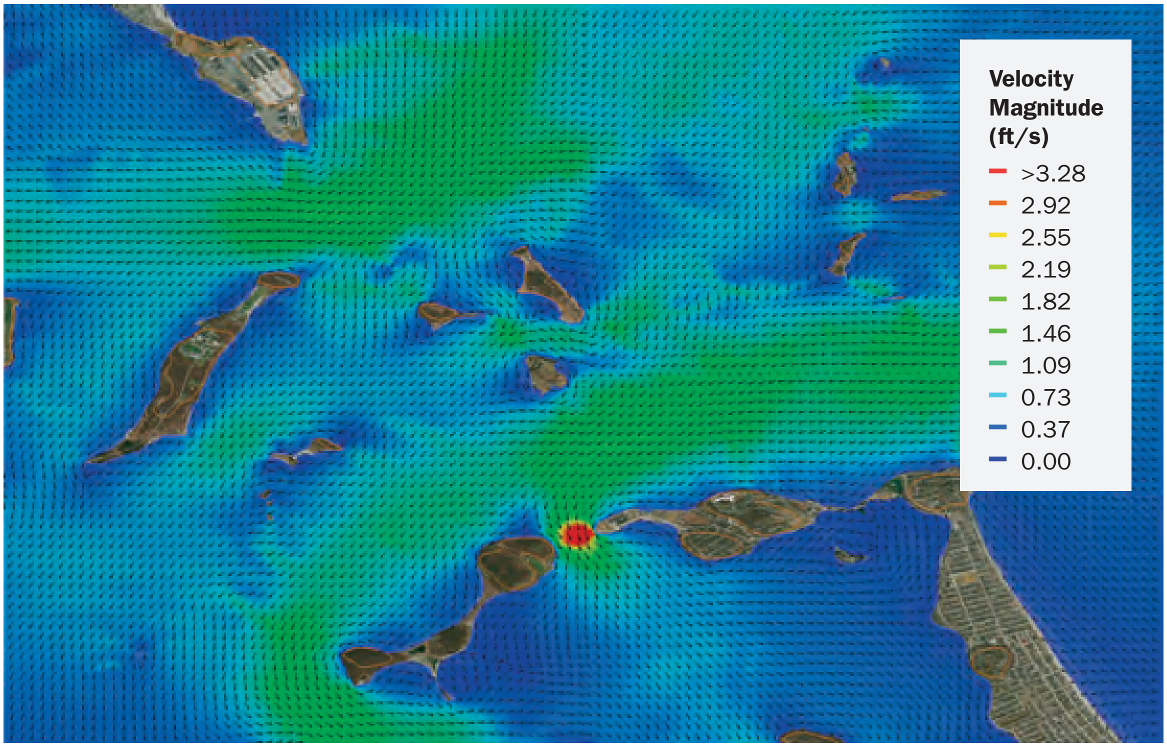


Time series of water surface elevations are presented without (black solid line) and with (green dashed line) the barrier at four observation stations within the harbor.

Source: Woods Hole Group

FIGURE 5.9

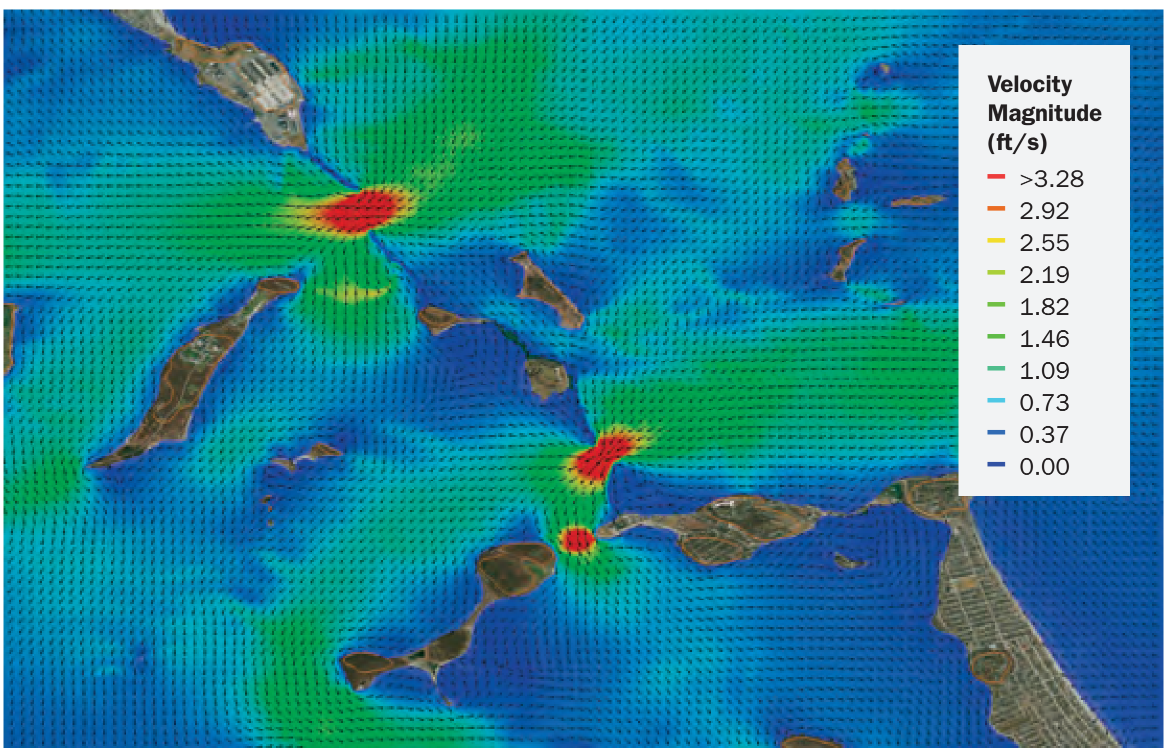
Simulated Existing Tidal Currents in Boston Harbor During Peak Flood Tide (1 ft/sec = 0.6 knots)



Source: Woods Hole Group

FIGURE 5.10

Simulated Existing Tidal Currents in Boston Harbor During Peak Flood Tide (1 ft/sec = 0.6 knots)



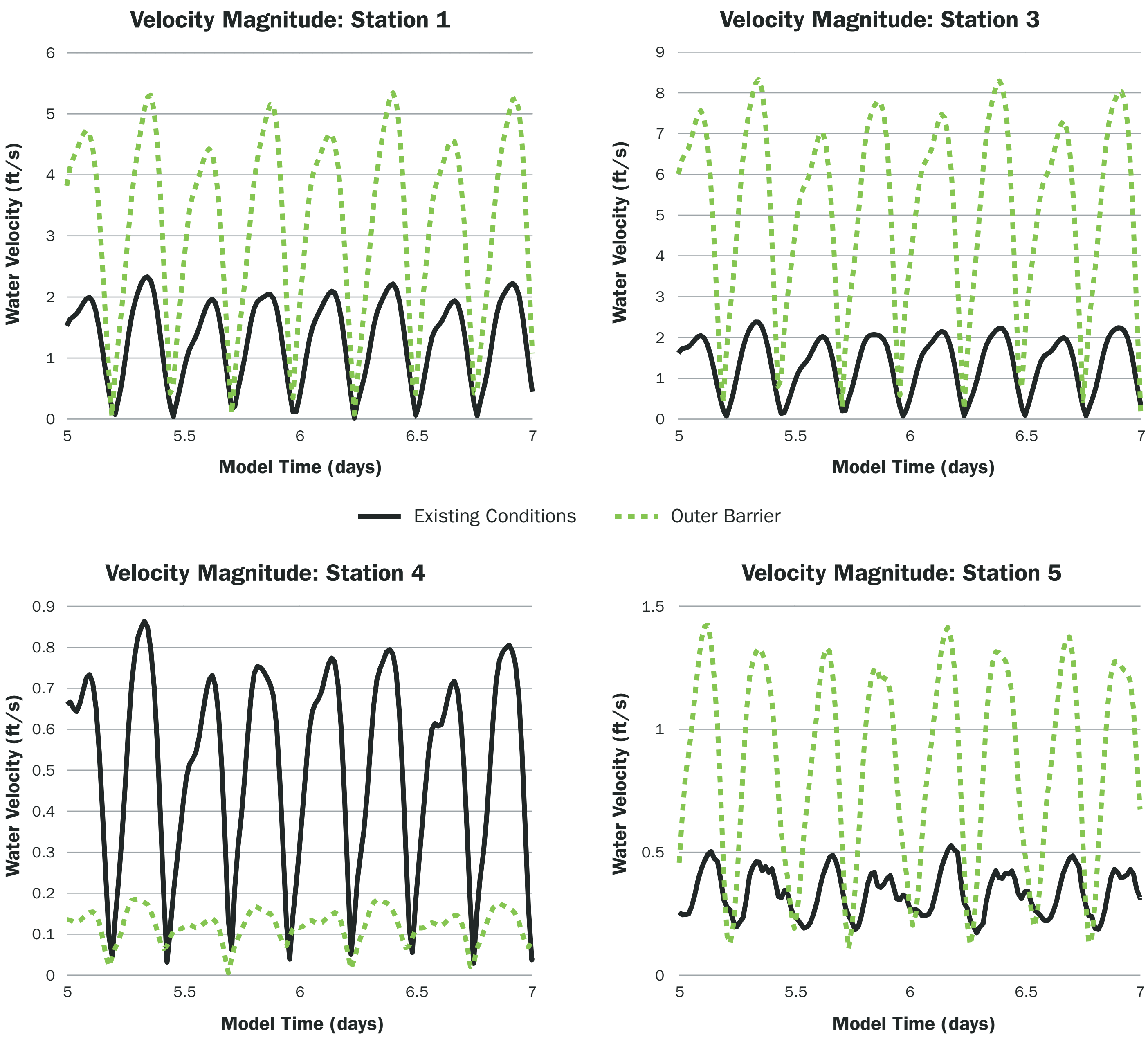
Source: Woods Hole Group

indicate velocity magnitude (reds are higher), while the vectors indicate the direction of current flow.

Visual comparison of Figures 5.9 and 5.10 shows some clear changes in tidal current magnitudes, especially in the vicinity of the gate openings. However, there are also some relevant changes that can be observed at specific locations inside the harbor. For example, there is a clear increase in velocity on the western end of Long Island with the barrier in place. As such, while the water surface elevations throughout the harbor would not change significantly, the circulation dynamics and localized velocities would be expected to be modified by the implementation of an Outer Harbor Barrier.

FIGURE 5.11

Simulated Change in Tidal Current Magnitude Caused by Outer Harbor Barrier



Time series of current velocities are presented without (black solid line) and with (green dashed line) the barrier at four observation stations within the harbor (1 ft/s = 0.6 knots)

Source: Woods Hole Group

Figure 5.11 shows how the velocity magnitude changes at four of the velocity stations over a sample two-day time period. The horizontal axis presents model time in days, while the vertical axis presents the magnitude of the current velocities. The black solid line is the current magnitude for existing conditions, while the dashed green line presents results with the barrier in place.

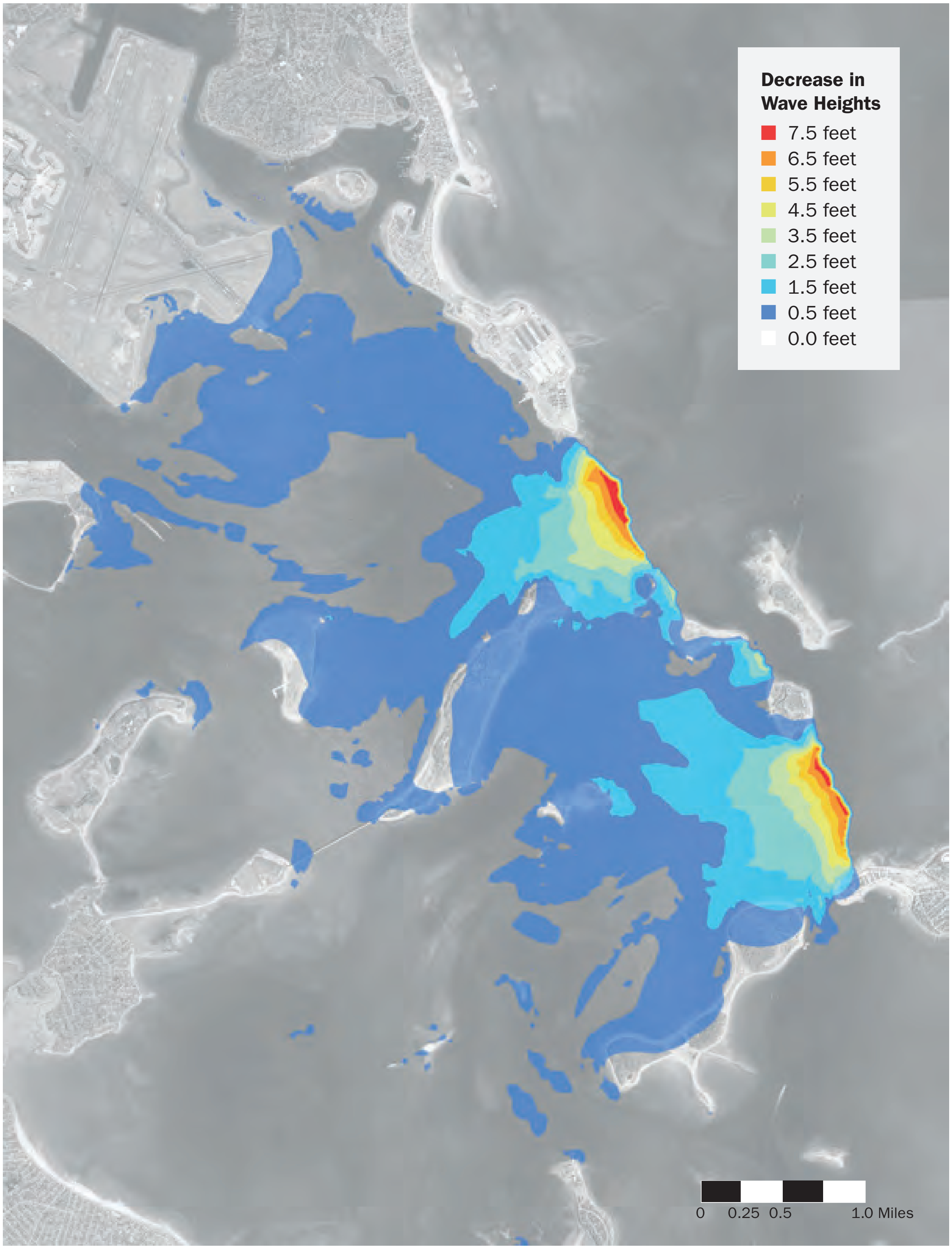
Figure 5.11 shows that the OHB would increase maximum tidal velocities from approximately 1.3 knots to 3.3 knots at the northern navigational opening (1,500-foot gate, V1), and from 1.3 knots to 5.1 knots at the southern navigational opening (650-foot gate, V3). These high velocities would make navigation challenging for certain vessels, such that entry and exit into the harbor might not be available throughout the entire tidal cycle. Additionally, the maximum tidal velocities in the area just landward of the barrier between Gallops and Georges Island (V4) would drop from 0.5 knots to 0.1 knots.

Current velocities would also increase on both the western and eastern ends of Long Island. Because the northern gate opening is larger than the southern gate opening, more water would now be required to enter the northern portion than the southern portion of Boston Harbor in order to fill the harbor. This would result in a net flow from north to south at either end of Long Island in order to maintain equilibrium in the water level. As such, when compared to existing conditions, the OHB would result in different tidal circulation between north and south, depending on the direction of the tide. Net flow would run from north to south as the flood tide comes in, and from south to north as the ebb tide goes out.

With the gates closed, the OHB would also decrease wave heights compared to existing conditions. Figure 5.12 shows the reduction in heights for an event similar to the Perfect Storm of 1991. As can be seen, the wave height reduction along most shorelines is approximately one foot or less, and in the inner harbor there is essentially no change. This is not overly surprising since the wave heights along the shorelines are not that large even under current storm conditions due to the overall sheltering of the harbor (the islands, while not reducing the surge, effectively

FIGURE 5.12

Decrease in Wave Height (feet) with Gates Closed Compared with Existing Conditions (no barrier) for Storm Similar to Perfect Storm of 1991 with 0 SLR



Source: Woods Hole Group

attenuate waves). These results also demonstrate the importance of wind-generated waves in the harbor. There is a decline in the wave height difference at distances further landward from the barrier. Thus regeneration under the large winds occurring during storm events is a major component of waves in the harbor, and the barrier does not inhibit that condition. Although non-storm wave conditions are generally small, the barrier is expected to reduce day-to-day swell conditions from the ocean. In addition, while not modeled, the average wave conditions in the harbor would likely be slightly reduced on an annual basis.

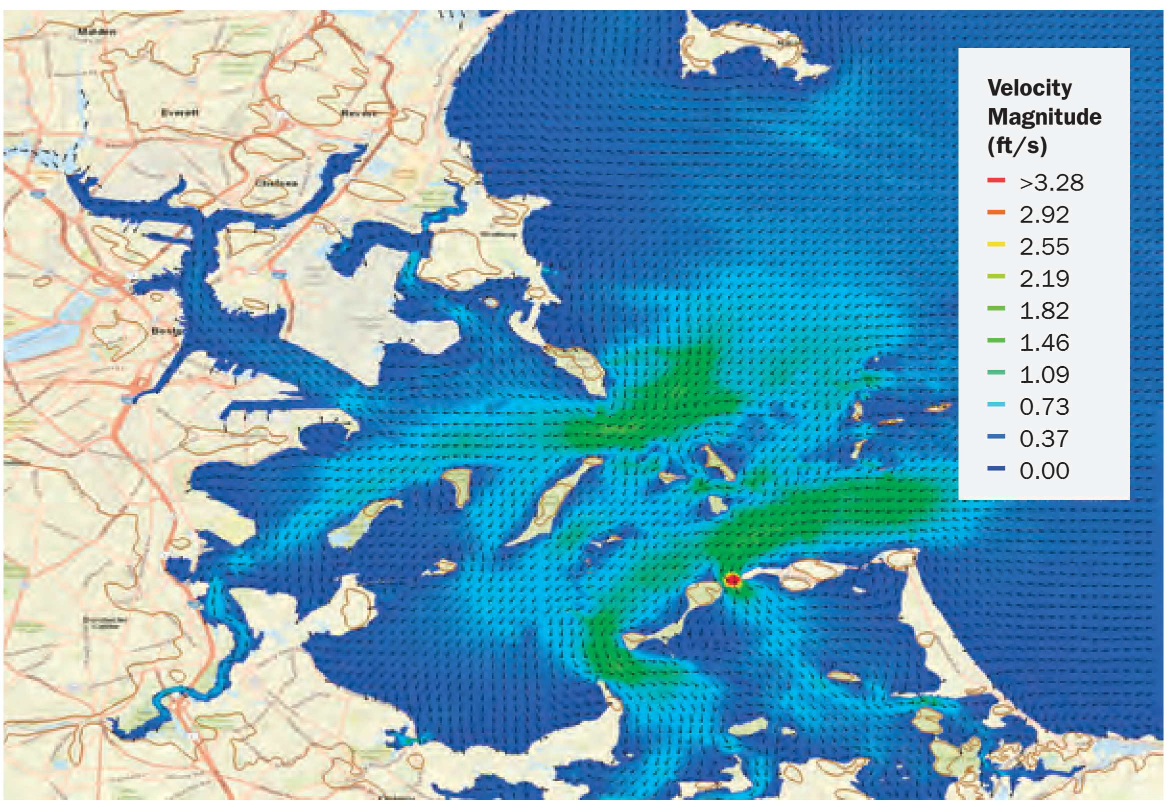
These effects could be expected to have some impact on the net shoreline change and sediment movement (discussed in Section 6). It is likely that these conclusions, based upon 0 SLR, may change slightly with SLR added, since it has been clearly demonstrated that increased water depths impact both storm surge and wave conditions.

POTENTIAL IMPACTS TO GREATER OCEAN CIRCULATION

Potential impacts to larger oceanic circulation patterns by the OHB were also investigated using the hydrodynamic model. While there were no differences in circulation dynamics found for cases when the barrier was open under normal tidal conditions compared to present circulation (Figures 5.13 and 5.14), with the gates closed during storms, local circulation dynamics outside of the barrier did change (Figure 5.15). Specifically, the magnitude and direction of tidal currents along the shoreline of Hull were altered. Under existing conditions, flood tidal currents run along the shoreline of Hull, entrained by the entrance to Boston Harbor; however, with the barrier gates closed, flood tidal currents are not as well defined along this stretch of coastline. In fact, as shown below, the flood tidal currents with the gates closed during storms may be perpendicular to the coast. This could result in changes to the sediment transport patterns and nearshore currents in this area, especially during the time proceeding, during, and just following a storm surge event when the barrier gates are closed. However, Hull may also require significant shoreline alterations and protection due to future sea level rise.

FIGURE 5.13

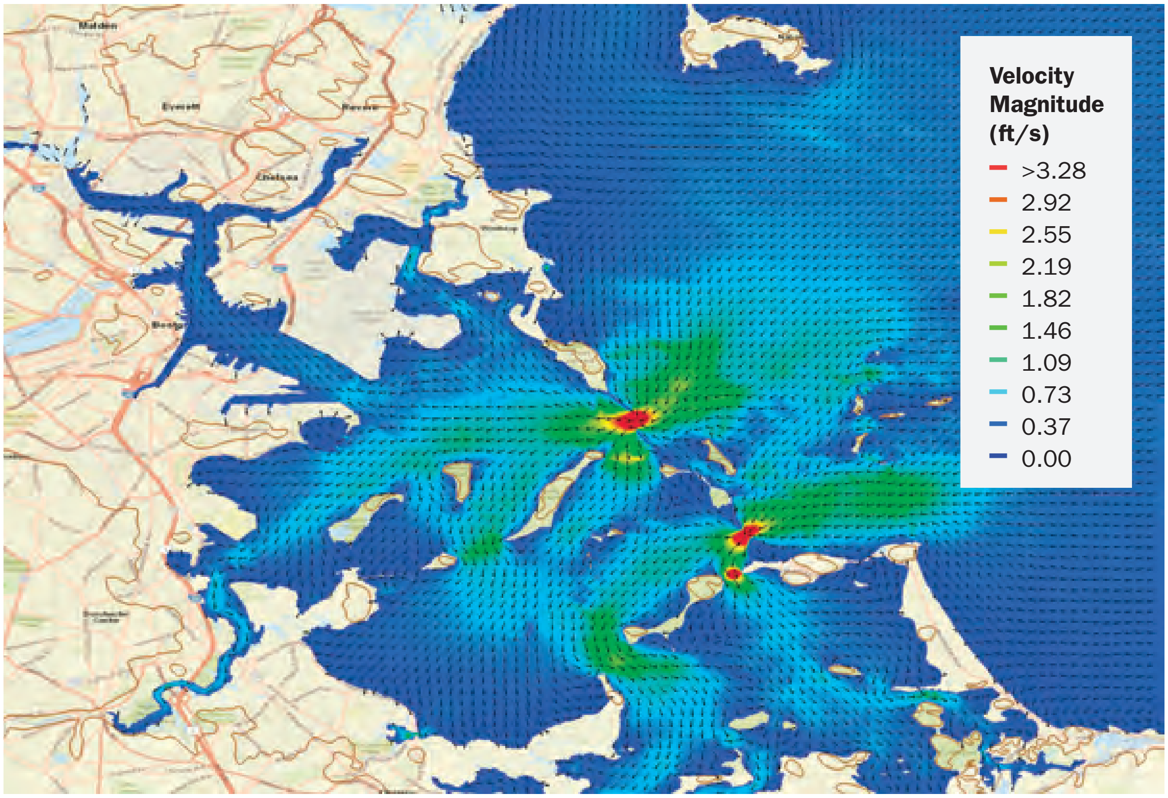
Circulation with No Barrier



Source: Woods Hole Group

FIGURE 5.14

Circulation with Barrier Open



Source: Woods Hole Group

FIGURE 5.15

Circulation with Barrier Closed During Storm

Source: Woods Hole Group

POTENTIAL IMPACTS TO TIDAL FLUSHING

While the OHB would have insignificant impacts on the range and levels of the tide within Boston Harbor, its impacts on general circulation might induce some changes to water quality within the harbor. Since the tidal range remains the same with or without a barrier, basic calculations of tidal flushing would also remain similar. We carried out particle tracking simulations, in which tens of thousands of particles are tracked in Boston Harbor, for conditions with and without the OHB. With the barrier in place, results indicated specific local zones of stagnation compared to existing conditions. Generally, these areas were located adjacent to the barrier itself, as shown in Figure 5.16. This change in tidal flushing might not have significant impacts on the overall water quality within the harbor, but the results indicate that some areas would be more prone to sediment deposition and/or water stagnation (see Section 6, Environmental Impacts).

Hydrodynamic Changes with the Inner Harbor Barrier

The Inner Harbor Barrier (IHB) was evaluated in a similar manner to the potential OHB. The same 30-day tidal simulations were also conducted for a scenario with an inner barrier located between South Boston and Logan Airport. Because the size of the required opening (approximately 1,500 feet) is not much less than the width of the current channel at this location, the barrier had minimal impacts on the hydrodynamics. This lack of effect is not surprising for two reasons: the smaller volume of water (relative to the outer harbor) that needs to be exchanged in the inner harbor through the proposed barrier opening, and the similarity of the opening size at the barrier gate to the existing opening. As expected, the tides in the inner harbor, landward of the barrier, remained the same with or without the barrier in place, and tidal currents (Figure 5.17 and Figure 5.18) only change in the immediate vicinity of the proposed barrier, with peak differences in magnitude increasing from 0.4 knots (existing conditions) to 0.6 knots (with barrier). Essentially, there would be a minimal change to the hydrodynamic within the harbor for the inner barrier configuration when the gates of the barrier are open.

As with the outer barrier, the tidal benchmarks occurring within the inner harbor will not be impacted by the presence of the barrier structure, since tidal range is not attenuated. Without attenuating the tide, these tidal benchmarks will continue to rise in concert with sea level rise. Therefore, the IHB (with gates open) would not protect the city from future nuisance flooding that would be caused by increased mean sea levels. The IHB can only serve as a storm protection structure that can effectively protect the inner city from a storm surge condition.

However, when the gates of the barrier are closed during a storm event, the Charles and Mystic River discharge will also be sequestered behind (landward of) the gates in the inner harbor. While this process was not a concern for the OHB (due to the large storage capacity of outer Boston Harbor), the smaller storage capacity of inner Boston Harbor is not adequate to store freshwater volumes during the time period of a closed barrier (approximately 24–48 hours for a nor’easter event) and would cause upstream flooding in the system.

FIGURE 5.16

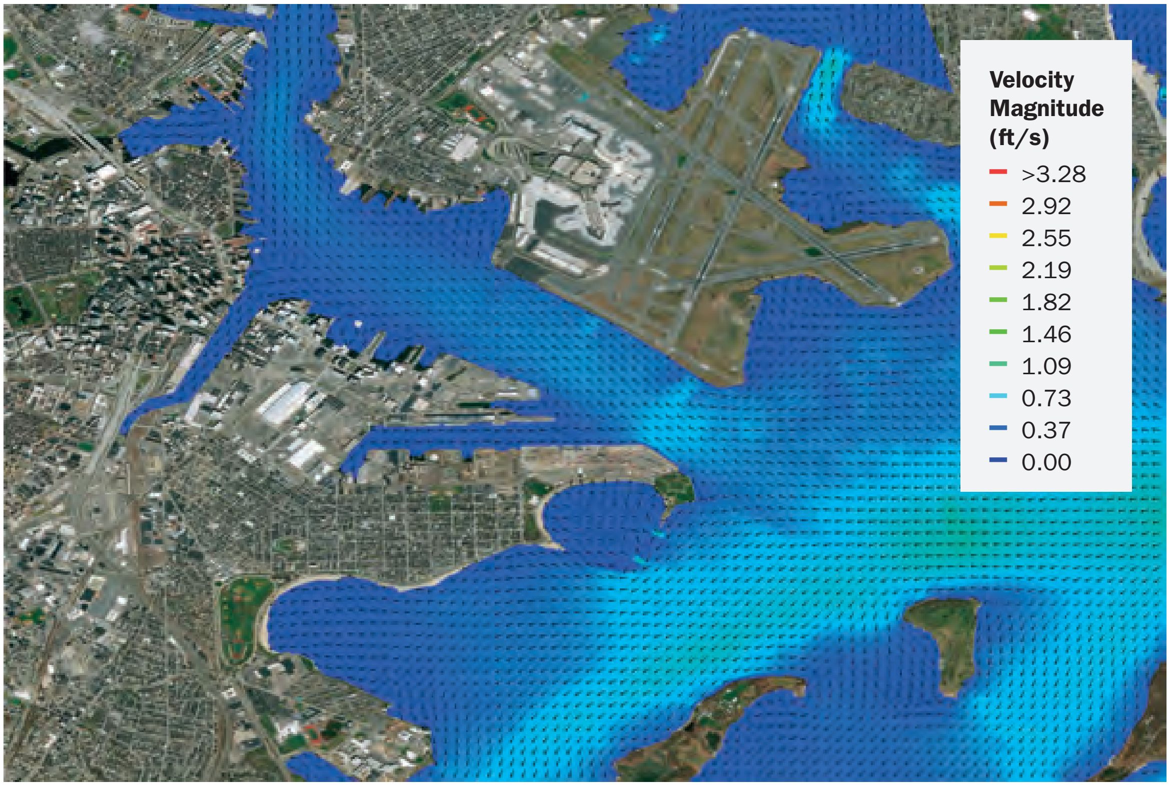
Location of Potential Stagnation with the Outer Harbor Barrier, as Revealed During Particle Tracking Simulations

Source: Woods Hole Group

> Because the northern gate opening is larger than the southern gate opening, more water is now required to enter the northern portion than the southern portion of Boston Harbor in order to fill the harbor. This results in a net flow from north to south at either end of Long Island in order to maintain equilibrium in the water level.

FIGURE 5.17

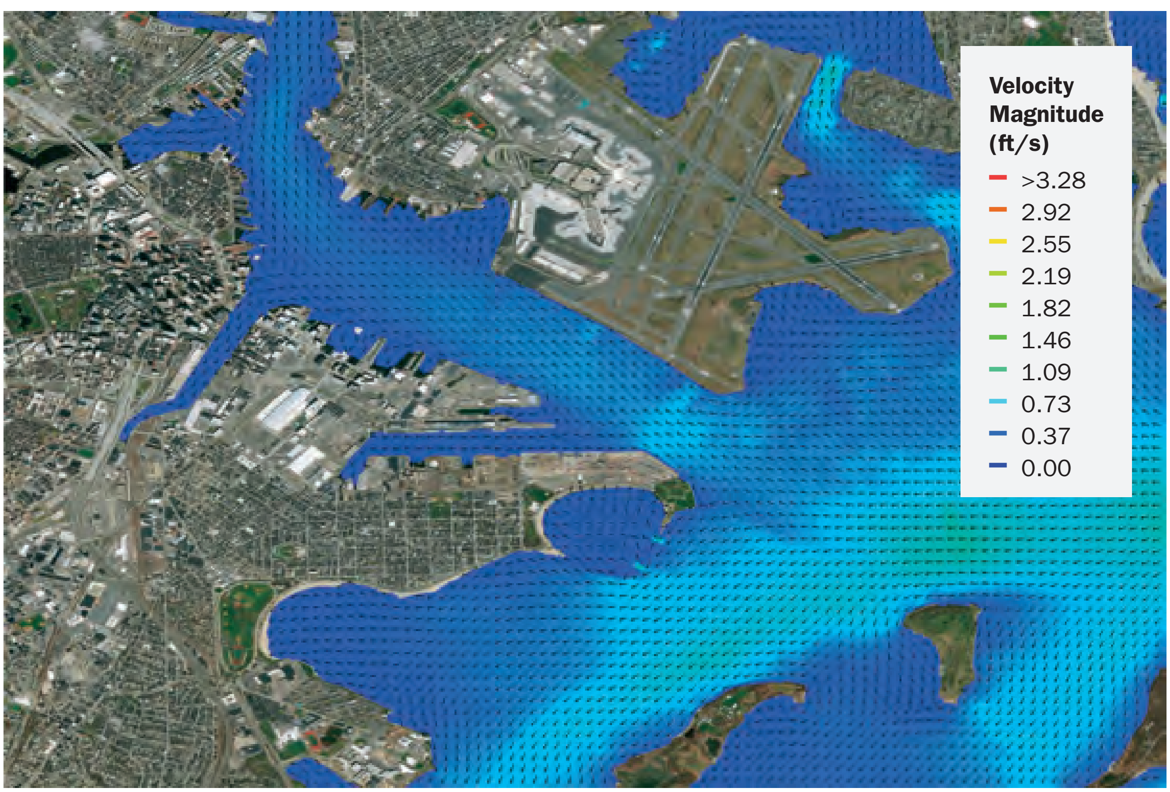
Velocities with No Inner Barrier (1 ft/s = 0.6 knots)



Source: Woods Hole Group

FIGURE 5.18

Velocities with Inner Barrier in Place and Opened (1 ft/s = 0.6 knots)



Source: Woods Hole Group

Therefore, additional engineering elements such as pumps would be required to manage this freshwater discharge during gate closures, as described in further detail in Section 4. Even with the pumps, however, there is the potential for environmental impacts, which are discussed in Section 6.

Gate Closure Analysis

Once a barrier system is built, eventually it will require very frequent closure as future high tide elevations approach the present elevations of storm tides. The analysis is based upon the shore-based protection scenarios described previously in Section 3. The analysis applies equally to both the Inner and Outer Harbor Barriers. The City of Boston and several other municipalities within Boston Harbor have already carried out coastal flooding vulnerability assessments. Boston has also conducted several pilot projects to develop conceptual designs and costs for barriers on the flood pathways into Boston, such as the East Boston Greenway and the Schrafft Building area in Charlestown (Climate Ready Boston, 2017). The flood barrier systems are designed to manage flooding with elevations of approximately 14 feet NAVD88—approximately the 1% flood elevation in 2070 under a moderately high SLR scenario. In the closure analysis, we investigated how frequently closure would be necessary under several SLR scenarios and with multiple levels of shoreline protection.

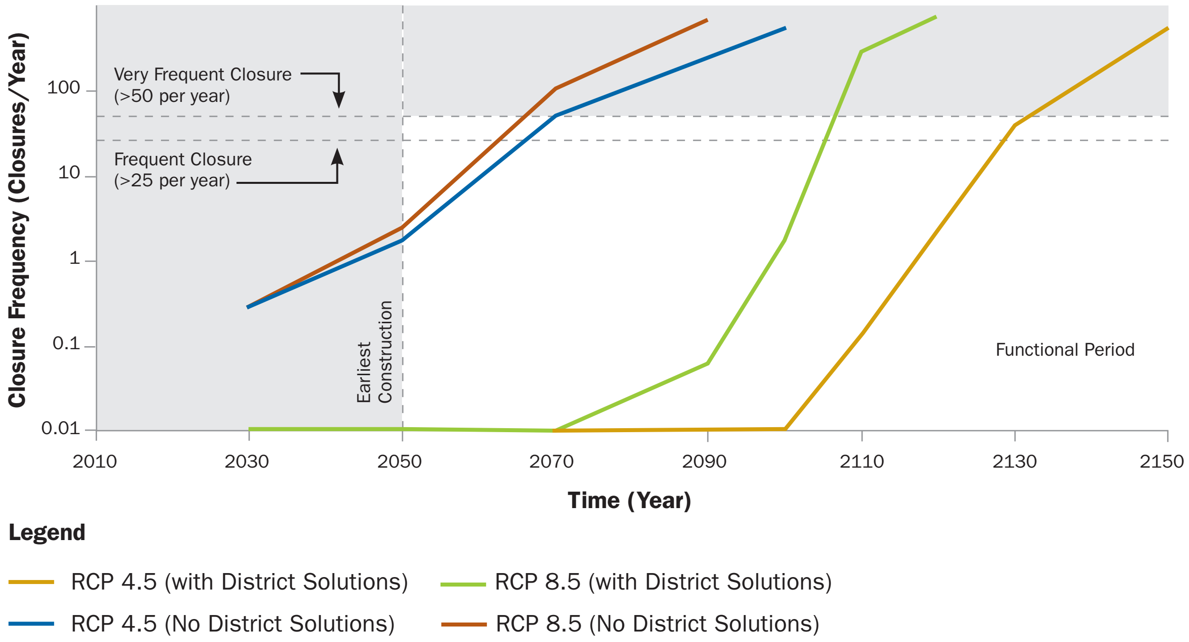
We calculated the number of annual closures by determining when gates would need to be closed to prevent exceedance of the shoreline protection elevation, using the historical water surface elevation record at the Boston NOAA tide gage (established in 1921 at Fort Point Channel) with no past SLR adjustments but with SLR scenario increases. This assumes no increased intensity of frequency of storm events in the future. If there were more than one exceedance on one day, it only counted as one closure. In addition, for the case of no shoreline protection systems, we set the actual start date of operation to 2050 because of the time needed to design, permit, and construct a system.

Closing the sector gates used in the barrier would take a significant amount of time (6–8 hours). Therefore, these gates could not be closed on a daily basis, nor are they mechanically designed to be opened and closed regularly. Therefore, the closure analysis assumes that gate closures exceeding 50 times per year would be unrealistic. This is a relatively high operational limit, as it is likely that closures weekly or more would be unrealistic.

Additionally, while the analysis is based on the historical storm records, it likely underestimates the amount of times the barrier would actually be

FIGURE 5.19

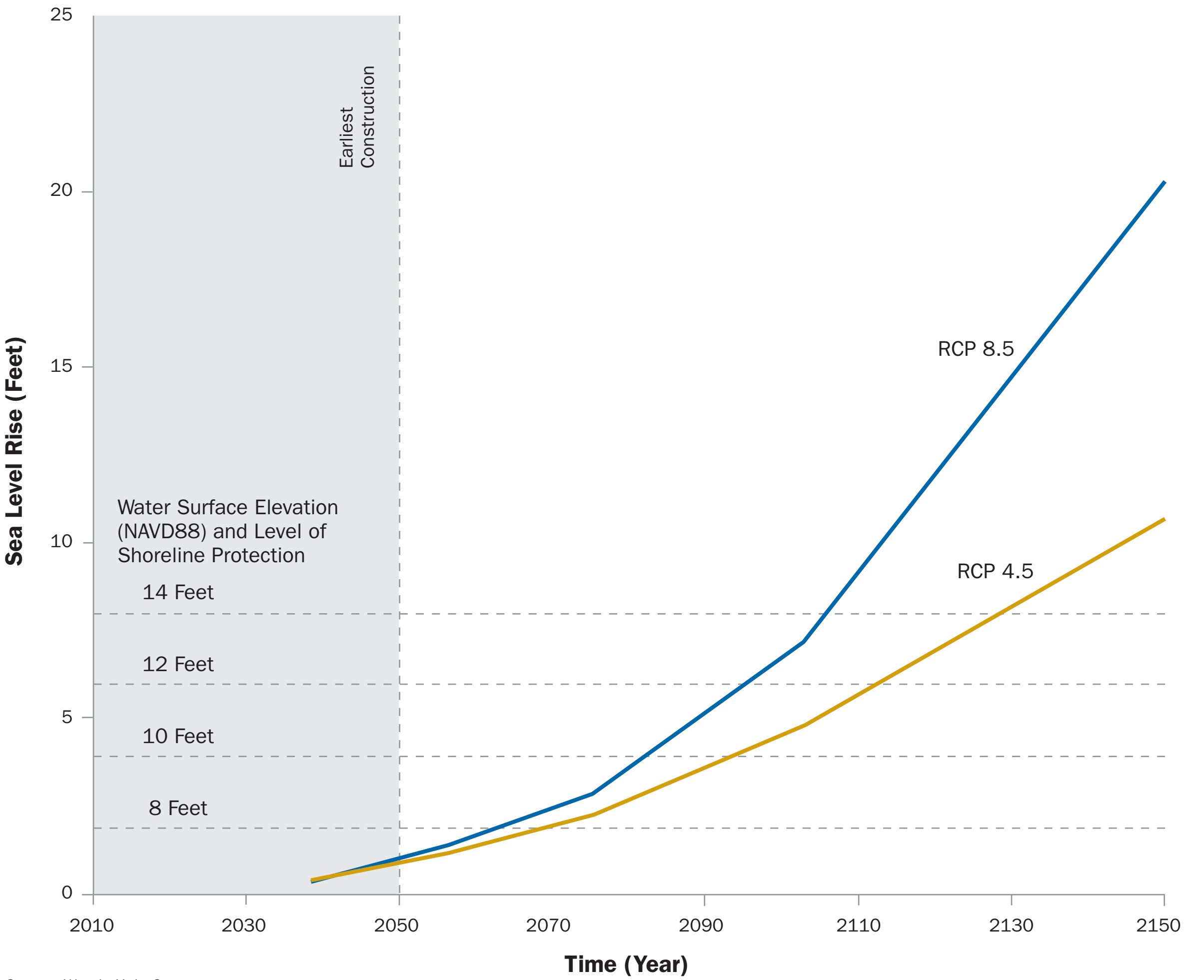
Timeline for Boston Harbor Barrier Functionality



Source: Woods Hole Group

FIGURE 5.20

Time Period when the Closure Frequency Threshold is Exceeded with Various Elevations of Shoreline Protection



Source: Woods Hole Group

closed. For example, when a storm is predicted to occur, the barrier would likely be closed even if the storm surge is not predicted to be high enough to cause problems, because of the inherent uncertainty of storm predictions and the desire to ensure that flooding would be prevented. As such, the closure analysis is conservative from the standpoint that functionality lifetime of the barrier might actually be less than the results of this analysis.

Figure 5.19 shows the closure frequency (closures/year) on the vertical axis, with time (years) on the horizontal axis. The gray areas show periods of time either before construction (prior to 2050) or when closure frequency exceeds 50 times per year. Specifically, these scenarios include (1) the moderate RCP 4.5 emission scenario (the basis for the economic benefit and cost analysis carried out in Section 8) with no shoreline/district solutions (critical elevations remain the same as existing conditions); (2) the RCP 4.5 emission scenario with shoreline/district solutions in place to a protective elevation of approximately 14.0 feet NAVD88; (3) the RCP 8.5 emission scenario with no shoreline/district solutions (critical elevations remain the same as existing conditions); and (4) the RCP 8.5 emission scenario with shoreline/district solutions in place to a protective elevation of approximately 14.0 feet NAVD88. The analysis assumes that the earliest construction completion of a barrier is 2050 (to account for the significant design, permitting, funding, and construction time expected), that closing the sector gates more than 50 times per year causes the system to become inoperable, and that closing the gates every week or more is

unrealistic. The figure also shows that the lifetime of the proposed barrier is even more limited if it were only able to close 25 times per year.

Figure 5.20 presents the two SLR curves (one for RCP 4.5 and one for RCP 8.5) and when these levels exceed the closure frequency threshold based on various elevations of shoreline protection. For example, if the barrier is closed when water levels exceed 10 feet NAVD88, then once the curves exceed that level, the barrier becomes nonfunctional with its present configuration and goals.

The closure analysis was used in the economic analysis using RCP 4.5 in Section 8. If a barrier was built in 2050, then we assumed the municipalities in Boston Harbor would take interim measures to manage coastal flooding between the present and 2050 by adapting shorelines to manage flooding to 12 feet NAVD88. Figure 5.20 shows this system would function to 2110 under RCP 4.5. In the economic analysis, 2100 was used instead of 2110. In addition, the closure analysis above estimated that a harbor barrier would not be needed until 2100 if shore-based protection was provided to the equivalent of 14 feet NAVD88. Based upon an analysis of flood frequencies over time, there remains the possibility that some events greater than 14 feet NAVD88 could occur between 2070 and 2100; this event is essentially equal to the 0.1% annual chance exceedance probability with 3 feet of sea level rise. Therefore, it was assumed in this scenario a barrier would be built by 2070 and function as designed to 2130.

After a barrier is being too frequently closed to manage all events greater than the amount of shoreline adaptation, a barrier could still be used to lessen the impacts of storms. It, however, would not eliminate flooding caused by all events. In addition, as SLR continued to increase for centuries past 2100, which will occur even if all greenhouse gas emissions ceased today (Solomon, 2009), the flooding impacts would increase in severity. When a barrier system ceases functioning as designed, there are several options that could be investigated separately or in combination:

- Increasing the elevation of shoreline protection by expanding coastal flood protection systems and adding new sites if needed;

- Increasing the shoreline resilience through strategies such as by letting some areas flood ("Living with Water"), retreating, and protecting individual assets;
- Implementing a storm surge forecasting system to allow operation of the gate system for larger storms but allowing lesser flooding during normal tidal conditions; and
- Converting the gate system to a lock system, which would mitigate the frequent closures. Without significant and expensive additional features on the barrier to allow interchange between the ocean and the interior of the barrier system, however, the harbor would become a brackish or freshwater lagoon instead of a previously saline system. In addition, shipping and boating would be significantly more impacted than with the barrier as presently designed (see Section 9).

Hydrodynamic Conclusions

By intentionally minimizing the barrier openings as much as feasible while still maintaining navigational ability, we attempted to maximize tidal attenuation due to a proposed barrier. Model simulations were conducted using the Boston Harbor Flood Risk Model to evaluate potential changes in Boston Harbor's tide cycles, currents and overall circulation as compared to current conditions. The key findings include:

- There is no change in tidal attenuation caused by either an outer or inner Boston Harbor barrier. A storm surge barrier that continues to allow navigation of large vessels would not have a measurable impact on the tidal range—or height of the twice-daily high tide—inland of the barrier. As sea level rises, any theoretical effect would slacken, not increase. A barrier that generally maintains navigational requirements would only serve the purpose of storm surge protection, and would not protect Boston Harbor from sea level rise and/or nuisance flooding without closure of the gates.
- As designed, the OHB would cause significant changes to tidal circulation, currents, and velocity, especially in the vicinity of the barrier openings, and in the volumetric flux between the northern and southern portions of the harbor. These hydrodynamic changes would be expected to have impacts on Boston Harbor navigation, sediment movement, and water quality.
- The IHB would have minimal impact on the tides and currents in the harbor; however, additional engineering elements (e.g., pumps) would be required to handle freshwater discharge from the upstream watersheds (e.g., Charles and Mystic River Basins) for times when the barrier was to be closed.
- Overall oceanic circulation outside the barriers would not be influenced by an outer or inner barrier; however, some localized changes might occur in the vicinity of adjacent shorelines (e.g., Hull and Winthrop) that should be further investigated if an OHB was to advance further in concept.
- The OHB may create some zones of stagnation, or reduced energy, compared to existing conditions, which may change the sediment transport processes and possibly water quality in these areas. The IHB may have significant influence on the water quality levels upstream of the barrier during storm conditions (when the gates are closed).
- In the early years of operation the frequency of closure of a barrier would be no more than a few times per year. Because of rising sea levels, and assuming the system was designed to be closed each time the water level is above the level of protection provided by shore-based measures, after 50–60 years the frequency of closure would have increased so much that the barrier could no longer function as designed.
- There exist several options to manage the barrier system when it ceases functioning as designed; examples include increasing the elevation of shoreline protection, and converting the gate system to a lock system.

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6 Environmental Impacts

The environmental assessment focused on the major impacts on water quality, habitat quality, and ecosystem services.

Our understanding of the engineering and hydrodynamic considerations of storm surge barriers has advanced well ahead of our understanding of the environmental impacts of such structures, particularly their impacts over time and on a regional, ecological scale. This is a new, emerging area of research worldwide (De Vriend et al., 2011; Tuin et al., 2017). While multiple studies have been conducted of the environmental impacts of the Netherlands Delta Works project (e.g., Bakker et al., 1994; Van der Tol and Scholten, 1997; Reise, 2005; Eelkema et al., 2011; Troost and Ysebaert, 2011; Eelkema et al., 2012; Eelkema et al., 2013; Van Wesenbeeck et al., 2014; Ysebaert et al., 2016) and some on the New Orleans delta barriers (Costanza et al., 2006; Van Ledden et al., 2012), few such studies exist for large system-wide barriers, and none to date for the St. Petersburg barrier. Research on the effects of storm surge protection barriers on river deltas is useful in considering potential impacts of a barrier in Boston; however, the geology, habitats, and hydrology of Boston Harbor differ considerably from that of the coastal Netherlands or New Orleans area, which limits the transferability of the results.

Assessing how an Outer or Inner Harbor Barrier might impact Boston Harbor environmentally requires extrapolating from existing knowledge of the components of the system, and coupling that knowledge with modeling. The environmental assessment in this section is necessarily qualitative. It is based on general concepts and logical relationships, and on knowledge of this specific system drawn from experts familiar with various aspects of it—water quality (Robert Chen), coastal geomorphology (Mark Borrelli), coastal habitats (Jarrett Byrnes and Lucy Lockwood)—as well as a highly limited set of modeled future scenarios (Woods Hole Group, as described in Section 5). It is not currently possible to achieve fine detail at spatial, temporal, or quantitative levels without further modeling and/or experimentation. The overall assessment is consistent with other sections of this report and highlights areas that are unknown or are worthy of further study. This assessment is not intended to be used in permitting processes, as the impacts on individual locations and specific levels of change are not predictable currently without additional modeling and/or experimental studies.

A key factor in assessing environmental impacts of a storm surge barrier in Boston Harbor is that major environmental changes will be taking place independent of barrier construction due to climate change. Warming water and air temperatures (IPCC, 2013), changes in precipitation (Feng, 2017; Prein et al., 2017), and rising sea levels (Chen et al., 2017; Sweet et al., 2017; Douglas et al., 2016) will have a significant impact on Boston Harbor ecosystems regardless of barrier construction.

Assessing how an outer or inner harbor barrier might impact Boston Harbor environmentally requires extrapolating from existing knowledge of the components of the system, and coupling that knowledge with modeling.

This section assesses environmental impacts of several barrier configurations in Boston Harbor. We consider present-day conditions and compare them to conditions in the future with 5 feet of sea level rise (SLR) without a barrier, and 5 feet of SLR with a barrier in place, built as described previously. This study is not meant to be comprehensive, but rather a first assessment of what might be expected under these various conditions as well as what needs further study. We note that there are many unknowns about how a complex socio-ecological system might respond to the presence of a major physical barrier at the mouth of Boston Harbor, but also note that there might be an equal set of unknowns that would result from the sum of all local adaptations. We frame our environmental assessment within the major impacts on water quality, habitat quality, and ecosystem services. For each of these topics, we use our judgment to develop “radar” diagrams to display present conditions and those expected with and without a barrier with 5 feet of SLR. As discussed at the end of Section 5, it is possible that a barrier system would eventually need to be closed frequently during the year—as much as 50 times per year. This situation would cause substantial operational as well as logistical issues. This environmental assessment is based on an assumption of several (3–10) closures per year for major storms. Under future scenarios of up to weekly closures for regular tidal flooding, the environmental impacts are not discussed in detail in this report.

Boston Harbor: A Changing System

Boston Harbor has been and will continue to be a system subject to and capable of great change. The harbor has recently undergone possibly the most extensive and expensive estuarine recovery in the history of the world, dubbed the "Boston Harbor Clean-up." To address an unacceptably polluted harbor, experts from the engineering, environmental science, social science, policy,

In 1988, Boston Harbor was widely known as the dirtiest estuary in America. After a lawsuit, the formation of the Massachusetts Water Resources Authority, the construction of the Deer Island Treatment Facility, and continuing removal of combined sewer overflows, Boston Harbor's ecosystem has been dramatically improved.

and economic fields came together to take a holistic view at possible futures and to make rational choices about how to proceed. While Boston now has one of the cleanest urban harbors, unfortunately it is now one of the most vulnerable cities in the world to the impacts of SLR (Hallegatte et al., 2013). Moving forward will require an integrated decision-making process that considers multiple temporal and spatial scales of both proposed actions and potential responses. Boston Harbor has already changed due to rising seas, but will continue to change in the future. In this section we attempt to compare today's conditions with future conditions. If nothing is done, the environmental impacts of 5 feet of SLR will be dramatic. It is almost certain that we will respond and adapt to SLR over the next 50 to 100 years. Here, we consider the environmental impacts of both the Outer Harbor Barrier (OHB) and Inner Harbor Barrier (IHB) described previously. However, these environmental impacts should be compared to the environmental impacts of piecemeal local and district-wide adaptations over the same timescales if we are to make rationale choices about our possible futures.

Boston Harbor History

In 1988, Boston Harbor was widely known as the dirtiest estuary in America (MWRA, 2008a). After a lawsuit, the formation of the Massachusetts Water Resources Authority (MWRA), the construction of the Deer Island Treatment Facility, and continuing removal of combined sewer overflows, Boston Harbor's ecosystem has been dramatically improved (MWRA, 2008a). Oxygen has returned to surface sediments, water clarity has increased, biodiversity has increased, and the Harbor is swimmable over most of the year. Extensive modeling and monitoring before and after the Deer Island construction have demonstrated improvements of the water quality, habitat quality, and ecosystem services of Boston Harbor (MWRA, 2008a). The general consensus is that the $5 billion price tag on the clean-up was a bargain. The Boston Harbor Islands were designated a National Recreation Area in 1996. Boston Harbor provides an active lobster fishery, recreational fishing for key species such as striped bass, and a destination for millions of recreational swimmers, boaters, and fishers every year. Real estate bordering the harbor and properties with harbor views are highly prized, and development along the waterfront continues, such as that in the Seaport District. The balance of waterfront development, environmental quality, and public access continues to be of great concern for all Bostonians.

Assumptions

CLIMATE CHANGE

Average annual temperatures across New England have increased by 2° F over the last 100 years (CRB, 2016), and relative sea level in Boston Harbor, already almost a foot higher than 100 years ago, is expected to increase by 1–2 feet by 2050 and 3–6 feet by 2100 (Douglas et al, 2016; CRB, 2016). Sea surface temperatures in the Gulf of Maine are rising faster than 99% of the global ocean (0.41° F/year; Pershing et al., 2015), affecting cod and lobster fisheries as well as the entire ecosystem. In addition, increased frequency of large storms is predicted (NCA, 2014), and weather and climate events resulting in $1 billion damage in the United States have been increasing dramatically (Smith, 2016). Change has already occurred in Boston Harbor and its shorelines and will continue with expected increasing impacts as climate change accelerates. These changes will impact all people, businesses, and institutions in the Boston area whether we decide to do nothing, allow for local adaptation efforts, or conduct large-scale planning and construction projects.

BOSTON HARBOR STORM SURGE BARRIER DESIGNS

When considering harbor-wide adaptation strategies, it has been determined in Section 5 that a barrier narrow enough to act as a tidal restriction, effectively reducing the tidal range, is not feasible as it would interfere with shipping operations and would likely have unacceptable negative environmental impacts. The size of the opening evaluated in this report is the minimum allowable according to the USACE. Additionally, the scale of these harbor-wide features precludes the closing of the barrier at every high tide due to the time it takes to close the massive swing gates and mechanical stress. A large harbor barrier could be capable of closing during infrequent coastal storm events and could be effective in tempering storm surge and some wave impacts within Boston Harbor. The nature of storm surges associated with nor'easters would require barrier closings of approximately 46–84 hours (WHG, 2017). Closures of 6–8 hours may be sufficient to protect against storm surges associated with faster moving tropical storms or hurricanes.

CONSERVATION OF ENERGY

As discussed in Section 5, the tidal range in Boston Harbor (the difference between high and low tide) is unchanged by construction of either the OHB or IHB as described. If we consider the high tide to low tide transition through the mouth of Boston Harbor with or without a harbor barrier in place, an equivalent gravitational potential energy (same mass of water falling the same tidal height) will be transferred into the Harbor as kinetic energy. This is a consequence of the Law of Conservation of Energy.

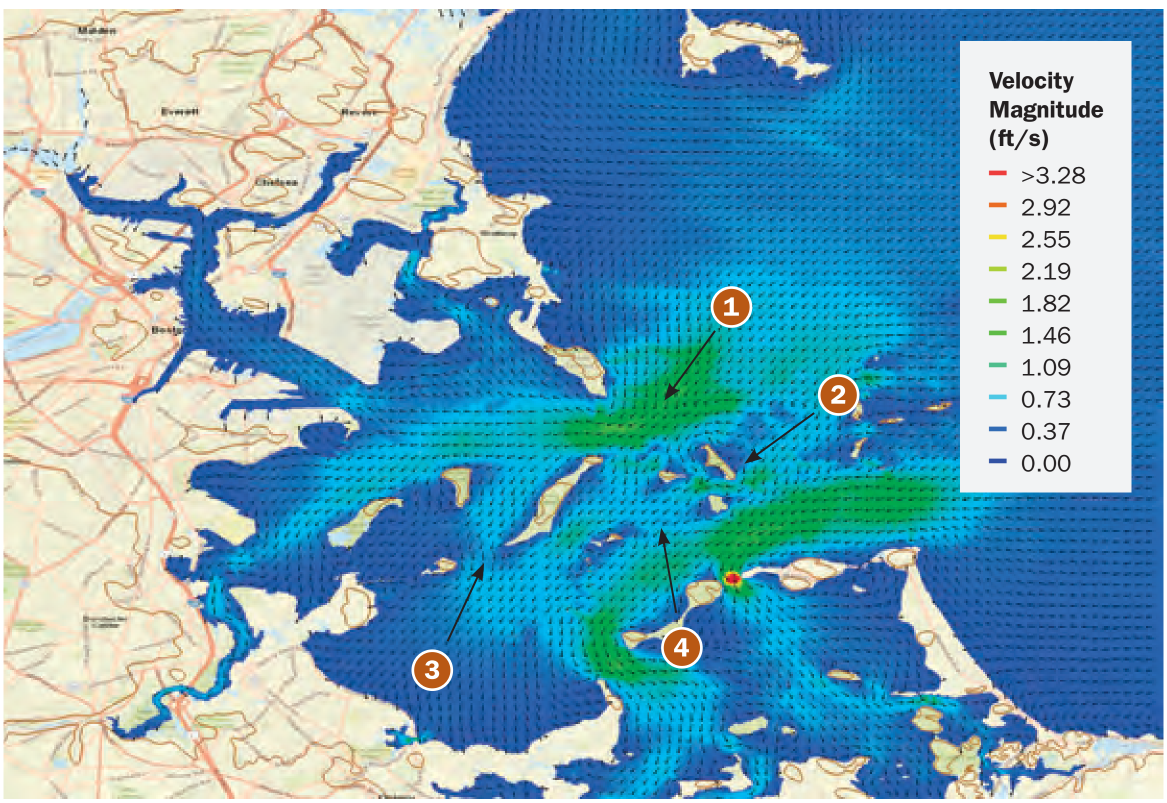
Outer Harbor Barrier Environmental Assessment

TIDAL CURRENT VELOCITY AND WAVE CHANGES

Throughout this section, the terms "velocity" and/or "current velocity" refer to tidal current velocities, unless otherwise stated. Comparing the scenario with the OHB in place versus no barrier, Figures 6.1 and 6.2 show the model results with dramatically increased current velocities near the barrier openings at maximum flood

FIGURE 6.1

Modeled Current Velocities Under Present Day (2016) Conditions

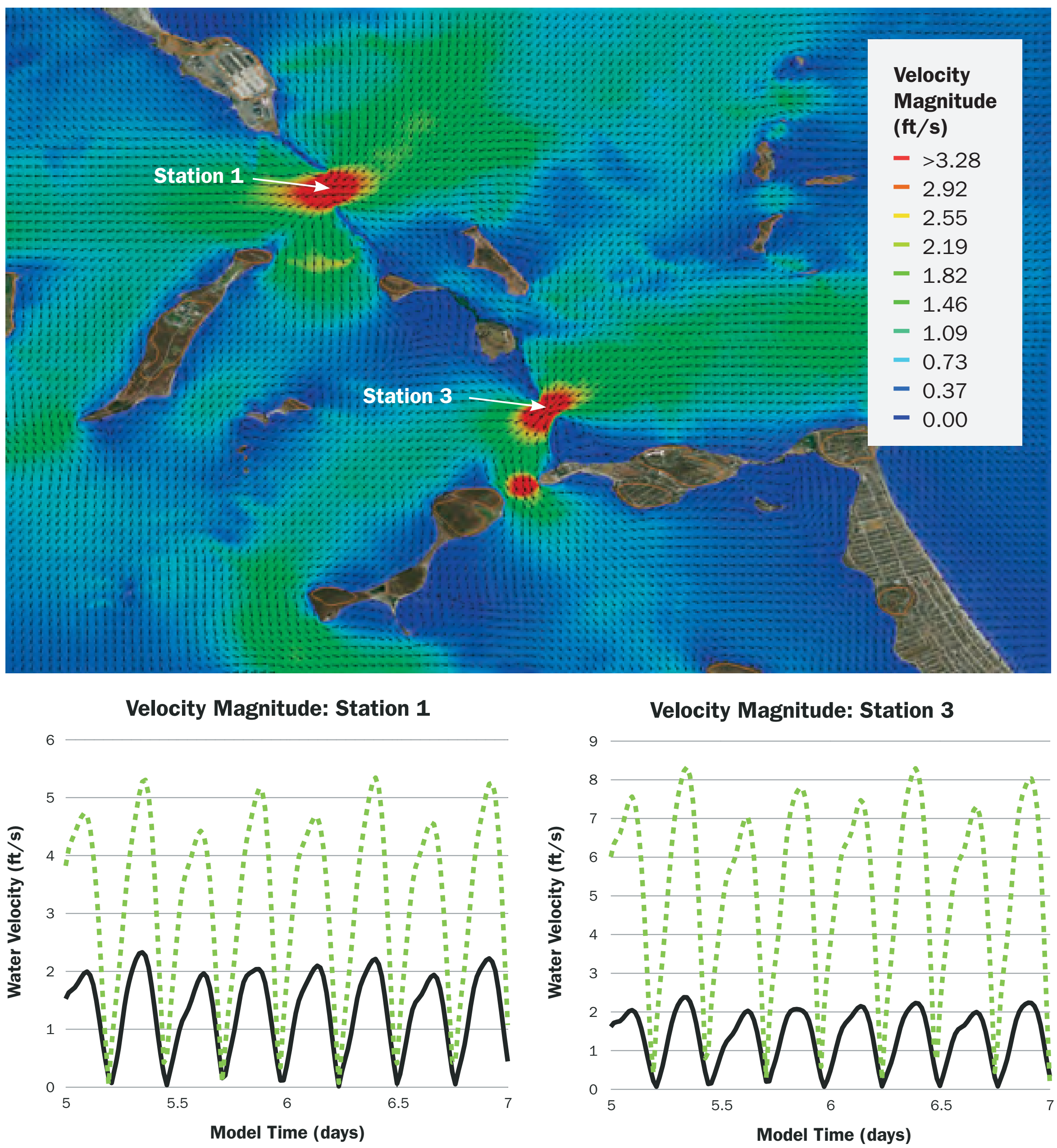


Source: Woods Hole Group

tide. At the northern gate, peak velocities change from ~2 ft/sec to >6 ft/sec (1 to 3.5 knots), and at the southern gate, peak velocities change from ~2 ft/sec to ~8 ft/sec (1 to 5 knots). Due to more water coming through the larger northern gate (1,500 feet wide) than the southern gate (650 feet wide), water must flow between Long Island and Moon Island to equilibrate the volumes resulting in greater velocities between these islands: 0.5 ft/sec to 1.5 ft/sec (0.3 to 0.9 knots). As more kinetic energy is dissipated at these locations, by necessity there is less kinetic energy at other locations within the harbor. Figure 6.2 shows a lower-velocity zone behind the barrier, for example (0.9 ft/sec to 0.2 ft/sec). These slower velocities imply marginally longer residence times, slower flushing from shallow areas, lower oxygen concentrations, and higher nutrient and

FIGURE 6.2

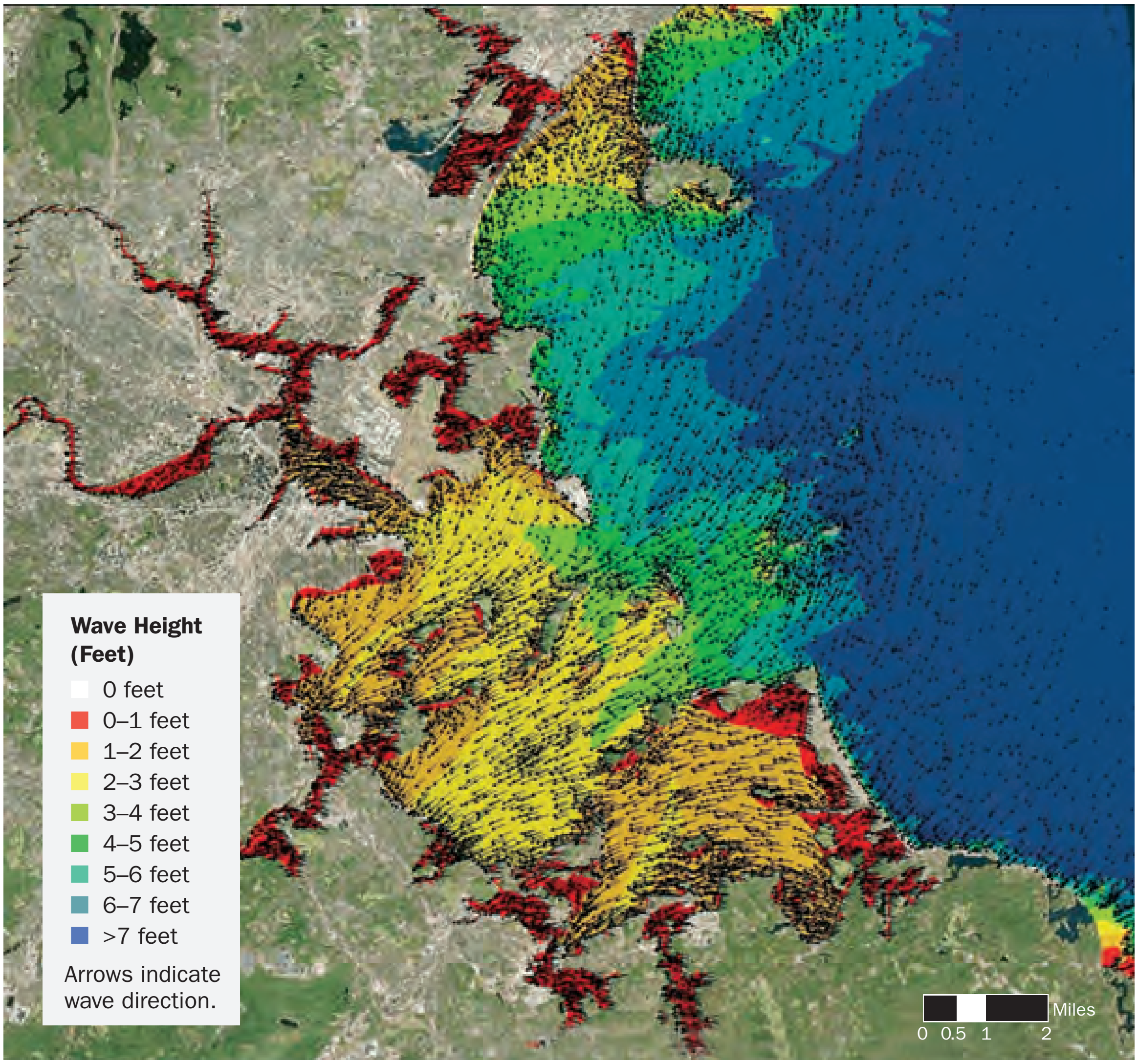
Currents Due to an Outer Barrier



Source: Woods Hole Group

FIGURE 6.3

Wave Model Results from a Moderate Coastal Storm (Nor'easter) in Boston Harbor With No Barrier



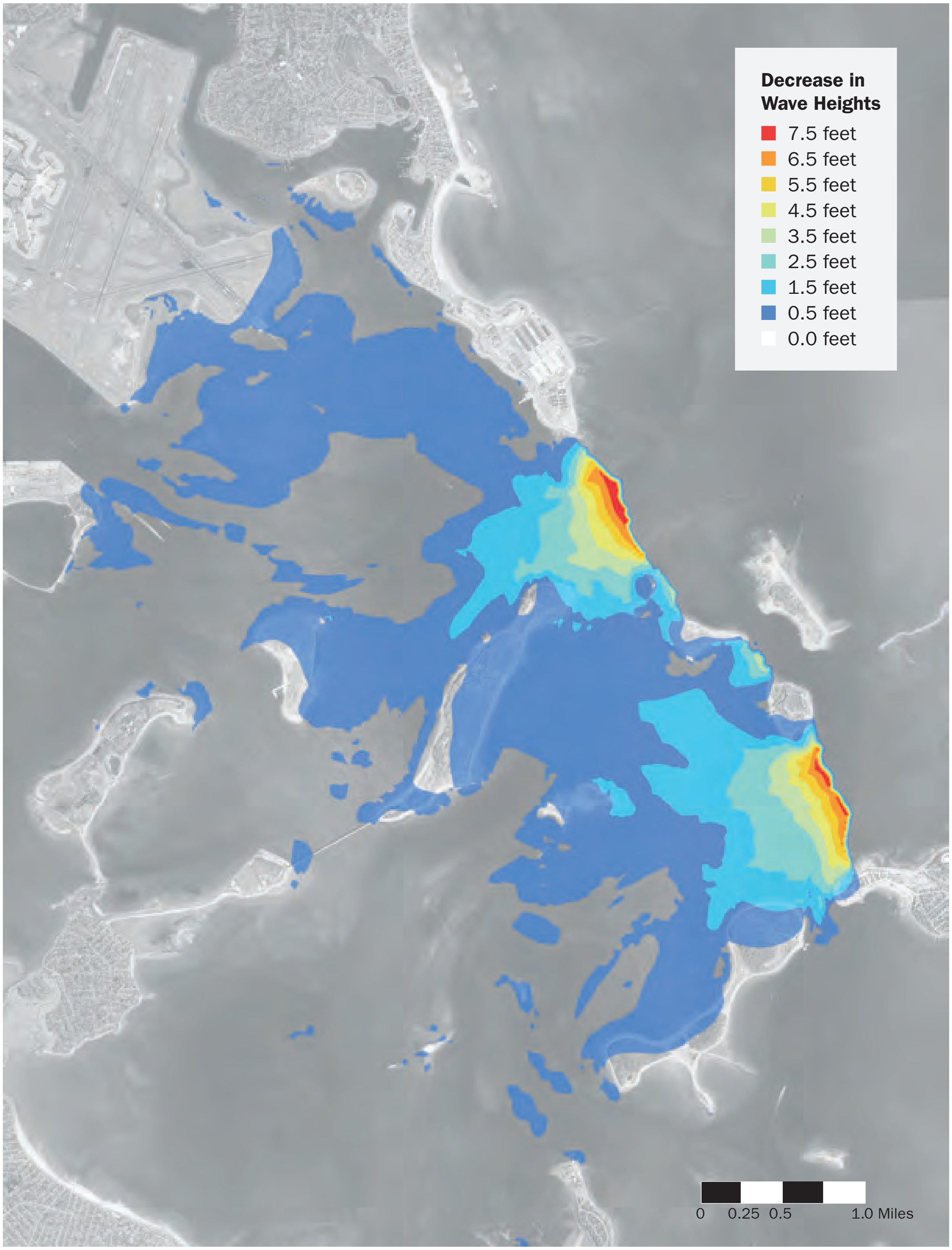
Source: Woods Hole Group

contaminant concentrations. As velocities can be as much as 3–5 times higher with a barrier in the areas proximal to the barrier, we expect lower velocities in other areas of the harbor (~10–20%). This will have dramatic impacts in a few affected areas, and minor, but possibly measurable, effects in other areas.

Additionally, energy is added to the harbor in the form of waves, though the harbor is sheltered by the many islands of both bedrock and modified drumlins, or unconsolidated material, and is relatively shallow, as discussed below. Wave heights during a moderate nor'easter are shown in Figure 6.3, ranging from 4 feet at the mouth to 0–1 foot along most of the shorelines. The large fetch of Massachusetts Bay allows waves under most conditions to enter Boston Harbor and dissipate their energy within the harbor, mostly near the harbor mouth. With a barrier in place, some of this wave energy would be dissipated along the barrier, with a small amount making its way through the narrow openings, implying less total energy entering the

FIGURE 6.4

Wave Model Results from a Single Storm Scenario Showing the Decrease in Wave Heights in Boston Harbor Due to a Closed Harbor-wide Barrier Compared to No Barrier at All



Source: Woods Hole Group

harbor. Much of this energy would dissipate relatively soon after it enters the harbor, as it does without the barrier. The fetch within the harbor can be quite significant and would create waves of 1 to 2 feet along the shorelines during a storm, regardless of the barrier being open or closed.

There is a potential to greatly decrease the wave energy when the barrier is closed. Figure 6.4 shows the decrease in wave height due to the presence of the OHB (closed) under the conditions of a single large historical storm event. Waves are reduced by greater than 7 feet at the location of the barrier openings, but this decrease is rapidly attenuated farther into the harbor compared to no barrier at all. As can be seen, much of the harbor has less than 0.5 feet of decreased wave heights along the shorelines. This suggests that during a storm, shoreline waves are only slightly lower with a closed barrier, if at all. This slight decrease in wave height (which could be 0.5–1.0 feet on some islands in direct shadow of the harbor mouth such as Castle Island, Thompson Island, and Spectacle Island) would reduce erosion and resuspension during episodic storm events. Some wave energy in areas exposed directly to the ocean would be dissipated by a closed barrier. There would still be increased resuspension due to storm winds (compared to fair weather conditions) even with the OHB closed. Any reduction in wave energy would reduce sediment resuspension and shift shallow areas from higher-energy sandy bottom environments and beaches to finer-grained bottom environments and mudflats. This would tend to shift some beaches into mudflats and/or salt marshes. An example of this phenomenon at a smaller scale is Malibu Beach. A sandy, high wave energy beach adjacent to Savin Hill was lost when Morrissey Boulevard was constructed and limited the wave energy through the narrow opening. While tidal heights are similar, the shore shifted to a low-energy environment, and marsh grasses took over the beach. Every year, the grasses are removed and sand is added to some of the beach so that local residents can use the recreational beach (Boston Globe, 2007).

Residence Times

Boston Harbor mixing is dominated by tidal current velocities on the order of 0.65–1.3 ft/s. Density and wind-driven currents range from 0.16–0.33 ft/s. Tides are semidiurnal and the average tidal range is 8.9 feet (Signell and Butman, 1992). Tidal exchange is strongly controlled by the geometry of the complex coastline and islands that subdivide the harbor, and bottom friction, which affects water flow patterns. The result is that exchange between Boston Harbor and Massachusetts Bay is largely channeled through President Roads in the north and Nantasket Roads in the South. Flood water that re-enters the harbor is drawn uniformly from a region that extends approximately 3 miles seaward into

Any reduction in wave energy would reduce sediment resuspension and shift shallow areas from higher-energy sandy bottom environments and beaches to finer-grained bottom environments and mudflats. This would tend to shift some beaches into mudflats and/or salt marshes.

Massachusetts Bay. Constriction at President and Nantasket Roads causes ebb tidal flows to exit in narrow jets (up to 2.65 ft/s) and to be delivered beyond the 3-mile flood boundaries. The result is a continuous flushing of the harbor over successive tidal cycles. For each tidal cycle, 40% of harbor water flows into Massachusetts Bay and 58% of this ebb tide returns. Because the flood tidal water is not perfectly mixed in the harbor, flushing times are not the same for water in all parts of the harbor. Water released near President and Nantasket Roads has a shorter residence time (around 0.5 days) than water introduced around the periphery (around 10–17 days) (Signell and Butman, 1992). Models considering tidal- and wind-driven circulation suggest an average flushing time of 10 days (Signell, 1992; Signell and Butman, 1992).

Comparing 5 feet of SLR to conditions today implies longer residence times as the same tidal prism would be flushing a larger Harbor volume. The current average harbor depth of 23 feet would increase to about 28.5 feet, suggesting residence times that are ~25% longer on average. With 5 feet of SLR and an Outer Harbor Barrier in place, the mixing times of some areas (~25% of the harbor) would actually decrease as strong jets force the water out into Massachusetts Bay beyond the area that is drawn upon for water reentering the harbor (Woods Hole Group, 2017; particle tracking modeling), but other mixing times increase farther away where particles can be "trapped" in shallow water areas close to shore (~20% of the harbor). This leads to longer residence times in shallow water areas that may result in increased sedimentation in these areas and low dissolved oxygen conditions.

> Tidal currents would increase in some areas and decrease in others, with varying degrees of impact depending on the scale of those changes. Even the direction of the currents could be reversed in some areas.

Circulation

As discussed above, tidal currents would increase in some areas and decrease in others, with varying degrees of impact depending on the scale of those changes. Even the direction of the currents could be reversed in some areas. Overall, the OHB would likely lead to scour near the barrier openings and siltation behind the barrier and in some shallow-water shoreline environments. While model outputs suggest areas of greatest change in current velocities and circulation patterns, the depth-averaged, 2-dimensional model that was used leaves some uncertainty regarding local circulation, especially during differing wind conditions at different tidal stages. This four-dimensional (x, y, depth, and time) estuarine system may produce unpredicted local shifts in circulation, as demonstrated by physical alteration in Venice Lagoon (Ghezzo et al., 2010; Solidoro et al., 2010).

Additionally, tidal currents would cease almost entirely during the 46- to 84-hour closures to prevent storm surge waters from entering the harbor during extratropical storms. Although the effect of this short-term cessation of tidal flow has not been studied, localized impacts would likely be seen. Higher current velocities driven by storm surge or combined wave and current interaction provide beneficial effects to many natural processes and will be discussed in more detail below.

Shorelines

In general, the creation of a harbor-wide storm-surge barrier such as the OHB would reduce the wave energy along the islands in the lee of the barrier. When closed, this barrier would reduce wave heights up to 1–2 feet on some islands (Figure 6.4). The removal of some of the influence of storms (singular, very high-energy events that are the primary drivers of coastal change) would attenuate the substantial role that storms play in shaping the shoreline and benthic surficial sediments along these islands. These storms have been the driving force of change in these areas since Boston Harbor was inundated following deglaciation (Himmelstoss et al., 2006). The barrier would have direct and immediate short-term and long-term impacts to the physical processes (waves, tidal currents, and sediment transport patterns) as well as indirect impacts to benthic and intertidal habitats along these shorelines.

Rates of storm-related coastal erosion along many of the harbor's mainland beaches and shorelines would likely see moderate reductions as a result of the barrier, based on barrier impacts to storms waves (Figures 6.3 and 6.4). While some of the storm-induced erosion would be caused by waves created behind a closed barrier due to the fetch within the harbor, there would likely be a reduction in tidal currents as well as wave induction behind a closed barrier in certain locations. This would increase the survivability of the Boston Harbor Islands and somewhat reduce property damage along all shorelines of Boston Harbor, Hull, and Winthrop. The project life of certain coastal erosion adaptation structures may be extended as forces undermining those structures could be slightly reduced—for example "vertical erosion" at the base of a seawall. The projected SLR, however, would see critical natural, as well as cultural, resource areas inundated on the islands; up to 26% of Rainsford Island, for instance, could be inundated with a 3.28-ft rise in sea level (Maio et al., 2012).

However, the beneficial aspects of storms will also be diminished. For example, storms, via the process of overwash, can help some low-lying coastal landforms keep pace with SLR (Ashton and Ortiz, 2011). During storm events elevated water levels allow ocean water to wash over these areas, depositing sediment and increasing the elevation of the coastal landform. Further, these overwash events often deposit sediment into deeper waters in a fan-like landform; these "washover fans" in turn provide substrate for the establishment or enhancement of biologically productive habitat such as salt marsh, eelgrass, and/or other submerged aquatic vegetation. These beneficial aspects of fine-grain sediment distribution to shallow backwater areas of the Harbor and the

supply of sediment to vegetated intertidal and subtidal ecosystems would be somewhat reduced for some areas with an outer harbor barrier.

Changes to bottom grain size in particular and sediment transport patterns (erosion and accretion) in general would be more predictable in the future with a barrier in place as storm events, the primary agent of coastal change, will have a lesser impact. These changes would likely include an overall fining of bottom types in areas distant to the barrier openings, as more suspended load is likely to be deposited, given the higher residence times during barrier closures. These closures and the resulting absence of rapid tidal currents associated with storm events would prevent coarser grained material from being transported throughout Boston Harbor and could change sediment composition in some areas.

In areas of close proximity to the harbor-wide barrier openings, the current velocities would increase from 1–2 feet per second (ft/s) to up to 10 ft/s based on hydrodynamic modeling, with the highest rates in proximity to the smaller barrier opening. It is not clear how a barrier would affect future dredging requirements (frequency, dredging volumes, locations) for Boston Harbor. It is likely that dredging of rapidly-accumulating, fine-grain sediments at the bottom of shipping channels would increase due to the reduction in intensity of high-energy storm events, though the channel in close proximity to the barrier openings would likely remain cleared by higher tidal current velocities. Riverine currents and inflows may have greater impacts on benthic sediment deposition with the reduction of oceanic storm forces. It is unclear how these changes will affect overall turbidity in the water, with potential follow-on effects to submerged aquatic vegetation. Sediment transport studies will need to address the new hydrodynamics of Boston Harbor to determine changes in bottom substrates resulting from alterations in sediment transport patterns in the Harbor.

Shoreline Assessments

Long-term shoreline change rates (century-scale) along eight representative islands in Boston Harbor (Gallops, Georges, Long, Lovells, Peddocks, Rainsford, Spectacle, and Thompson) vary widely from 4.9 ft/yr of erosion to >2.6 ft/yr of accretion. More than 65% of those shorelines are eroding at an average rate of 0.47 ft/yr. The remaining 35% of shorelines are accreting at a rate of 0.52 ft/yr (Mass GIS, 2017). It should be noted that much of the natural accretion (disregarding beach replenishment and other anthropogenic alterations) seen along these shorelines is a result of erosion elsewhere on the same island.

Along erosional shorelines in Boston Harbor, there is a strong, and expected, relationship between shoreline orientation and erosion rates (Jones et al., 1993; Himmelstoss et al., 2006). Shorelines facing the northeast experience higher rates of erosion, as the prevailing winds of the most damaging extratropical storms, the nor'easters, come from the northeast. In certain instances, this erosion is naturally mitigated by the development of cobble or boulder "lag deposits" (Himmelstoss et al., 2006). Drumlins consist of till, sediment deposited during the last deglaciation. Till is a mix of poorly-sorted sediment, with grain sizes ranging from mud to large cobble and even boulders. During wave exposure, the finer-grained material is eroded out of the bluffs and the coarser-grained material—in this instance, pebbles, cobbles and boulders—is left behind. Areas where natural accretion is occurring are typically sites where the eroded material from another part of the island has been, or is being, deposited.

Immediately behind the OHB, near the openings, may be the most difficult to project coastal evolution, given the combination of higher tidal current velocities and small reductions in storm wave energy. Islands behind the barrier would see a dramatic reduction in storm-driven shoreline change; yet, this area would see some of the highest tidal currents. The combination of these two factors could be part of a positive or negative feedback cycle with regard to erosion or deposition, and further study is warranted. Areas behind the barrier but distal to the openings may become lower-energy areas and could see substantial sediment deposition, which could interfere with navigation. As discussed below, boat wake was not seen to play a major role in shoreline change along the islands at this time.

Coastal Bluffs (Boston Harbor Islands)

Coastal bluffs within the project area are found primarily on the Boston Harbor Islands. The main influence on these bluffs is erosion due to wave

action, with those bluffs located in more unprotected, seaward-facing areas eroding more rapidly. Many of the bluffs found within the project area are eroding more rapidly than the general shoreline. Himmelstoss et al. (2006) developed a model for the evolution of the drumlin bluffs along the inner islands of Boston Harbor. They showed that natural bluffs would continue to erode until the finer-grained sediment (clay, silt, and sand) was eroded by wave action, leaving behind a "cobble retreat lag."

Five feet of SLR will result in the substantial diminishment of coastal bluffs due to submersion and erosion. Some of the bluffs that had eroded and developed a cobble retreat lag would likely see further erosion as the waters inundated the lag deposits, reactivating the erosion cycle at the base of the bluffs. As mentioned above, the bluffs on the Boston Harbor Islands are particularly susceptible to erosion, as they are composed of unconsolidated glacial till which is easily eroded by wave action and tidal currents. Hughes et al. (2007) examined the impact boat wake had on the eroding bluffs and noted that there was no conclusive evidence that waves generated by boats played a role in bluff, or shoreline erosion. Given sea level rise and changing energy regimes with an OHB, impacts from boats may need to be reexamined in the future.

Based on the work done by Himmelstoss et al. (2006), changes seen along large portions of coastal bluffs will be determined by the material exposed to wave energy. If coarse-grained materials are eroded from the bluff forming lag deposits, erosion will be greatly reduced. Given the natural variability inherent in drumlin fields such as Boston Harbor, this will likely be very site-specific. Future studies could look at the subsurface material for each island and develop an "erodibility index" that may help mangers direct, prioritize and/or mitigate conservation efforts if needed.

Water Quality

A radar diagram was constructed with zero in the middle and 5 at the outer perimeter. Each spoke is a different indicator. Water quality was assessed on a scale of 1 to 5 (5 being best) in terms of nutrients, bacteria, water clarity, dissolved oxygen, and sediment quality. These scales range from 1 being "totally degraded" and not supportive of normal ecosystem function to 5 being "pristine" with no anthropogenic impact. Though the scales are qualitative and the assessments specific to each individual indicator, they are based on expertise within each area discussed. The exact quantification of each indicator can vary based on a wide diversity of definitions, metrics, or scoring systems, but based on logic presented in each section, the comparative values are most likely consistent among any scoring system used. Ratings are given in Figure 6.6 and summarized in Table 6.1.

The exact quantification of each indicator can vary based on a wide diversity of definitions, metrics, or scoring systems, but based on logic presented in each section, the comparative values are most likely consistent among any scoring system used.

NUTRIENTS

Nutrients such as nitrate and phosphate vary with season, depth, and location in the harbor. Summer values are lower due to photosynthetic uptake. Surface values are often higher than bottom waters as the sources of nutrients are often related to freshwater inputs. The large tidal flushing of Boston Harbor (~1/3 of harbor volume per tide) limits eutrophication (Taylor, 2011). Nutrient inputs from sewage discharged at the mouth of the harbor prior to 2000 and from rivers and combined sewer outfalls (CSOs) have all decreased over time. There has been a modest decrease in average and maximum values of nutrients since 1994 at most locations within the harbor even as the Deer Island Outfall went online in 2000 (MWRA, 2017).

While the overall inputs of nutrients are likely to continue to decrease due to new EPA regulations (stormwater phosphorus maximum loadings), increasing water temperatures will promote bacterial respiration and stratification, thus tending to enhance nutrient concentrations in some locations. Increased water volume and residence time with 5 feet of SLR with no barrier could lead to slightly higher nutrient levels in backwater areas; but overall, SLR alone should have little effect on nutrient concentrations and cycling, as flushing rates, oxygen concentrations, and river loadings will remain similar to current conditions. Given that a 1 on the radar diagram represents a very high nutrient loading leading to regular eutrophication, and a 5 is an oligotrophic system experiencing primary productivity limited by nitrogen, Boston Harbor presently ranks as a 4: a relatively healthy estuary in terms of nutrients, mainly due to tidal flushing and reductions in nutrient loading. It will remain a 4 with 5 feet of SLR. However, the predicted impacts of various trajectories of river nutrient inputs and the impacts of temperature, stratification, and SLR on nutrient dynamics at various locations within the harbor are important areas for future research.

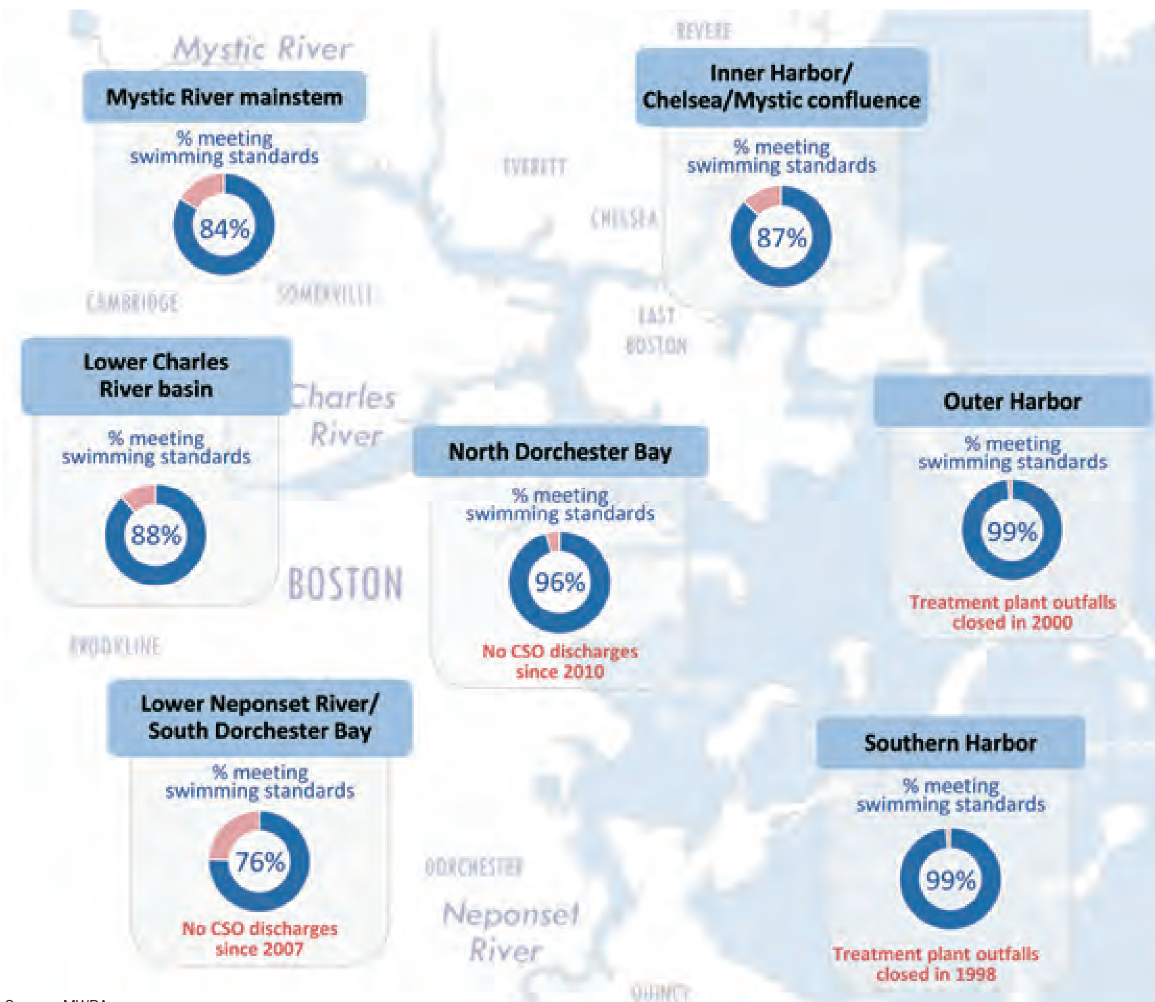
The major impact of a barrier would be increased residence times and decreased wave-induced mixing in shallow backwaters that receive less flushing, and a lack of flushing due to barrier closings during storm events. These effects would likely increase nutrient concentrations somewhat in these areas and could reduce its overall nutrient ranking to a 3.5 with the presence of a barrier and 5 feet of SLR. Most of the harbor would not be affected, however, as flushing rates and residence times with and without a barrier are similar.

BACTERIAL WATER QUALITY

As a result of the outfall pipe being relocated and a major 20-year emphasis on the CSO improvement project, bacterial water quality has improved significantly since the 1990s. In 2016, there were 160 postings (>104 cfu enterococci per single sample) as a result of over 15,000 samples from 586 locations on marine beaches across Massachusetts. More than three-quarters of the postings were due to elevated bacterial levels (enterococci or fecal coliform). Four beaches in Boston Harbor—Tenean, Constitution, Wollaston,

FIGURE 6.5

Bacterial Water Quality Monitoring Stations within Boston Harbor



Source: MWRA

and Malibu—were found in exceedance. Many of the elevated levels were related to rainfall events. In general, Boston Harbor remains swimmable for most of the days and most of its locations (Figure 6.5; Annual Beach Report, 2016). The main criterion for beach closings is enterococci measured in the morning and reported 24 hours later. In addition, beaches are automatically closed following large rain events where CSOs are known to release raw sewage to certain areas of the harbor. We expect that the CSO improvement project will continue even though the major improvements have already been completed.

As a result of increased residence times, and especially decreased flushing after a storm event, the bacterial water quality following a storm event would likely get significantly worse with the OHB in place. While storm events carry many fecal bacteria from streets, catchments, and animal waste throughout the Boston Harbor watersheds down rivers and into the harbor, these bacteria are rapidly mixed into Massachusetts Bay. Sediments associated with bacterial contaminants as well as the bacterial counts themselves are reduced within 2–3 days following a rain event. If the storm surge barrier is closed for 54–84 hours, all of this contaminated "first flush" freshwater will be trapped within the harbor, fine-grained contaminated sediments will be deposited, and bacterially contaminated waters will be trapped until the barrier is opened.

Currently, the harbor's bacterial water quality would rate a 3, with a 1 representing no exceedances and a 5 representing a chronically contaminated estuary. It will likely remain a 3 given 5 feet of SLR, but might decrease to a 2 in certain low-flushing areas, given 5 feet of SLR and a barrier. High bacterial counts could also occur during the closure of the barrier for up to 84 hours during storm events, with a freshwater lens carrying road runoff and CSO effluent sitting on top of the higher density harbor water (see Section 5).

WATER CLARITY

Water clarity is better now than in the 1990s in a few specific areas of the harbor, such as those adjacent to Nut Island and Deer Island, due to the elimination of sediment sludge releases from outfalls within Boston Harbor. However, there is not a clear increase in Secchi Disk depths over time over the last 30 years (*www.mwra.com*). As is typical for an urban estuary, water clarity ranges from 6.6–13.2 feet in Secchi Disc depths depending on season, tide, and location.

Generally, water clarity would likely remain similar before and after a barrier is in place, as modeled current velocities are identical in most (90%) of the harbor (Figures 6.1 and 6.2). Some exceptions include possible slight decreases due to greater residence times, nutrients, and stratification, which result from lowering energy throughout the harbor with a narrow barrier opening, especially far away from the harbor mouth in shallow areas. Increased primary productivity in these areas could mean more phytoplankton in the water column. However, sediment resuspension will be reduced during storms, so water clarity should be enhanced somewhat in the few days following a storm compared with no barrier. In close proximity to the barrier opening, water clarity could be enhanced by increased current velocities not allowing fine-grain, slowly-sinking sediments to remain suspended in the area. Particle tracking simulations (Woods Hole Group, 2017) suggest that fewer particles would remain in the harbor in the presence of a barrier, presumably due to the increased velocities of ebbing waters forming a jet that shoots particles from the 10% of the harbor proximal to the mouth far enough into Massachusetts Bay that they do not return on the next incoming tide. However, particles nearshore will remain trapped nearshore. Overall, there would be locations with increased water clarity and areas with decreased water clarity, mostly due to changes in circulation and current velocities. This water quality indicator currently rates a 3, given that a 1 is a completely turbid system that does not allow light penetration beyond the very surface, and a 5 is an oligotrophic system that allows benthic productivity everywhere. Water clarity would likely remain a 3 given 5 feet of SLR. This could drop overall to a 2.5 with 5 feet of SLR and the presence of a barrier. It is not clear how much impact the trapping of a thin layer of particle-rich surface freshwater would have on water clarity during a closure of the barrier, but it would likely lower water clarity temporarily.

While storm events carry many fecal bacteria from streets, catchments, and animal waste throughout the Boston Harbor watersheds down rivers and into the harbor, these bacteria are rapidly mixed into Massachusetts Bay.

DISSOLVED OXYGEN

Dissolved oxygen (DO) fluctuates from 6–10 mg/l with tide, depth, location, and season. DO is generally high in spring and low in fall. High flushing rates help reventilate the water column, so the Boston Harbor system rarely goes anoxic. Historically, surface sediments and bottom waters went hypoxic and anoxic due to high sediment oxygen demands (SOD) and high biological oxygen demands (BOD) resulting from effluents with organic carbon-rich sludge and effluent in the harbor. With the removal of sludge dumping, the relocation of the sewage effluent outfall into Massachusetts Bay, and the removal or improvement to most of the CSOs, BOD has been drastically reduced. There are still numerous organic matter inputs into this urban estuary. If a 1 is a chronically eutrophic system and a 5 is system fully saturated with DO from surface to bottom, Boston Harbor would currently rank a 3.5 (see Figure 6.6). Decreased residence times, increased temperatures, and increased respiration rates should lower available dissolved oxygen—especially in shallow backwaters of the harbor—by 2100 with 5 feet SLR and climate change. Increased water temperatures will also increase benthic respiration rates again in areas of high surface to volume ratios (i.e., shallow areas). Reduced DO will result in a decrease in benthic biodiversity and could lead to surface sediment or bottom water hypoxia events which would greatly degrade habitat quality. With 5 feet of SLR, this would reduce water quality with regards to DO to a 3. The inability of storm events to ventilate the entire harbor and surface sediments through resuspension, and to increase interstitial flushing, will also lead to increases in overall eutrophication and hypoxia in some areas in the presence of a barrier. Reduced wave action and resuspension would add to this effect. With 5 feet of SLR and a barrier, the DO rating would drop to a 2.5.

SEDIMENT QUALITY

Sediment concentration of metals and hydrophobic organic contaminants (e.g., polycyclic aromatic hydrocarbons) are a result of sources, biodegradation, and burial. Sediment processes are slow compared to water column processes. Even after water quality has improved due to the Harbor clean-up, sediment quality takes years to recover (mostly through slow resuspension and flushing of particles out of the harbor or burial with clean sediments). Current sediment quality would rate a 2.5 if a 5 is contaminant-free and fully oxygenated sediments, and a 1 is anoxic "black mayonnaise." There are still several areas of the harbor that would rate a 1.

Given 5 feet of SLR, the sediment quality will likely remain the same (2.5, see Figure 6.6), with some minor improvements over time as contaminated sediments are buried beneath cleaner sediments. The problem areas would probably remain. With 5 feet of SLR and a barrier, as described above, fine-grain sediments would be allowed to settle more in shallow backwaters because of decreased wave action, the removal of sediment-mobilizing storms, and decreased current velocities. These fine-grain sediments are associated with hydrophobic organic and metal contaminants. We expect that sediment contaminant concentrations will be directly correlated with the percentage of fine-grain sediments in any particular sediment sample. Therefore, sediment quality would become worse in shallow backwaters, and better in sandy

TABLE 6.1

Assessment of Boston Harbor Water Quality Factors with Present Conditions (0 feet SLR), Future Conditions (5 feet SLR), and Future Conditions with a Harbor-wide Barrier Installed (5 feet SLR + barrier)

Water Quality Factor	Metrics	Data Sources	0 ft SLR Water Quality (1=poor, 5 = high)	5 ft SLR Water Quality (1=poor, 5 = high)	5 ft SLR Barrier (1=poor, 5 = high)
Nutrients	Nitrate concentrations	MWRA	4	4	3.5
Bacteria	Enterococci counts/100 ml	MWRA	3	3	2
Water Clarity	Secchi depth	MWRA	3	3	2.5
Dissolved Oxygen	mg L^{-1}	MWRA	3.5	3	2.5
Sediment Quality	% of fine grains, volume Sediment contaminants	Byrnes Model*	2.5	2.5	2

* For details of the Byrnes Model, please see section below on Subtidal Barrier Impacts.

Source: UMass Boston

areas near the barrier where fine-grain sediments would not be able to settle due to high bottom water current velocities. Overall, this could lead to more and larger contaminated sediment areas, resulting in a rating of a 2.

Habitats

For the purposes of this assessment, we will define a number of habitat types for Boston Harbor, including subtidal, intertidal, and shoreline habitats that are not mutually exclusive.

Subtidal

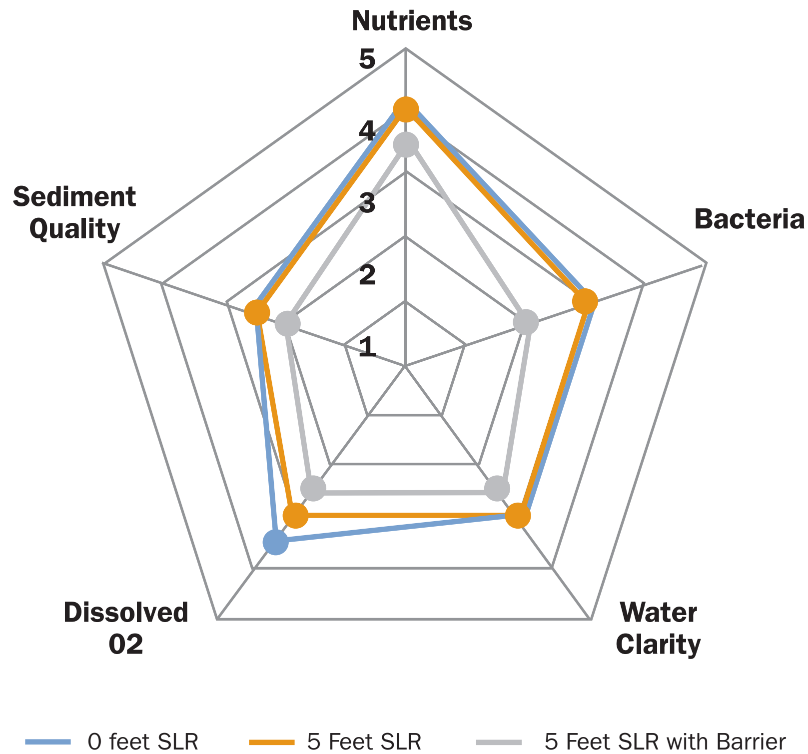
The subtidal area of Boston Harbor is the portion of the seafloor that remains submerged underwater at all tide levels. In coastal areas not affected by glacial processes, there is a gradual fining of bottom sediment with increasing water depth and distance from shore. This is not the case in Boston Harbor due to the deglaciation processes that shaped the harbor seafloor. Boston Harbor has heterogeneous sediment distribution with patches of silt/clay (mud) dispersed among the other major sediment types (Li et al., 2010). Different areas of the Harbor have different dominant surface sediment types that can be broadly grouped into four classifications based on sediment size: mud, sand, gravel and rock (Figure 6.7). Various types of surface substrate serve as habitat for macroalgae (seaweed), fish, crustaceans, shellfish and other invertebrate marine organisms. The surface substrate determines which species can live there (Hale and Helshe, 2006; Kritzer et al., 2016).

While not exclusively the defining driver of benthic habitat type, surficial substrate serves as a proxy for three major subtidal habitat types: muddy, sandy, and mixed (gravel and rock) (Stevenson et al., 2014). Eelgrass beds and designated shellfish growing areas are special cases of subtidal habits for the purposes of this study. A map of shoreline habitat and potential shellfish habitat has been constructed for this report (Figure 6.8).

Under present conditions, Boston Harbor subtidally is predominantly muddy substrate with extensive areas of sand, particularly in the northern half of the Harbor, and lesser regions of mixed gravel and rock in the erosional areas of the harbor where bottom currents are higher. The bottom substrate type tends to correlate with the strength of the current velocities in the area—muddy in low-energy regions of the harbor with sand to gravel and rock where current velocities

FIGURE 6.6

Boston Harbor Water Quality Ratings with SLR Scenarios



Source: UMass Boston

and thus scour are greater (Knebel and Circe, 1995).

All sub-tidal habitats in proximity to the OHB openings would be dramatically impacted by the semi-diurnal (twice-daily) tidal currents. Areas further from the barriers but near naturally-occurring tidal restrictions might also see similar effects. Those effects would include scour by tidal currents in proximity to the barrier openings, and deposition of fine-grained material further from the barrier openings. These changes would also depend on the substrate that the scouring currents impinge upon. Results from the hydrodynamic model conducted for this study by Woods Hole Group show maximum tidal current velocities of approximately 5.5 ft/s at Station 1 (1,500-ft gated opening) and approximately 8.5 ft/s at Station 3 (650-ft gated opening) (Figure 6.2); Woods Hole Group, 2017).

SUBTIDAL BARRIER IMPACTS

The barrier has the potential to alter the substrate available for biogenic habitats throughout the harbor. To evaluate the effects of the harbor barrier on available habitats on the seafloor, we built a

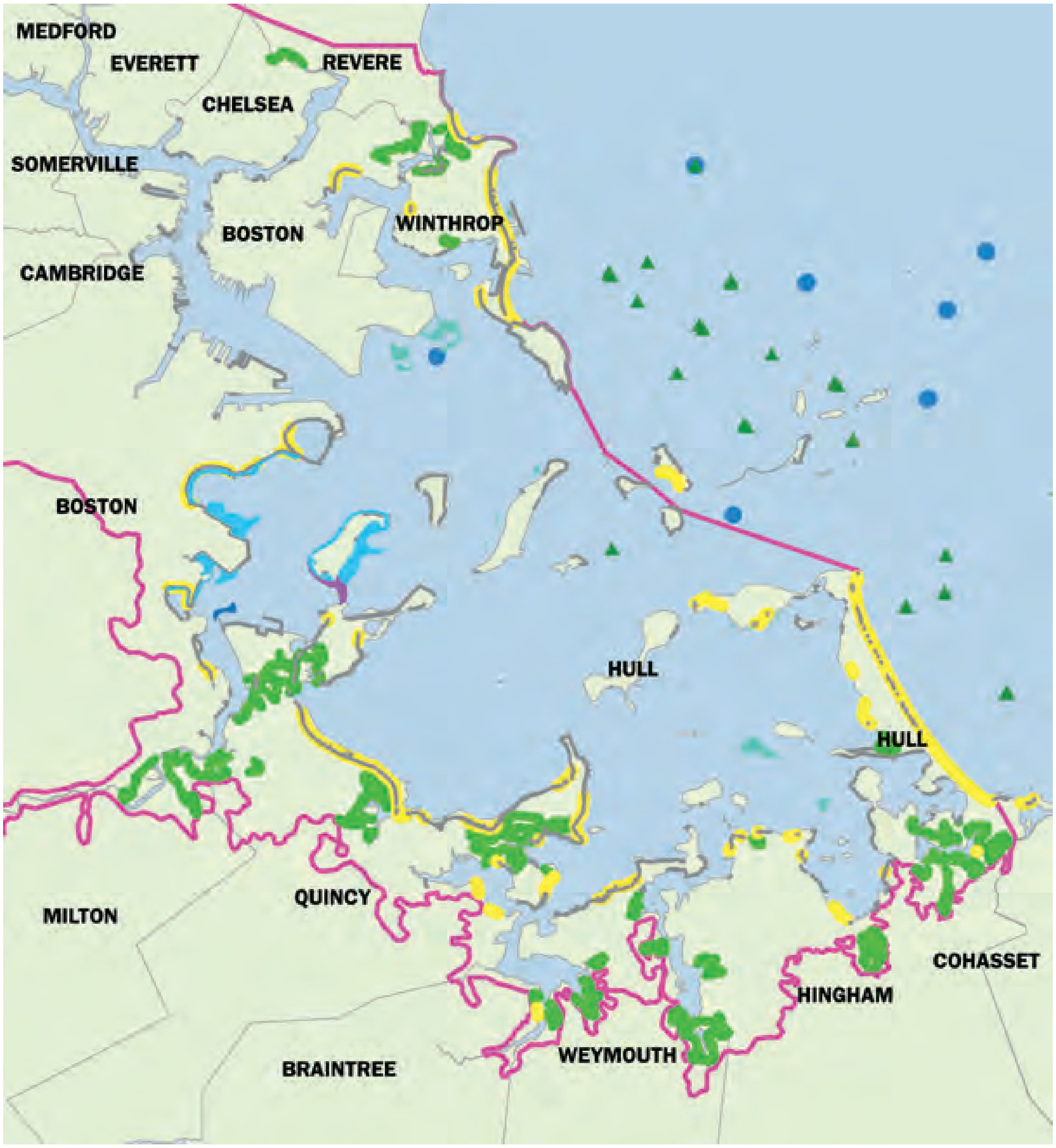
FIGURE 6.7

Present Day (0 Feet SLR) Distribution of Surface Sediments

Source: UMass Boston. Compiled from MassGIS, 2017 and MORIS, 2017 data

FIGURE 6.8

Present Day Habitat Types in Boston Harbor



Legend

Habitat and Shoreline Types

- Harbor Barrier Assessment Project Bounds
- Hardened Shoreline
- Beach Shoreline
- Salt Marsh Shoreline
- Eelgrass Beds (2012 & 2017 surveys)
- Kelp Beds
- Attached Mussel Beds

Shellfish Suitability Areas

- Blue Mussel
- Razor Clam
- Soft-shelled Clam

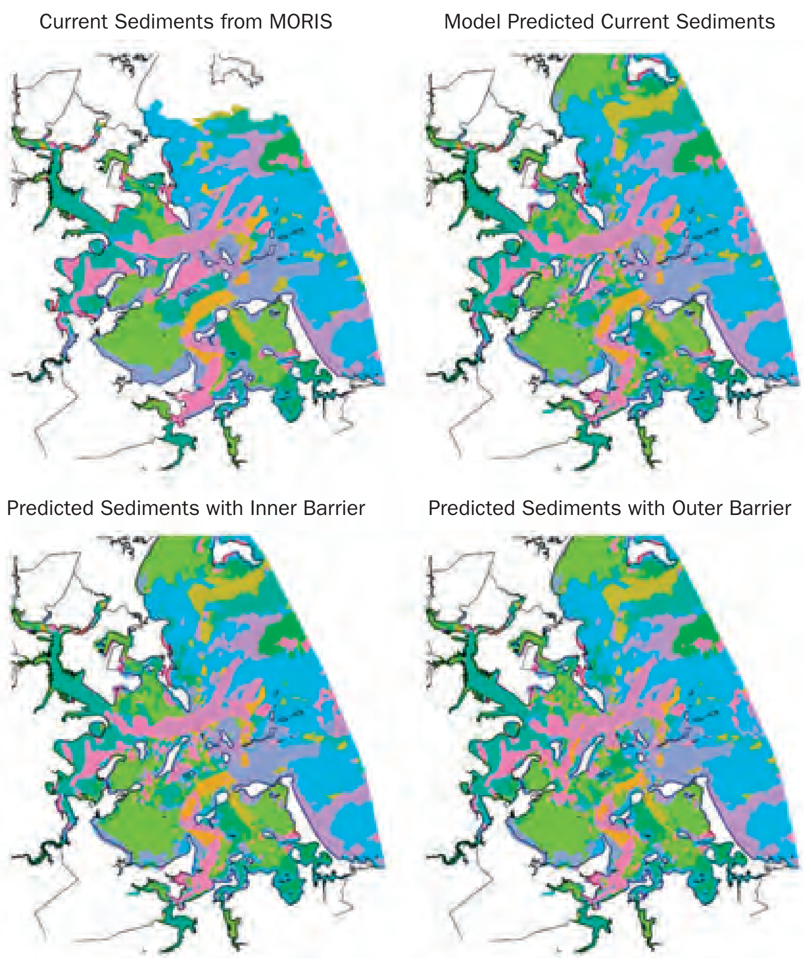
Source: UMass Boston. Compiled from MassGIS, 2017 and MORIS, 2017 data

Miles: 0, 2, 4

model (the "Byrnes Model") to classify surficial sediment types throughout the harbor (Figure 6.9, top left) based on the CZM Surficial Sediments in Massachusetts State Waters from 2015, which uses the Barnhardt et al. (1998) classification scheme and is available via the Massachusetts Ocean Resource Information System (MORIS, 2017). Our model classified sediments as a function of harbor depth, maximum current velocity at peak flood tide, distance to shoreline, and distance from harbor mouth using a regression tree approach for habitat classification (James et al., 2013). Velocity and depth were derived from the BH-FRM flood model outputs. Our classifier achieved 90% classification accuracy (Figure 6.9, top right). When the model was used to evaluate changes in sediment types under the OHB conditions, we found that the relative distribution of habitat types stayed fairly constant (Table 6.2) despite slight changes in surficial sediment distribution (Figure 6.9, bottom row).

FIGURE 6.9

Distribution of Surficial Sediments Throughout Boston Harbor



Legend

Sediment Type

- Gravel
- Gravel with Mud
- Gravel with Rock
- Travel with Sand
- Mud
- Mud with Gravel
- Mud with Rock
- Mud with Sand
- Rock
- Rock with Gravel
- Rock with Mud
- Rock with Sand
- Sand
- Sand with Gravel
- Sand with Mud
- Sand with Rock

Source: UMass Boston

MUDDY SUBTIDAL

At present, the subtidal muddy areas provide preferred habitat for winter flounder (*Pseudopleuronectes americanus*) which in their juvenile stage are important prey for other fish species. Eels, skate, sand lances, juvenile lobsters, and other fish species also make use of muddy subtidal regions. The muddy subtidal areas also support a rich diversity of marine polychaetes, oligochaetes, and platyhelminths (worms); amphipods; gastropods (snails); and several clam species where mud sediments are not too fine (Stevenson et al., 2014; Pembroke et al., 2016).

Muddy subtidal areas are impacted by tidal currents, tidal exchange, and sediment resuspension during storm events and deposition post-storm. In the project area, the muddy subtidal has recovered substantially from earlier pollution (Taylor, 2011), although pockets of polluted and anaerobic sediments remain. This is particularly true in industrial or formerly industrial areas and in inner regions of the harbor with lower current velocities and limited water exchange (Kalnejais et al., 2010; Li et al., 2010). This habitat is rated with a quality of 3 (Figure 6.10).

Muddy subtidal areas are likely to expand slightly with a 5-foot rise in sea level and become finer-grained as the additional water depths further reduce the wave and tidal energy reaching the seafloor. Silts and clays could overlay some formerly coarser-grained subtidal areas. The amount of muddy subtidal area might be expected to increase as muddy intertidal areas become submerged. If sea level rise results in retreat of development from some low-lying developed areas, it is possible that some of that sea-reclaimed area may also become muddy subtidal over time as formerly intertidal or upland surfaces become covered by fine-grained sediment from riverine inflows and storm-driven sediment transport, in the form of suspended load, within the harbor. To date almost no research exists on the response of previously intertidal or upland regions to submergence, so it is unclear what quality of habitat "drowned" salt marshes and grasslands would provide, much less that of submerged areas in the built environment. These areas are likely to be very limited, so the overall area and quality muddy subtidal as a habitat for the species mentioned above is likely to retain a quality of 3 with 5 feet of SLR.

Construction of an OHB might also produce a modest increase in the spatial extent of muddy subtidal habitat as parts of the harbor would become relatively lower-energy as storm waves and storm- and wind-driven currents play a lessor role. This would reduce the amount of resuspension that now occurs during a storm and also reduces the amount of suspended load that could have been carried out of the harbor during a falling tide. At the same time, the fine-grained subtidal areas close to the barrier openings would be altered quickly by the new high-energy regime there. Away from the high-velocity currents at the barrier openings, fine-grain subtidal areas would be expected to increase in spatial extent in more protected areas of the harbor. Reduction in energetic storm flushing of the harbor will decrease resuspension of fine-grain sediment; thus once deposited, this material will likely remain on the seafloor and more fine-grained (and perhaps finer-grained) material will be deposited. Assuming Boston Harbor is able to maintain or improve its current water quality, particularly in terms of pollution and contaminants from upland and riverine sources, the presence of an outer barrier should not result in degraded habitat conditions for muddy subtidal areas, and thus such habitat remains with a 3 quality rating.

SANDY SUBTIDAL

Sandy subtidal habitat is less abundant within Boston Harbor but serves as important nursery habitat for a number of fish species including winter flounder (*Pseudopleuronectes americanus*), sand lance (*Ammodytes americanus*), and little skate (*Leucoraja erinacea*) as well as soft-shelled clams (*Mya arenaria*). Adult stages of many species also frequent sandy subtidal habitat. Of the four broad habitat classifications, it has the broadest use among commercially-harvested marine organisms (Stevenson, 2014). Tidal currents can transport finer sediments which would otherwise settle and convert the area to muddy substrate. The existing sandy substrate in Boston Harbor is given a quality of 4.

TABLE 6.2

Percentage of Surficial Sediment Habitat Types (defined by the type of sediment with >50% cover) Current Observed versus Modeled by Regression Tree Analysis in Boston Harbor

Sediment	Current Sediments from MORIS	Model Predicted Current Sediments	Predicted Sediments with Inner Barrier	Predicted Sediments with Outer Barrier
Gravel	6.49%	7.46%	7.46%	7.16%
Mud	33.46%	39.69%	39.69%	39.46%
Rock	39.89%	35.24%	35.24%	35.29%
Sand	20.16%	17.62%	17.62%	18.08%

Source: UMass Boston

The extent of sandy subtidal habitat would most likely not change significantly within Boston Harbor with 5 feet of SLR. Some intertidal sandy areas would be converted to subtidal sandy habitat expanding the acreage. However, with 5 feet of SLR, the processes that maintain sandy subtidal areas, strong current velocities and wave energy, will be somewhat reduced by the increased depth, potentially resulting in a decrease in substrate grain size and a commensurate shift in benthic habitat. Thus, in lower-energy regions of the harbor, some muddy intertidal areas might encroach upon sandy subtidal areas over time, although this likely would be equaled in scope by the increase in area of formerly intertidal sandy regions. With SLR of 5 feet, sandy subtidal habitat retains a quality of 4.

Installation of the OHB, as noted earlier, would increase current velocities in areas of the harbor in proximity to the barrier gates while creating lower-energy regions in other parts of the harbor, particularly those areas adjacent to higher tidal currents. As jets of water enter (rising tide) and exit (falling tide) the harbor through the gates, areas of little to no current velocity would occur to either side of the incoming or outgoing jets. These areas would very likely transition into low-energy areas. This effect would be much more pronounced inside the barrier.

Sandy subtidal areas are moderate- to high-energy environments with sufficient energy to transport sand-sized material, so shifts in the distribution and extent of sandy subtidal habitat would reflect shifts in currents and storm-driven wave action within the harbor. However, with construction of an OHB, some sandy subtidal areas could rapidly change to fine-grained muddy subtidal areas. Absent large storm waves, sand transport, as bedload, could be somewhat reduced (Figure 6.4). Storms waves can move material in almost any direction, though waves with the most fetch (i.e., from the open ocean) are the most effective. These storm waves increase the variability of sediment transport and even short-term subtidal evolution, migration, and change. This storm-driven natural variability would be diminished in Boston Harbor post-barrier installation. The sandy subtidal areas in Boston Harbor might thus decrease in surficial extent and likely decrease in quality; with an OHB combined with SLR, the habitat declines to a quality of 3.5.

> In lower-energy regions of the harbor, some muddy intertidal areas might encroach upon sandy subtidal over time, although this likely would be equaled in scope by the increase in area from formerly intertidal sandy regions.

MIXED SUBTIDAL

The mixed subtidal habitat within Boston Harbor is a combination of the rocky and the gravel substrate types. These two groups were combined because there were very limited amounts of rock-boulder habitat within Boston Harbor itself (although ample areas of this habitat type exist just outside the harbor in Masachusetts Bay). Gravel-cobble habitat (combined with the limited harbor rock-boulder habitat) is home to many fish species, including juvenile cod (*Gadus morhua*) and the important prey species cunner (*Tautogolabrus adspersus*). It is also the primary habitat of lobster *(Homarus americanus*) and other crustaceans, along with sessile invertebrates such as blue mussels (*Mytilus edulis*) and habitat-forming algal species such kelp (e.g. *Saccharina latissimi*) (Stevenson et al., 2014). The current mixed subtidal habitat is rated 4 (Figure 6.10). A 5-foot rise in sea level is not expected to have significant impact on the mixed subtidal regions, so this habitat would continue to have a quality rating of 4.

The existing mixed subtidal areas are, however, somewhat vulnerable to an OHB installation. These types of habitats are created and sustained by energy levels, water clarity, grain size, and other substrate characteristics that would be changed by an OHB. These bottom types exist due to the processes that prevent them from being covered by finer-grained sediments in the long term (strong tidal currents and high-energy events such as storms). As discussed above, an OHB might change some regions of the harbor to relatively lower energy areas, and thus bottom types such as mixed subtidal could become overlain with fine-grained material. Once such areas experienced this type of sedimentation, it is unlikely they would ever revert back to mixed bottom type with an OHB in place because the driving process that could re-suspend this material—high-energy events—would be reduced. Much of the mixed subtidal bottom type not maintained by semi-diurnal tidal currents could be reduced with an OHB and 5 feet of SLR. Under these conditions, this habitat is given a quality rating of 3.5.

EELGRASS

Eelgrass (*Zostera marina*) needs shallow waters, low turbidity, and areas protected from waves and strong currents. Little of the once extensive eelgrass meadows in Boston Harbor now exist, but efforts continue at restoration. A number of eelgrass beds have been successfully re-established, with a particularly healthy one in East Boston waters just off of Logan Airport, and recent reports have documented the expansion of eelgrass within Boston Harbor (Pembroke, et al., 2016). Key eelgrass influences are current, water temperature, and tidal flushing. This habitat currently is given a quality of 3.

Eelgrass habitat is of particular concern, as eelgrass bed will be threatened by SLR as increased water depths leads to lower light availability. Rising water temperatures are also expected to have a significant effect. Without human intervention, the limited amount of eelgrass beds currently in Boston Harbor may face limited areas for migration, as existing beds are submerged below photosynthetically viable water levels, while newly submerged shallow water areas are likely to be of poor quality substrate and conditions for eelgrass. Eelgrass habitat under 5 feet of sea level rise is thus rated a quality of 2.

The construction of an OHB would affect eelgrass areas only so much as some of the underlying benthic substrate might be altered from sandy or cobble to lower-energy muddy regions that would not be conducive to eelgrass survival or expansion. Not all eelgrass areas would be threatened with such substrate change; therefore, the much greater influence will be sea level rise and warming waters from climate

change. Eelgrass habitat with 5 feet of SLR and an OHB would thus remain at 2.

INTERTIDAL

The intertidal area of Boston Harbor is the portion of the shore area that is submerged during extreme high spring tides and continues seaward to a lower boundary defined by the lowest area exposed during lowest spring low tides (Bell et al., 2005). As with the subtidal regions, habitat for macroalgae (seaweed), fish, crustaceans, shellfish, and other invertebrate marine organisms is determined largely by intertidal substrate type. Intertidal habitats are strongly affected by waves, water flow, and slope, however, so these additional factors need to be considered in assessing intertidal habitat (Schoch and Dethier, 1996; Bertness et al., 2001; Harley and Helmuth, 2003). For the purposes of this study, the harbor intertidal area can be broadly grouped into three habitat classifications based on the dominant substrate: mud (mudflats); hard substrate such as rock/gravel, anthropogenically hardened intertidal areas such as rip rap, and engineered wall (rocky intertidal); and salt marsh.

Sandy intertidal habitat is found primarily as an extension of sandy beach shoreline areas or sandy subtidal areas and thus has been included as part of subtidal sandy habitat with the upper intertidal portions considered part of sandy beach habitat, rather than as separate habitat type itself.

Potential substrate changes play a role in assessing impacts from SLR and of an OHB on intertidal habitats (Perkins et al., 2015). Overall, the impacts would be similar to those discussed above for subtidal areas. Intertidal habitats are also impacted by waves. Under current conditions, storm waves affect the shorelines, intertidal habitats, and to a lesser extent the subtidal areas throughout the harbor (Figure 6.3).

MUDDY INTERTIDAL (MUDFLAT)

Intertidal mudflats are important habitat for a variety of infaunal invertebrate species, along with an even greater variety of mollusks, gastropods, and crustaceans than subtidal mud habitat. In addition, the diverse set of mudflat-dwelling invertebrates is prey for a variety of resident and migratory fish and bird species (Paton et al., 2005; Phillipe et al., 2016; Taylor, 1998). Muddy intertidal habitat within Boston Harbor varies in quality depending on proximity to historically polluted shores and rivers, along with the degree of tidal flushing (Brown et al., 2015). While biodiversity is returning to the mudflats (Pembroke et al., 2016), many areas still suffer from elevated levels of contaminants such as heavy metals (Li et al., 2010). Given the contamination issues in much of the Harbor, this habitat has a quality of 2 (Figure 6.10).

Much of the shallow intertidal mudflats currently in Boston Harbor will become muddy subtidal habitat under conditions of a 5-foot rise in sea level. New intertidal mudflats may appear in conjunction with "drowned" salt marsh areas and formerly upland vegetative areas, but it would take considerable time for such new intertidal areas to convert to healthy mudflats. Thus, muddy intertidal habitat with 5 feet of SLR remains with a quality of 2.

An OHB would likely create a modest increase in the extent of muddy intertidal area within Boston Harbor (Perkins et al., 2015). Some formerly sandy areas would be overlain by fine-grained sediments in the lower-energy environments created by a barrier. While expansion of mudflat areas might provide greater habitat for certain shellfish species, the quality of that habitat would depend upon the water quality in the absence of storm-driven flushing of the Harbor. Excess nutrient loads or pollution in the form of heavy metals, petrochemicals, and other toxins could accumulate in some shallow areas or through deposition when attached to fine sediments. Given the potential for the creation of new intertidal mudflats when SLR is combined with the construction an outer barrier, balanced by the risk of contaminating existing and new intertidal mudflats due to changes in current flow and flushing by such an outer barrier, the quality rating of intertidal mudflats under such conditions remains a 2.

ROCKY INTERTIDAL

Rocky intertidal habitat is currently influenced by large tidal currents, wind and storm-generated waves, and rocky substrates. Most of the rocky intertidal habitat in the harbor is located on the Boston Harbor Islands, a prime example being that on Rainsford Island. Biodiversity is being impacted by invasive species such as the Asian shore crab (*Hemigrapsus sanguineus*), the sea squirt (*Didemnum vexillum*), and the orange sheath tunicate (*Botrylloides violceus*), along with warming water temperature and human activity (trampling, harvesting) (Airoldi et al., 2005). Water quality sometimes affects the scattered pockets of rocky intertidal habitat along mainland shorelines such as at Raccoon Island or Squaw Rock. This habitat is given a quality of a 4 as a relatively healthy system affected by invasive species and warming waters (Figure 6.10).

While much existing rocky intertidal habitat could become subtidal with 5 feet of SLR, new natural and anthropogenic hard substrate

intertidal areas would be created by the rising water level. Much of the new rocky intertidal areas would likely be in the form of coastal protection structures (bulkheads, seawalls, rip rap revetments, and breakwaters). Some new hard-substrate intertidal habitat might be in the form of newly inundated human-made substrate such as building foundations, roads, paths and parking lots. This would provide lower quality intertidal habitat, and thus overall the rocky intertidal habitat in Boston Harbor would decline to a quality of 3. The same rating of a 3 would accompany SLR with a barrier.

ENGINEERED SHORELINE INCLUDING BARRIER HABITAT

Biodiversity on erosion control structures within Boston Harbor is currently primarily influenced by the location of the structure within the intertidal zone, the substrate type used for its construction, and its design. Older granite-block jetties and seawalls located entirely or primarily within the mid and lower intertidal zone have much higher biodiversity than, for example, cement seawalls built in the upper reaches of the intertidal zone. Existing rip rap shoreline or revetment along Boston Harbor generally exhibits low biodiversity, as do the steel and cement bulkheads that line most of the inner harbor. Given that most of the erosion control structures within the project area are located in the upper intertidal zone or are constructed with materials and/or designs that are not biologically friendly, the habitat quality overall is given a 2 (Figure 6.10).

With a 5-foot SLR, some of the existing erosion control structures would be submerged as mixed subtidal habitat or would become poor-quality rocky intertidal habitat. The remaining shoreline areas of rip rap, granite block, cement, and steel bulkheads would continue to be of low biological value thus rating a quality of 2 with or without a barrier.

Running from Hull to Winthrop across approximately 4 miles of Boston Harbor, an OHB would dramatically change habitat in its immediate proximity. In these areas, it would replace or interact strongly with beach (Hull), existing adaptation strategies (Winthrop and Revere) and subtidal areas (Boston Harbor). In addition, it would replace coastal bluff and beach areas of Gallops and Georges Islands, areas that are already armored to some extent. This engineered structure is likely to have limited habitat value unless constructed with diverse substrate in mind which would cost significantly more.

An OHB would provide novel habitat for colonization by intertidal and subtidal organisms. Portions of the wall exposed to the open ocean would likely be colonized by organisms typical to hard substrates around Massachusetts, as are found on the outer harbor islands (Bell et al., 2005; Eddy and Roman, 2016). As this would be novel bare substrate, the potential would exist for a high amount of cover by non-native species (Airoldi and Bulleri, 2011; Airoldi et al., 2015). The degree to which these communities would resemble natural New England subtidal communities would depend on the match between wall-building materials and natural morphology. Along the gaps of the wall itself, high flow rates are likely to encourage a diverse community of subtidal filter feeders (Palardy and Witman, 2014). Either harbor barrier design would provide the opportunity to innovate, deliberately developing biologically-functional engineered rocky intertidal habitat. Ongoing research and current projects in Boston, Seattle, Australia, Israel, Italy, and the UK all provide guidance on emerging best practices (see for example Dafforn et al., 2015; Ido and Shimrit, 2015; Martins et al., 2015; Evans et al., 2016). The Hubline artificial reef project (Barber et al., 2009) should provide guidance on how to minimize the impact and maximize the benefit a barrier wall could provide to native communities.

> Biodiversity on erosion control structures within Boston Harbor is currently primarily influenced by the location of the structure within the intertidal zone, the substrate type used for its construction, and its design.

SALT MARSH

Currently, salt marsh destruction has been slowed, and salt marsh restoration has been successful in much of Boston Harbor. Salt marshes in the harbor are primarily influenced by freshwater inflows, sediment deposition, and exposure to wave action. Negative impacts on area salt marshes are invasive species such as the green crab (*Carcinus maenus*) and the common reed (*Phragmites australis*), rising sea levels, and human activity. Overall, the salt marshes are productive and healthy; thus this habitat has a quality of 4 (Figure 6.10).

While salt marshes are able to trap sediment and build upwards or migrate further inland in response to limited SLR, it is unclear whether the salt marshes around Boston Harbor will be able to keep pace with or adapt to an increase in sea level of 5 feet. Kirwan et al. (2016) have shown that salt marsh vulnerability to SLR has been overstated in some systems; however, one key finding in that study was the value of tidally-driven sedimentation to aid salt marsh systems in keeping pace with SLR, a factor that would need further study with regards to its applicability to Boston Harbor salt marshes. Another factor in salt marsh vulnerability is the presence of accommodation space, landward areas available to salt marshes to migrate into when keeping pace with SLR. Salt marshes can both migrate landward and vertically accrete to keep pace with rising seas; considerations for both would be needed in any more detailed analysis. Finally, it is not clear whether salt marshes can be nourished artificially by adding sediment (spraying slurries). These attempts might allow some salt marshes to be preserved. With SLR of 5 feet, salt marsh habitat in Boston Harbor is expected to decrease substantially and thus is given a rating of 2.

> Long-term changes in Boston Harbor salt marshes in response to the addition of an OHB will depend on how such a barrier might alter rates of sediment accumulation and storm-driven erosion.

Long-term changes in Boston Harbor salt marshes in response to the addition of an OHB will depend on how such a barrier might alter rates of sediment accumulation and storm-driven erosion. Increases in suspended load nearshore due to increases in residence time and decreases in wave energy are expected with the installation of a barrier, and this material could aid in the vertical accretion of salt marsh systems. As more sediment-laden water is introduced into the system, some of that sediment would 'settle out' of the water column and be deposited onto the surface of the salt marsh, thus increasing its elevation. If an OHB was able to increase rates of sediment accumulation in extant marsh habitats, it might provide a benefit to long-term durability of these marshes. Sediment load and accumulation modeling is needed to fully address how an OHB might alter the long-term prospects for Boston-area salt marshes. Finally, a reduction in large erosion-causing storm waves from an OHB would also increase the survivability of salt marshes. The rate of SLR and of sedimentation, coupled with factors including compaction, subsidence, and available space for salt marsh migration, will largely determine the ability of Harbor salt marsh habitat to keep pace with SLR. Salt marsh habitat with SLR and an OHB are given a hopeful quality rating of 2.5, as an OHB might redistribute more sediment toward the marshes. As an aside, if the suspended sediment from river inflow advects pollutants with the fine-grained sediments that accrete in the salt marsh, the marsh could provide a natural filtration mechanism that could improve water quality throughout the harbor.

SANDY BEACH

Sandy beaches are affected by wave action and wind action, thus making them extremely susceptible to erosion or dramatic change from storm events. Most sandy beach shoreline within the study area is located in the more protected inner regions of Boston Harbor, although many sections are still at risk from erosion. Sandy intertidal habitat is influenced primarily by current velocity, which can cause scouring and, when combined with wave action, can affect the deposition and movement of both sand and finer sediments. Storms, while infrequent, can have major impacts by moving and redistributing the beach and intertidal sand. Sandy intertidal areas within Boston Harbor are usually found in conjunction with shoreline beaches, although some exist as sandbars in shallower areas of the harbor. Human activity impacts the biodiversity of sandy beach areas but also takes advantage of a major ecosystem service provided by sandy beaches, that of recreation. While not a high biodiversity habitat, the sandy beach areas in Boston Harbor have recovered from earlier decades of pollution and are given a quality of 3 (Figure 6.10).

Sandy beach habitat would suffer significant declines in areas with 5 feet of SLR. Because most of the Boston Harbor sandy beach habitat borders on developed land, there is little or no room for the beaches to migrate inland in the face of SLR. Large amounts of the current intertidal beach area could become sandy subtidal habitat with 5 feet of SLR, and SLR alone could cause a drop in quality to a 2.

An OHB might have a positive impact on the harbor's sandy beaches, as erosion would likely lessen due to the decrease of storm wave energy. This would also increase the functional project life of any beach replenishment projects. Beaches would become more dissipative (lower slope) as they re-equilibrate to the new energy regime within the harbor. This could lead to an increase in intertidal habitat fronting sandy beaches as they become less reflective (steep). Lastly, the erosional areas along the mainland shoreline might transition into intermediate and/or depositional areas with concomitant habitat implications. Overall, an OHB might improve sandy beaches to a 2.5.

SUMMARY

Local habitat shifts are difficult to predict. They are based on current velocities and direction, sediment supply, wave action, depth, and light. Figure 6.9 shows that predicted impacts on surficial sediments throughout Boston Harbor with and without a barrier are quite minor. The top left figure shows the current data from MORIS. The top right shows that the model reproduces the actual data quite well. The bottom figures show model-predicted surficial sediments with an Inner Harbor Barrier and Outer Harbor Barrier, respectively. While the locations may not be precise, the patch size of predicted changes is probably more accurate. These minor differences under future conditions with and without a barrier are in agreement with model predictions of minor changes in current velocities (Figures 6.1 and 6.2) and directions as well as wave heights (Figure 6.4). However, some predicted changes would have potentially large local effects, especially on high-value habitats such as mixed subtidal areas (lobsters), seagrasses (nursery habitat), salt marshes (blue carbon, nursery habitat), and sandy beaches (recreation). The overall impacts of sea level rise are negative on the majority of habitats, while with careful design, some of the man-made structures in combination with protection from the worse storm impacts could improve habitat conditions in the future with the presence of a barrier. Results are summarized in Table 6.3 and Figure 6.10.

Ecosystem Services

Ultimately, habitat and water quality produce goods and services that can be measured especially by indicators that are important to people. While there are many diverse ecosystem services provided to a great variety of individuals and communities, here we focus briefly on fisheries, public access and recreation, and ecosystem functions.

FISHERIES

While there are a great variety of species within Boston Harbor, the main commercial fishery is lobster, the main potential aquaculture species

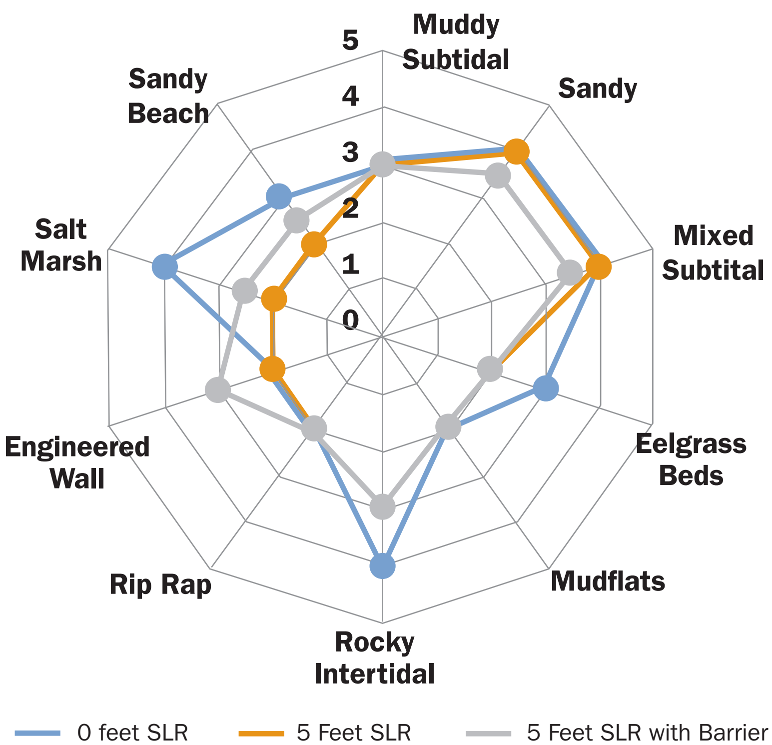
TABLE 6.3

Assessment of Boston Harbor Habitat Quality with Present Conditions (0 feet SLR), Future Conditions (5 feet SLR), and Future Conditions with a Harbor-wide Barrier Installed (5 feet SLR + Barrier)

Habitat Quality	Factors	0 ft SLR Habitat Quality (1=poor, 5 = high)	5 ft SLR Habitat Quality (1=poor, 5 = high	5 ft SLR Barrier Habitat Quality (1=poor, 5 = high)
Muddy Subtidal	Currents	3	3	3
Sandy Subtidal	Currents	4	4	3.5
Mixed Subtidal	Various	4	4	3.5
Eelgrass Beds	Depth, Light	3	2	2
Mudflats	Currents, Waves	2	2	2
Rocky Intertidal	Currents	4	3	3
Rip Rap	Design	2	2	2
Engineered Wall	Design	2	2	3
Salt Marsh	Sediment supply	4	2	2.5
Sandy Beach	Wave energy	3	2	2.5

Source: UMass Boston

FIGURE 6.10
Boston Harbor Habitat Quality Ratings with SLR Scenarios



Source: UMass Boston

are oysters and mussels (shellfish), and the main recreational fishery is striped bass (finfish). There are many unknowns, and therefore much uncertainty on how habitat change, temperature change, and the presence of a barrier might influence an individual species, but attempts are made to estimate relative impacts of SLR and a barrier.

Lobster Fishery
It is possible that by the time an OHB would be functional in 2050 or later, the current lobster fishery in Boston Harbor would be limited or non-existent due to warming water temperatures linked to climate change. Lobsters (*Homarus americanus*) are a cold-water species, and warming ocean temperatures have already shuttered once thriving commercial lobster fisheries in New York, Connecticut and Rhode Island, with populations declining in Massachusetts south of Cape Cod (Le Bris et. al. 2017. If lobster continue to remain in Boston Harbor within the OHB timeframe, however, the presence of a barrier could impact the seasonal migration of mature lobsters along the sea bottom, although the extent of such impacts is unknown. A related question is that of how the settling of juvenile lobsters on the cobble beds near the mouth of the harbor would be affected due to the presence of large sector gates and a narrowing at the harbor mouth with subsequent increases in velocity. Current velocities immediately at the sea floor boundary level could be significantly reduced from those higher in the water column and both mature and juvenile lobsters are known to survive in high-velocity zones within the Bay of Fundy, for example (Robichaud and Campbell, 1991). Thus, the lobster fishery is currently rated 3. Given the uncertainty of the extent and pace of ocean warming in coming decades, we continue to rate it a 3 based on expected SLR alone (i.e., not factoring in increased water temperatures), but drop the rating to 2 in the presence of a barrier.

Shellfish Fishery
There is little current shellfishing activity within the harbor, but there are areas of healthy mussels and discussions of growing oyster beds, with an experimental bed growing near Malibu Beach. The shellfish fishery therefore rates a 2 currently (Figure 6.11). With expected changes to the Harbor, including increased depth, there may be more areas that are available for shellfish farming in the future as shoreline is submerged and becomes tidal flats or shallows. Increased water temperatures and related increases in vibrio could make these stocks unviable, however. This rating will remain about a 2 with SLR. The possibility of incorporating marine bio-friendly “green” aspects to the barrier system could allow the planting of oyster beds in shallow constructed areas, thus leading to an increased area for oyster growth. Areas of high current velocity near the OHB gates might also support blue mussel (*Mytilus edulis*) aquaculture. Therefore, with the OHB we increase the rating to 2.5.

Finfish Fishery
The current striped bass (*Morone saxatilis* or “Stripers”) fishery is productive as a recreational fishery within Boston Harbor along with winter flounder (*Pseudopleuronectes americanus*), mackerel (*Scomber scombrus*), and several other species. The existing finfish fishery is rated a 3. The finfishery is likely to stay the same with SLR (a 3 rating), but may decline with the impacts of an OHB, with its constricted openings and higher velocities at the mouth of Boston Harbor (2 rating). While there is little existing research on these type of impacts, a barrier is considered likely to lower the numbers of stripers that migrate

into the Harbor. The larger influence on Boston Harbor's finfishery is the ongoing warming of Massachusetts Bay waters and the concomitant changes in species due to range expansion (warmer-water fish moving north) and range contraction (cold-water species moving north or farther offshore).

PUBLIC ACCESS

Thousands of people boat, paddle, and swim in the harbor, and walk, jog, bike, and explore its shores and pathways. While it is difficult to assess a value to these experiences in more than dollars generated by for-profit businesses, some qualitative indicators may be considered.

HARBOR RECREATION

The current use of the harbor by recreational boaters is quite high. A 4 rating could qualify the intense summer use with good water quality and a diversity of harbor and island views and experiences. This is likely to remain similar given SLR. The presence of an OHB could change the aesthetics of the harbor, but it might more significantly impact the safety of recreational boaters exiting or entering the harbor through narrower openings and increased current velocities. This would lead to a decrease to a 3. The closing of the barrier would reduce recreational boating, but this would likely be minimal during a storm anyway. Even with an open barrier, recreational boats might avoid the high peak velocities at the southern gate and use the northern gate, thus either reducing recreational uses outside the of Harbor or potentially impacting commercial shipping traffic.

SHORELINE LAND USE

Real estate values should be greatly enhanced by the removal of storm-surge threats. This could lead to greater development and movement of people and buildings to the shoreline, with negative impacts on or removal of natural ecosystems. If regulations were in place to engineer green adaptations to SLR, there could be an increase in real estate value associated with an increase in recreational value and sustainability. In addition, carefully designed berms and hard structures might increase public access to the outer harbor (e.g., walkways on the barrier itself or access to designed tidepools). Many intertidal use areas

may become drowned by SLR, but creative design of an OHB (or IHB) could incorporate intertidal elements. Currently, Boston Harbor shoreline use rates a 3. This rating could decrease somewhat to a 2.5 with SLR, but it could increase with thoughtful barrier design and investment to a 3.5.

ECOSYSTEM FUNCTIONS

There are many ecosystem functions performed by various harbor and shoreline habitats, including providing nursery habitat, increasing water quality through filtration, and removing and storing carbon. Critical functions accompany critical habitats such as salt marshes and eelgrass beds.

BLUE CARBON: SALT MARSHES

Salt marshes have high productivities, efficiently converting atmospheric CO_2 to organic matter that can then be stored as organic rich sediments. Salt marshes are one type of coastal ecosystem termed “blue carbon” systems that act naturally to sequester and store large amounts of atmospheric CO_2. Rising sea levels and therefore greater erosion will increase sediment supply for areas such as salt marshes and seagrasses, which need to keep building towards a rising water surface to prevent drowning. In this way, erosion of some areas will actually enhance sediment and associated carbon burial. Increased fine-grain sediments may reduce water clarity, which is critical to the health of eelgrass, however. The removal of dams in the rivers that drain to Boston Harbor could also be a long-term trend that increases sediment availability. Finally, alternative experimental methods such as spraying fine grain sediments from dredging operations over salt marshes to increase accretion might be effective (Slocum, et al., 2005; Wigand et al., 2017). The rate of sequestration may increase with increasing SLR rates, until the sediment supply is not enough to keep up and the marsh drowns. Decreased sediment resuspension events, increased sea level, and the inability to migrate landward will reduce the ability of marshes to sequester carbon. Decreased storm surges that could damage marshes may increase salt marsh survivability. Given a rating of 3 currently, this may increase with SLR—if the marshes can survive—to a 3.5, and increase even further with a barrier to a 4, but this function may deteriorate to a 1 if the salt marshes eventually drown.

STORMWATER REMEDIATION

The harbor provides a great service by taking sewage, nutrient-rich waters, and road runoff, purifying water through filtration in salt marshes, recycling nutrients through biogeochemical cycling, and flushing waters out of the harbor. The harbor is currently able to provide this function given the reduced organic-matter loading following the Harbor Cleanup, thus it has a current rating of 4. A larger volume and therefore longer residence time would imply a slightly decreased ability for stormwater remediation, for a rating of 3.5. With the barrier closed for up to 84 hours

TABLE 6.4

Assessment of Boston Harbor Ecosystem Service Ratings with Present Conditions (0 Feet SLR), Future Conditions (5 Feet SLR), and Future Conditions with a Harbor-wide Barrier Installed (5 Feet SLR + Barrier)

Ecosystem Service	Factors	0 ft SLR Habitat Quality (1=poor, 5 = high)	5 ft SLR Habitat Quality (1=poor, 5 = high)	5 ft SLR Barrier Habitat Quality (1=poor, 5 = high)
Shellfish	Vibrio	2	2	2.5
Finfish	Migration	3	3	2
Lobster	Larval settling	3	3	2
Harbor Recreation	Aesthetics, Currents	4	4	3
Shoreline Land Use	Design	3	2.5	3.5
Carbon Storage	Sediment supply	3	3.5	4
Storm Water Remediation	Flushing rate	3	2	2

Source: UMass Boston

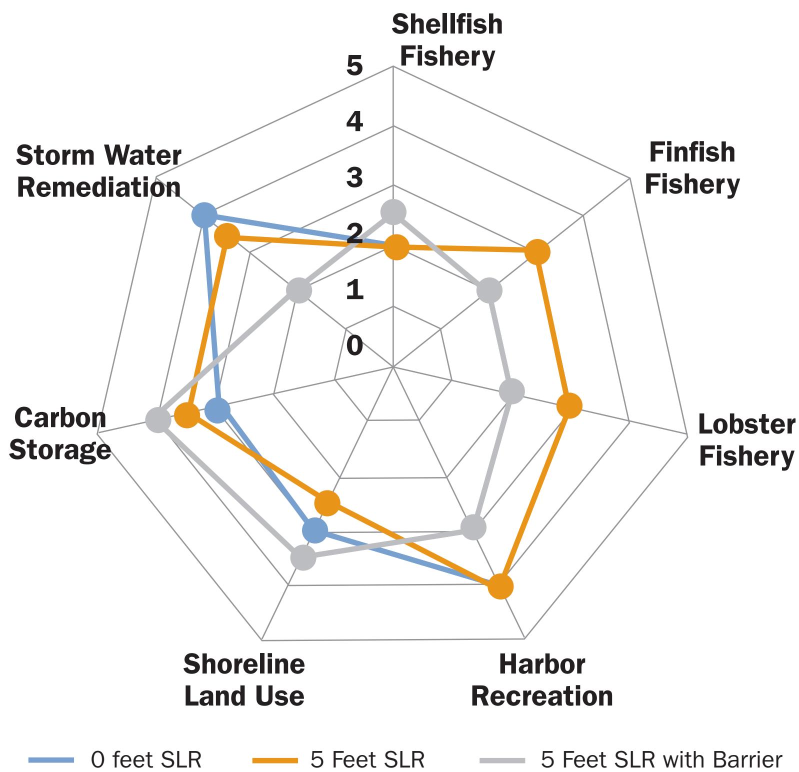
during a storm event, this ability will likely diminish greatly to a rating of 2.

ECOSYSTEM SERVICES IMPACT SUMMARY

Overall, it is very hard to assess ecosystem services as there is much uncertainty about how critical, high-value species and habitats would respond to SLR and the presence of an OHB. We expect finfish and lobster fisheries may degrade slightly, while shellfish aquaculture potentially may increase slightly. Carbon storage could increase slightly due to increased fine-grain sediments near shore. Stormwater remediation and overall recreation would likely decrease slightly due to the presence of a barrier. Shoreline land use may decrease in terms of beach usage, but real estate values might increase due to the protection from storms that the barrier would provide. Results are in Table 6.4 and Figure 6.11.

FIGURE 6.11

Boston Harbor Ecosystem Service Ratings with SLR Scenarios



Source: UMass Boston

Other Considerations

In addition to the possible construction of an OHB, over the next 30 to 80 years other significant environmental changes are projected for Boston Harbor. Increased warming of land and water surface temperatures with climate change is likely to reach 3–4 °C by 2100. This will impact Boston Harbor ecosystems by favoring warmer-water species, welcoming certain marine invasive species, and decreasing the availability of oxygen. In addition, water column and benthic respiration rates will increase, possibly leading to an increased tendency for eutrophication. Surface water warming will also increase stratification, further enhancing eutrophication. The decrease in storm-related mixing will also promote eutrophication events compared to periods with no barrier. It is likely that SLR (possibly 1 foot by 2050, 5 feet by 2100) will threaten the Boston Harbor Islands, so that people will further armor these areas even without storm-related erosion, a process that has already begun. Similarly, local adaptations by private businesses, residents, and other coastal landowners would likely continue even with the existence of a harbor-wide strategy.

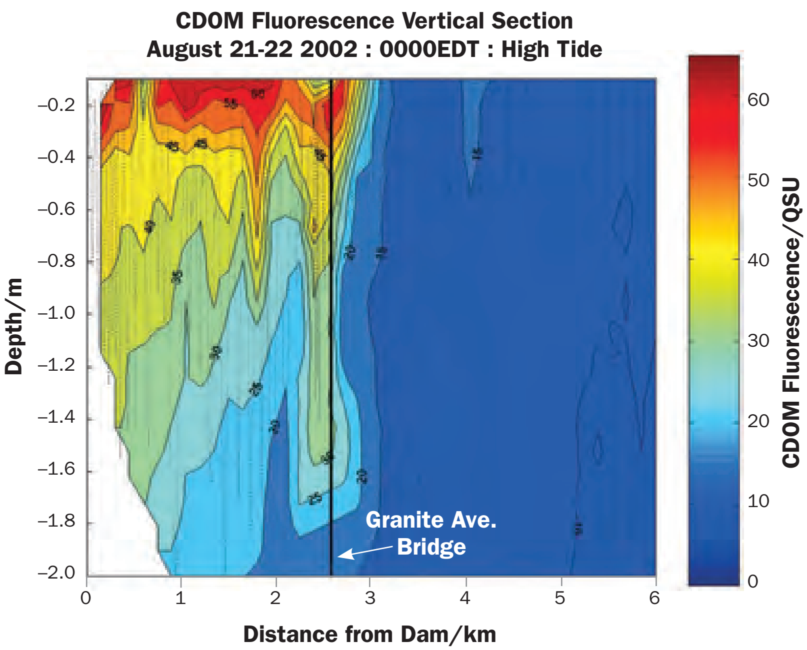
HIGH-RIVER DISCHARGE EVENTS

The harbor's major rivers—the Charles, Neponset, and Mystic—are all dammed as they enter the harbor. The Charles and Mystic have dams directly adjacent to the harbor, and the Neponset's Lower Mills dam is reached by current high tides and would become more of a barrier to seawater intrusion with 5 feet of SLR. This discussion will not address the possibility that 5 feet of SLR will cause breaching or flooding seawater flanking any of these dams during a coastal storm and we are assuming that the release of freshwater will be controlled by these dams. In this case, the presence or absence of an open barrier now or with 5 feet of SLR could be thought to have minimal influence on the water flow, water quality, and residence time of contaminants entering Boston Harbor from these rivers, whether during coastal storm or under calm conditions. The total freshwater discharge of a major storm event behind a closed OHB would increase the sea level by less than 1 foot (Woods Hole Group, personal communication).

The presence of a tidal restriction in the form of an OHB, even if it does not significantly affect tidal height, can alter the estuarine mixing of fresh and salt water. For example, as observed at the Neponset's Granite Avenue Bridge, there is a deepening and "trapping" of surface freshwater at the tidal restriction, as measured by the

FIGURE 6.12

Chromophoric Dissolved Organic Matter (CDOM) in the Neponset Estuary Measured by the Mini-Shuttle



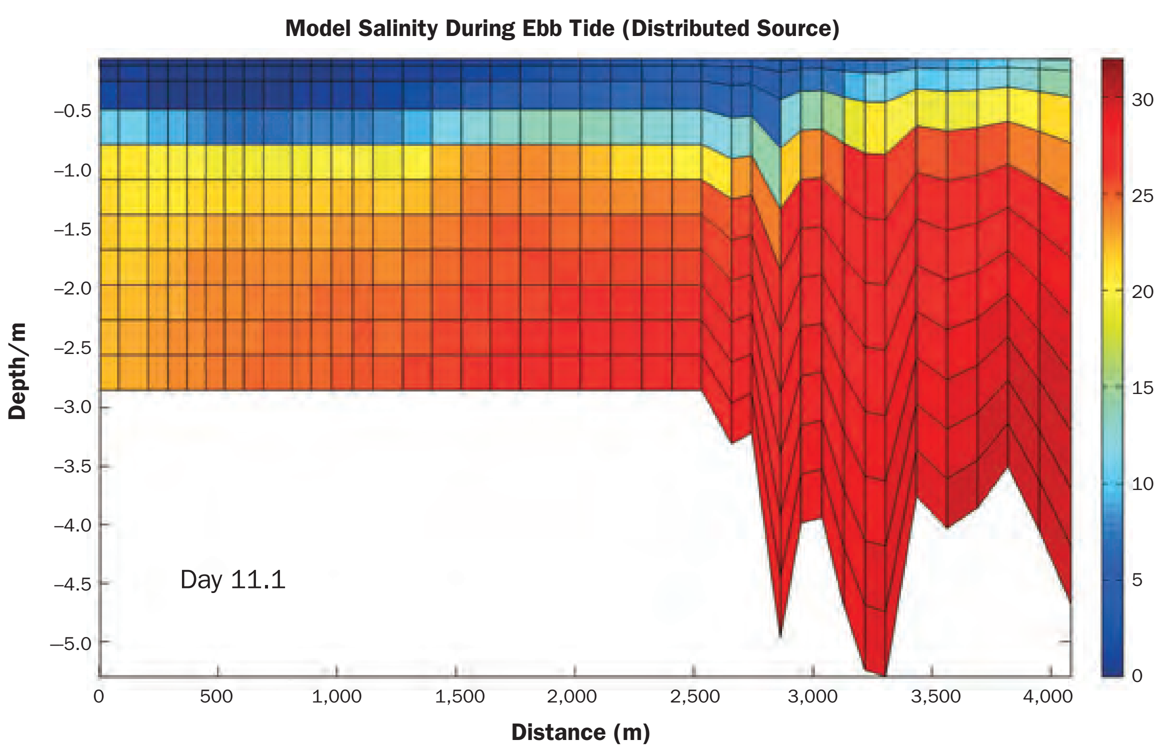
Source: Gardner et al., 2005

Mini-Shuttle, a high resolution undulating vehicle capable of mapping salinity and other water properties in inches vertically and several feet horizontally (Figure 6.12; Gardner et al., 2005). This trapping of freshwater temporarily behind a tidal restriction (indicated by high chromophoric dissolved organic matter (CDOM) fluorescence, which is high in freshwater and low is seawater), is likely sensible to any marine organism transecting the estuary (e.g., fish). How this short-term deepening of freshwater, as well as potentially higher levels of possible contaminants, might affect fish migration, feeding, or reproductive behavior is unknown. It should be recognized that this freshwater is released at the maximum ebb tide, so the trapping phenomenon is temporary.

Additionally, freshwater discharge could affect the harbor during a storm event and a closed barrier. We know that elevated river discharge of low-salinity water flows rapidly along the surface (upper foot) of the harbor out into Massachusetts Bay (Chen, unpublished data). Higher resolution (~1-ft vertical layers rather than the standard ~3-ft) models can resolve this surface thin layer (Figure 6.13; Jiang, unpublished data). Freshwater,

FIGURE 6.13

Salinity Modeled During a Rain Event in the Neponset Estuary—Distance in Meters from the Lower Mill Dam (Baker Dam)



Source: M. Jiang, 2010. Personal Communication.

especially during "first flush" storm events is likely to carry higher loads of bacteria, particles, polycyclic aromatic hydrocarbons (PAH), nutrients, and heavy metals than normal discharge times. While this surface "sheet flow" would exit the harbor within hours during a storm with no barrier, it is likely that it would be trapped behind a closed barrier for up to 84 hours during a nor'easter. Once again, this surface flow would likely leave the harbor and be mixed rapidly in Massachusetts Bay over several tidal cycles of flushing after the barrier was opened. It is unknown what organisms would be affected by this more contaminated surface layer with a residence time of 3 days with a barrier, versus a residence time of a few hours without the barrier. It is also unknown how the changed surface appearance may affect recreation or aesthetic ecosystem services over the few days during and after a major storm event.

HARBOR BARRIER CONSTRUCTION IMPACTS

There is not sufficient detail concerning the design and construction of either barrier configuration to fully assess the environmental impacts of the construction phase of the proposed project; however, they are likely to be considerable. Dredging and resuspension of contaminated surface sediments, increases in turbidity and therefore reduction in water clarity during underwater and shoreline construction, large construction noise effects on fish and marine mammal behavior, and increased shipping during construction are just a few of the construction-related impacts that would be expected to negatively affect Boston Harbor, if only for a limited period. The land-based traffic, material movement, and noise impacts on upland and shoreline environments would make the construction effort itself the source of major environmental issues for the harbor. Clearly, detailed analysis of construction-related environmental impacts would need to be done during the planning and permitting process for any harbor barrier.

KNOWN UNKNOWNS

While basic assumptions and first order effects of an OHB have been considered and discussed, it is clear that all aspects of a large engineered structure in Boston Harbor cannot be anticipated. As was true for the many alterations and experiments in Venice Lagoon (Ghezzo et al., 2010), even the direction of the impact (positive or negative) may be incorrect. While we may anticipate a general increase in fine-grain sediment deposition at a certain area, a host of complex interactions may actually result in a decrease. We do not understand yet how individuals and individual species will interact as a result of a large structure at the mouth of the harbor. We cannot accurately anticipate how climate change mitigation will proceed. We do not know how individuals and corporations would individually adapt their properties differently with a harbor-wide solution. That being stated, we can, however, make some testable predictions at the outset, based on oceanographic and ecosystem first principles, to assess the possible impacts an outer harbor storm surge barrier might have. Further, these analyses can direct, at least in part, a full, quantitative, spatial, and site-specific analysis of potential impacts that was beyond the scope of this report.

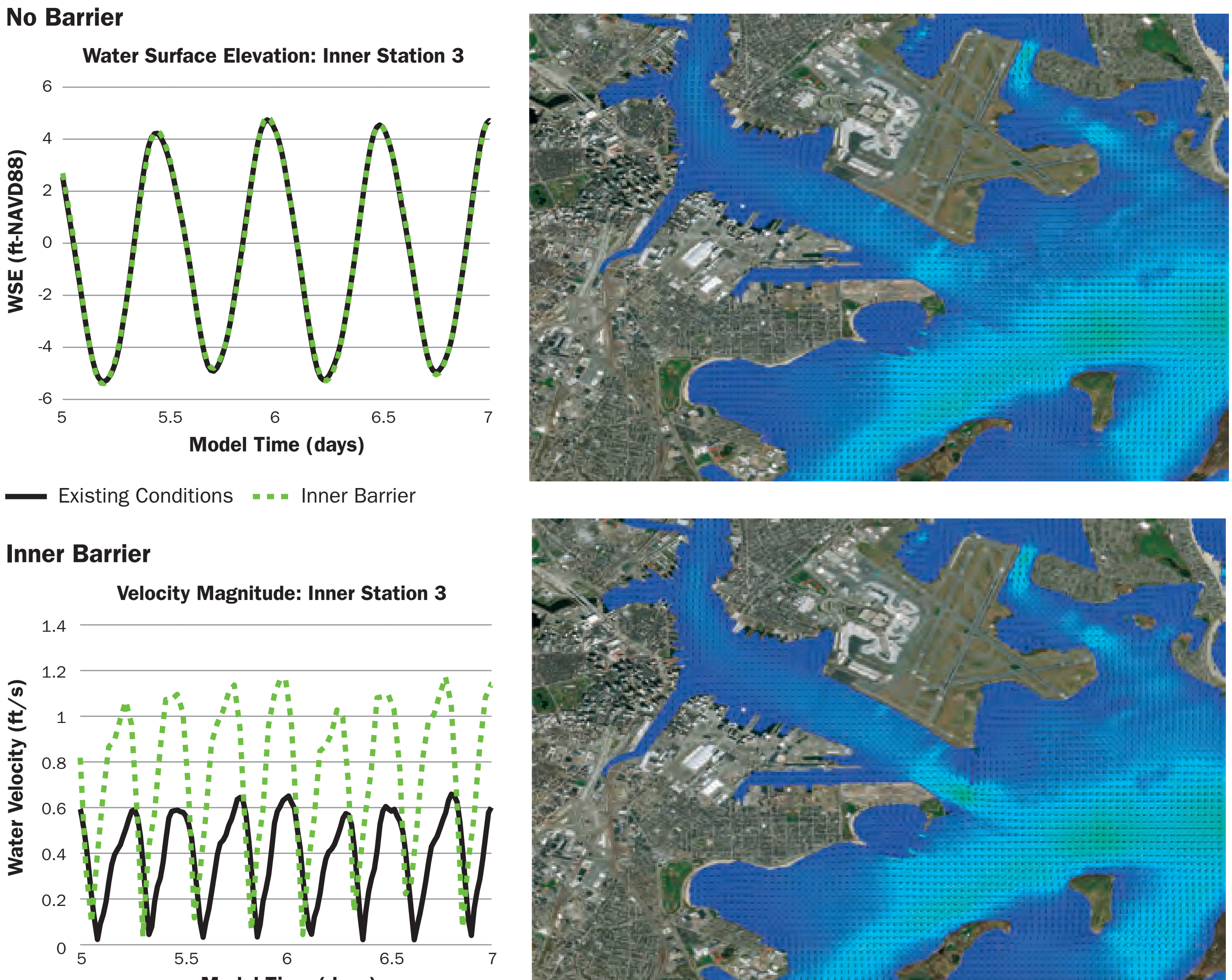
There is not sufficient detail concerning the design and construction of either barrier configuration to fully assess the environmental impacts of the construction phase of the proposed project; however, they are likely to be considerable.

Inner Harbor Barrier Environmental Assessment

A barrier constructed between the Seaport District and Logan Airport to protect inner Boston Harbor (the IHB alignment) would have much less environmental impact, positively or negatively, than the OHB considered. Modeling (Woods Hole Group, 2017) predicts no observable impacts on tidal elevations or exchange from an IHB in most of the outer and inner harbor, and moderate changes (0.6 to 1.2 ft/s) in tidal current velocities in close proximity to the barrier itself (Figure 6.14). Since the inner harbor has a long history of use by industry, most of the shorelines inside the IHB are already hardened with very little beach, mudflat, rocky intertidal, or salt marsh habitat. There are a few small pockets of natural or soft shoreline within the (e.g., Urban Wild, Chelsea Creek; Mary O'Malley State Park, Admiral Hill; the upper reaches of Chelsea Creek; Ryan Playground, North End; and some open area abutting the Amelia Earhart Dam in the Mystic River). The total ecosystem value (see Section 7) is not particularly high and is mostly focused in Chelsea. Under conditions with the IHB open, there would likely be minimal environmental impacts to water quality, habitat quality, or ecosystem services compared to having no barrier in the present day or with 5 feet of SLR. Waves and currents would be minimally affected. Little to no change in overwash events would be seen with an IHB. Changes to bottom grain size behind the barrier would likely be minimal. When the Byrnes model was used to evaluate changes in benthic sediment types under IHB conditions, we found that the relative distribution of habitat types stayed fairly constant despite slight changes in surficial sediment distribution (Figure 6.9).

FIGURE 6.14

Modeled Tidal Current Velocities Without a Barrier and with an Inner Harbor Barrier



Velocity Magnitude (ft/s)

>3.28, 2.92, 2.55, 2.19, 1.82, 1.46, 1.09, 0.73, 0.37, 0.00

Green lines are with the barrier and black lines are without a barrier. Sea surface elevations and current velocities are just outside the proposed barrier.

Source: Woods Hole Group

The largest environmental impacts of an Inner Harbor Barrier would be on water quality with the gates closed. With the smaller area and volume behind the gates with two large rivers—the Charles and the Mystic Rivers—draining into this volume, there are likely to be impacts on water volume and water quality. The barrier could be closed as long as 84 hours to protect against a nor'easter. With high precipitation in the Charles and Mystic River Watersheds, the discharge would likely surpass the storage capacity of the Charles River Dam and the Amelia Earhart Dam. In this case, the water would have to be pumped over the dams into the volume between the dams and the Inner Harbor Barrier. The predicted discharge rates (see Section 4) would increase the level of the water on the land side of the barrier by an additional 20–22 feet unless it was pumped out (WHG, personal communication). The water would then have to be pumped over the IHB to the open Boston Harbor. Environmentally, this would mean that the freshwater draining from the Charles and Mystic River watersheds, which contains loads of bacteria, nutrients, heavy metals, and organic matter from road runoff, catchment flushing, and remaining combined sewer overflow releases, would float above saltier (denser) water in a layer that thickens as the event unfolds to as much as half or more of the water column behind the IHB.

This dissolved and particulate contamination would essentially shut off the bottom layer from any exchange with the atmosphere or sunlight, likely resulting in a hypoxic state developing over 3.5 days (84 hours) in the area behind the barrier. This condition would essentially be relieved as soon as the Inner Harbor Barrier were to be reopened with largescale flushing to the much larger volume of the outer harbor, and eventually (over the next couple of tidal cycles) to Massachusetts Bay. Hydraulic engineering dictates that the intake of the IHB pumps would need to be situated near the bottom of the barrier wall rather than at the surface (upper 6.5 ft), and therefore would not serve to relieve this freshwater buildup. The particle and contaminant load would thus be retained within the Inner Harbor for several days, rather than being flushed out to Boston Harbor in a thin surface layer (<1.6 ft) in a few hours. This is the current pattern in the absence of an IHB, which would continue except when the barrier gates were closed. It is difficult to assess the potential impact of such freshwater trapping during storm events in terms of habitats and ecosystem services. Clearly, there would be short-term impacts on both behind the IHB as well as on water quality, but in the absence of further research, it is unclear the degree to which this would cause longer-term environmental impacts. The environmental impacts would be episodic in nature and would probably be worsened in future scenarios with more frequent closures.

The largest environmental impacts of an Inner Harbor Barrier would be on water quality with the gates closed. With the smaller area and volume behind the gates with two large rivers—the Charles and the Mystic Rivers—draining into this volume, there are likely to be impacts on water volume and water quality.

Conclusions

As with any complex, dynamic system, there are many unpredictable consequences of small- and large-scale shoreline adaptations. While SLR estimates may be reasonably plausible, human responses (individual, community, regional) are much harder to predict. It is not really reasonable to compare local adaptations only with the construction of a harbor barrier with no local adaptations. Consequently, the location, timing, and implementation process of local adaptations will affect the environment both locally and within the system as a whole. Given some of the uncertainties, there is the question of whether adaptations distributed in time and space are more flexible than a single large-scale solution. Can a distributed set of adaptations be implemented over time as knowledge is gained about what works? How might it be done so that improvements can be constantly made? How will the process and results of gradual environmental alteration under local adaption strategies differ from that of a one-time large-scale modification?

While we can assess the expected first-order impacts of a harbor barrier, we cannot at this time reasonably assess the potential impacts at the local level, for example at the 650 ft x 650 ft scale, as there are many small-scale features and parameters not included in any current model of Boston Harbor. Therefore, there are many uncertainties that remain, and many predicted environmental

impacts of a barrier system that would require further study.

Taking all of this under consideration, however, it does not appear that the presence of an OHB or IHB that is closed during storm events would cause any irreversible negative transformations of the entire harbor environment in terms of water quality, habitat quality, or ecosystem services. While there are some foreseeable impacts, most of these are moderate and/or limited spatially or temporally. For a great part of the harbor system, the climate change impacts of warming water and air temperatures plus 5 feet of sea level rise would cause more environmental change than a harbor barrier. Adding these two factors together (climate change plus harbor barrier) would have foreseeable and unforeseeable environmental consequences which may or may not be greater than those of district-level adaptations.

Predicting environmental impacts of ecosystem-wide adaptation strategies is challenging and needs to be considered over time and holistically throughout the entire system. Clearly, planning, experimentation, observation, and modeling will yield new information that can be used to maximize environmental health and ecosystem services provided by Boston Harbor while protecting societal infrastructure, culture, and economy.

There are many fascinating research questions that can be asked to help assess the impact of a harbor-wide adaptation to SLR. For example: What impact if any would a barrier have on migrating species? How would people use the harbor differently with or without a harbor-wide protection strategy? How would communities alter their adaptation strategies given a harbor-wide protection strategy? Can salt marshes be nourished to keep up with rising seas? What would be the impacts if the barrier system was closed as many as 50 times per year or more? Academic research, urban planning, economic forecasting, coastal engineering, and stakeholder engagement will need to be integrated and intertwined to address the grand challenge that sea level rise poses to the City of Boston and Boston Harbor.

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7 Ecological Economics

Ecosystem services are the direct and indirect benefits that humans derive from ecosystems.

Ecosystems in Boston Harbor and neighboring areas provide a multitude of services to society. Here we develop estimates of ecosystem service values and investigate how these values may change with sea level rise (SLR). Using results of a parallel study on environmental impacts in Section 6, we assess the effects of the proposed Outer Harbor Barrier (OHB) on ecosystem service values.

Economic Valuation of Ecosystem Services

Ecosystem services are the direct and indirect benefits that humans derive from ecosystems; in coastal environments these include nutrient cycling, climate regulation, habitat provision, and recreational uses (MEAB, 2003). While a general approach for ecosystem service identification and valuation has been developed, and there are many ecosystem valuation studies in the literature, the valuation of coastal protection projects remains a challenging task (de Groot et al., 2012; Reddy et al., 2015).

Economic value is a human construct and exists only in the context of human societies that make use of the market goods and services produced by people, as well as the ecosystem services supplied by the earth's environmental resources. Because it derives at least in part from people's preferences, which in turn are a function of their circumstances and understanding of the world, economic values are by definition more ephemeral and changeable than, for example, physical or chemical properties of resources. Some economic values can be estimated directly by observing the prices at which goods and services are traded in markets (e.g., the value of seafood). Other "non-market" goods and services are not traded; their economic value must be estimated by techniques such as travel cost, random utility models, hedonic methods, or contingent valuation. The selection of valuation methods for various ecosystem services is not always straightforward. Examples of such selection can be found in de Groot et al. (2002) and Wang et al. (2010).

In theory, ecosystem value is jointly determined by the supply of ecosystem services (e.g., the production of salt marsh as habitat for birds and fish) and demand for the services by society (people's willingness to pay) (Johnston et al., 2002). Thus, the value of an ecosystem is a function of its condition and the multiple services it provides. To avoid double counting, changes in multiple ecosystem services should be valued jointly (Johnston et al., 2011). Also, marginal ecosystem service value may rise rapidly when changes in the ecosystem condition pass a "critical threshold" (Farber et al., 2002).

Marine ecosystems are biological assets that potentially are capable of generating flows of returns indefinitely. Fenichel et al. (2016) describe a conceptual framework for computing the price of natural capital (e.g., ecosystem resources). The unit price of natural capital is a function of the stock of natural capital, and parameters characterizing ecological dynamics, human behavioral feedbacks, and the value of ecosystem service flows.

Economic value is a human construct and exists only in the context of human societies that make use of the market goods and services produced by people, as well as the ecosystem services supplied by the earth's environmental resources.

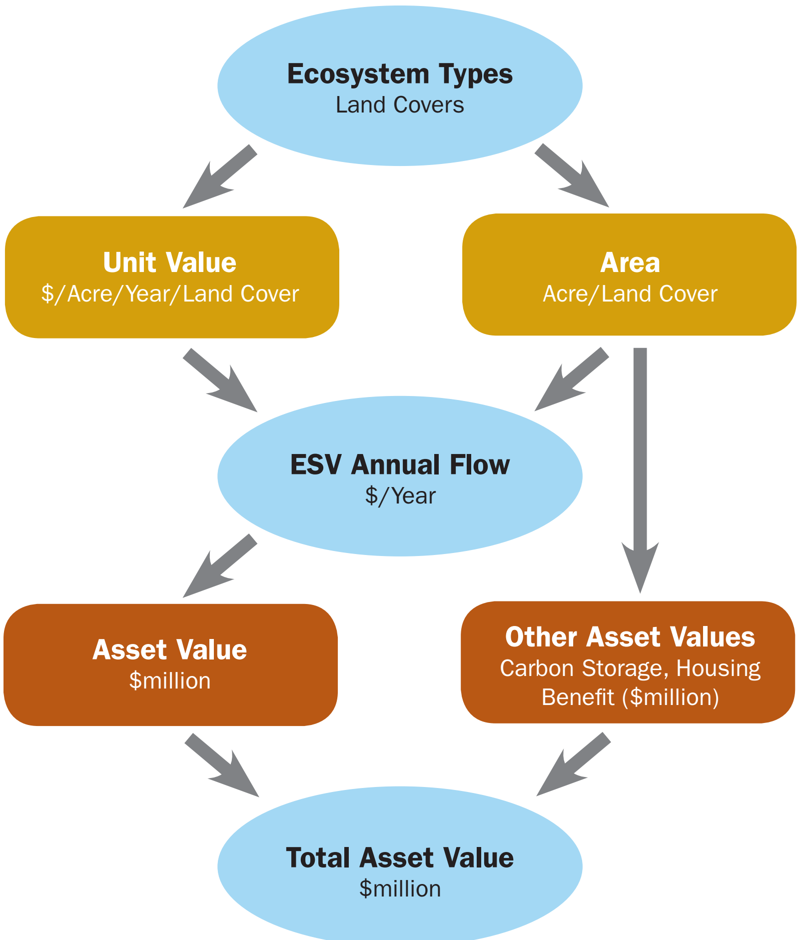
Unfortunately, valuation of ecosystem services at a specific location is typically a complex and time-consuming process. As the number of studies of natural resource and environmental valuation has grown over the past three decades, more now rely on benefit transfer techniques (i.e., adapting valuation information in the literature to the project sites) (Johnston et al., 2015). Initial efforts to integrate results of ecosystem valuation studies from different locations can be found in Costanza et al. (1997). More recently, researchers have been developing the Ecosystem Service Valuation Database (ESVD) that summarizes results of valuation studies around the world (Van der Ploeg and de Groot, 2010). Other compilations of ecosystem values can be found in Pendleton (2008), de Groot et al. (2012), and Kocian et al. (2015).

Methods

An ecosystem service valuation framework for the study is outlined in Figure 7.1. Since different coastal areas have different ecosystems that provide different services, the first step involves identifying ecosystem/land cover types such as wetlands, beaches, habitats, and recreational sites, and estimating relevant areas. Next, specific

FIGURE 7.1

Ecosystem Service Valuation Method



Source: Kocian et al., 2015

TABLE 7.1

Classification of Ecosystem Services

Provisioning Services
Energy and raw materials
Food
Water supply
Regulating Services
Biological control
Climate stability
Moderation of extreme events
Pollination
Soil formation
Waste treatment
Supporting Services
Habitat and nursery
Information Services
Aesthetic information
Cultural and artistic inspiration
Recreation and tourism
Science and education

Source: Kocian, M., Fletcher, A., Schundler, G., Batker, D., Schwartz, A., Briceno, T. (2015). The Trillion Dollar Asset: The Economic Value of the Long Island Sound Basin.

ecosystem services that each land cover provides must be identified (Table 7.1). The ecosystem service values are then estimated at the unit level by land cover.

Project-specific valuation studies can be very costly and not feasible for most coastal protection projects. Thus, researchers typically develop their estimates using benefit transfer techniques (Johnston et al., 2015; Woodward and Wui, 2001). For the study, we follow this general approach of Costanza et al. (1997) and utilize a simple unit value transfer method. Because valuation estimates of certain ecosystem services (e.g., recreational and health benefits) are significantly affected by population density, income, and other community characteristics at the study sites, a key step in the process is making adjustments to the valuation estimates for different local ecological and social conditions (Brander et al., 2006; Wolf et al., 2015; Johnston et al., 2015). For example, the vast majority of published ecosystem valuation studies are conducted in nonurban settings. Results from these studies have been used in cost-benefit analyses for coastal and marine ecosystem restoration projects in urban areas. Erroneous valuation of the ecosystems in coastal urban areas can have serious consequences that affect a large population in a shared environment.

In urban areas, a network of multifunctional open spaces, parks, waterways, trees, and woodlands is essential to support a high quality of life. Green space offers recreational or leisure opportunities to a large number of people. It is a place for children to play and people to meet, and therefore has a social function (Vandermeulen et al., 2011) and offers considerable public health benefits as well (Wolf et al., 2015). To reflect these important beneficial effects in the study area, we selected high-end estimates of ecosystem services in the literature and made additional adjustments (Figure 7.2). For the study, we consider 13 land-cover types; their estimated high- and low-end unit values and data sources are listed in Tables 7.2 and 7.3.

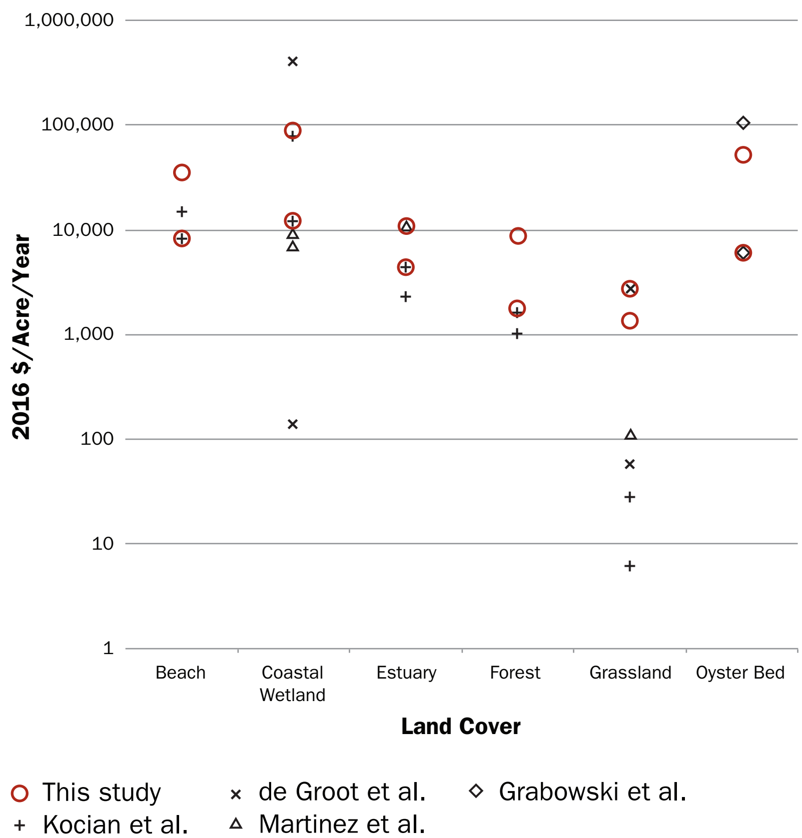
Typically, the unit ecosystem service values available in the literature are given in dollars per unit area per year (de Groot et al., 2012; Kocian et al., 2015). In the study, we estimate both the annual value and asset (capitalized) value of ecosystem services. We calculate the total asset value of ecosystem services as the sum of two components. One is the sum of discounted annual value flows over 100 years, and the other is a sum of additional asset (stock) values of other ecosystem services (Figure 7.1). The total ecosystem value is the sum of individual eco system services values across different land covers. Specifically, the total asset value is:

$$\text{Total Asset Value} = \sum_{t=1}^{100} \frac{\sum_{i=1}^{13} ESV_i \cdot S_i}{(1+\delta_t)^t} + \sum_{i=1}^{13} OAV_i \cdot S_i$$

where t = (1, 2, ..., 100) is the year; δ_t is the discount rate in year t; i = (1, 2, ..., 13) is the index for land cover types, ESV_i is the unit flow value of ecosystem service from land cover i (in 2016$/acre/year); S_i is the area of land cover i (in acres); and OAV_i stands for the unit asset value of other ecosystem services from land cover i (in 2016$/acre). OAV includes additional asset values of ecosystems for carbon storage and increased housing values (e.g., a premium added to property values due to the presence of nearby ecosystem amenities). Note that an asset value is the sum

FIGURE 7.2

Unit Ecosystem Service Values



Source: Woods Hole Oceanographic Institution

TABLE 7.2

Unit Ecosystem Service Values (2016$/acre/year)

Land Cover Types	Low	High	Data Sources
Marine Wetlands	$12,127	$89,462	Kocian et al. 2015; de Groot et al. 2012
Salt Marsh	$12,127	$89,462	Kocian et al. 2015; de Groot et al. 2012
Freshwater Wetland	$29,574	$39,930	Kocian et al. 2015
City Parks	$40,000	$80,000	Harnik and Welle 2009; David Evans and Associates and ECONorthwest 2004
Beach	$8,097	$35,032	Kocian et al. 2015*
Freshwater	$3,580	$21,288	Kocian et al. 2015
Oyster Bed	$5,821	$52,532	Grabowski et al. 2012
Estuary	$4,304	$10,804	Kocian et al. 2015; Martínez et al. 2007
Tidal Flat	$5,559	$9,265	Martínez et al. 2007**
Forest	$1,765	$8,849	Wolf et al. 2015***
Grassland/Openland	$1,325	$2,737	de Groot et al. 2012
Core Habitats	$100	$500	David Evans and Associates and ECONorthwest. 2004
Coastal Waters	$2,301	$4,304	Kocian et al. 2015

Adjustments: * Add city park values. ** 60% of the value for swamps-floodplains. *** Include health benefits based on US national per capita average value.

Source: Woods Hole Oceanographic Institution

TABLE 7.3

Unit Ecosystem Service Values (2016$/acre)

Annual Value ($/acre/year)			Asset Value* ($/acre)			
			Carbon Storage		Housing Market Effects	
Land Cover Types	**Low**	**High**	**Low**	**High**	**Low**	**High**
Marine Wetlands	12,127	89,462	12,312	13,050	21,324	21,324
Salt Marsh	12,127	89,462	12,312	13,050	21,324	21,324
Freshwater Wetland	29,574	39,930	4,936	85,414	6,070	108,854
City Parks	40,000	80,000	0	0	0	0
Beach	8,097	35,032	0	0	2,151	5,680
Freshwater	3,580	21,288	0	0	75	33,361
Oyster Bed	5,821	52,532	0	0	0	0
Estuary	4,304	10,804	0	0	26,514	26,514
Tidal Flat	5,559	9,265	0	0	0	0
Forest	1,765	8,849	2,378	18,537	33,411	33,411
Grassland/Openland	1,325	2,737	214	360	14,388	14,388
Core Habitats	100	500	0	0	0	0
Coastal Waters	2,301	4,304	0	0	26,514	26,514

Source: Kocian et al., 2015

In economic project analyses, the rate at which future benefits and costs are discounted relative to current values often determines whether a project passes the benefit-cost test. This is especially true of projects with long time horizons.

of discounted annual values over time, and thus OAV should not be discounted. For example, a property's value (asset value) is the sum of its discounted annual rental values over the life of the property.

In economic project analyses, the rate at which future benefits and costs are discounted relative to current values often determines whether a project passes the benefit-cost test. This is especially true of projects with long time horizons, such as those dealing with long-term ecosystem service values. For example, studies have shown that the discount rate schedule makes a considerable difference to estimates of the social cost of carbon (the present value of damages from emitting a ton of carbon dioxide) (Arrow et al., 2013). Although there may be other causes for the discount rate to decline over time (e.g., declining productivity and population growth), uncertainty about future discount rates has been identified as the main reason for a declining discount rate schedule. Future discount rates are inherently uncertain because of uncertainty in the rates of growth in consumption and return to investment (Arrow et al., 2013; Cropper 2013). In this study, we use the "approximate recommended" sliding-scale discount rates by Weitzman (2001). For comparison of economic values in other parts of the project, we also use two constant discount rates (3% and 7%) in our ecosystem value calculations.

The study evaluates four SLR scenarios: 0 ft, 1 ft, 3 ft, and 5 ft. The areas by land cover under conditions of Mean Higher High Water (MHHW) for each scenario are quantified using Geographic Information System (GIS) analysis. We divide the study area into four sub-areas by watershed: Mystic River Watershed, Charles and Neponset Rivers (combined) Watershed, Weir River Watershed, and Harbor Islands. The "Harbor Islands" watershed includes all areas of Boston Harbor inside the proposed OHB not included in the other three watersheds. Watershed boundaries adjacent to the harbor were adjusted slightly to assure no overlap with the Harbor Islands watershed.

TABLE 7.4

GIS Data Sources and Descriptions

Land Cover Types	Comments	Data Source	Source Dataset	Feature Class(es) and/or Features Selected	Priority
Marine Wetlands		MassGIS	National Wetlands Inventory	NWI_POLY.shp where WET_TYPE = "Estuarine and Marine Wetland"	1
Salt Marsh	Transitional salt marsh (estuarine intertidal scrub-shrub broad-leaved deciduous), regularly flooded marsh (salt marsh, estuarine intertidal emergent) and irregularly flooded marsh (irregularly flooded estuarine intertidal emergent)	WHG/CZM	SLAMM*	GRIDCODE** = 8 or GRIDCODE = 20	2
Freshwater Wetland	Riverine tidal emergent	WHG/CZM	SLAMM	GRIDCODE = 6	3
City Parks	This database contains outdoor facilities such as town parks, playing fields and conserved land. Studies indicate that value depends on size of park and visitor counts. Need more data—in process.	MassGIS	Land Use 2005	LANDUSE2005_POLY_SUFF.shp where LU05_DESC = "Participation Recreation"	4
Beach	This shapefile contains both estuarine beach (estuarine intertidal unconsolidated shore sand or beach-bar) data and ocean beach (Marine intertidal unconsolidated shore sand) data. Estuarine beaches convert to estuarine open water if inundated or eroded.	WHG/CZM	SLAMM	GRIDCODE = 10 or GRIDCODE = 12	5
Freshwater	Inland Open Water (Riverine, Lacustrine, and Palustrine open water)	WHG/CZM	SLAMM	GRIDCODE = 6	6
Oyster Bed	The American and European Oysters were located in greater harbor barrier project area.	MassGIS	Shellfish Suitability Areas (did not analyze Designated Shellfish Growing Areas)	SHELLFISHSUIT_POLY.shp where COM_NAME= "American or European Oyster"	7
Estuary	Estuarine Water (Estuarine subtidal)	WHG/CZM	SLAMM	GRIDCODE = 17	8
Tidal Flat	Tidal Flat (estuarine intertidal unconsolidated shore mud/organic or flat)	WHG/CZM	SLAMM	GRIDCODE = 11	9
Forest	If designated by the National Forest Agency.	MassGIS	Prime Forest Land	PRIMEFOREST_POLY_NORTHEAST.shp where PRIME= "1, 2 ,3"	10
Grassland/Openland	Features shown as pastures or brushland.	MassGIS	Land Use 2005	LANDUSE2005_POLY_SUFF.shp where LU05_DESC = "Open Land"	11
Core Habitats	No specific data set for birds. This Core habitat identifies specific areas necessary to promote the long-term persistence of Species of Conservation Concern.	MassGIS	Bio Map 2	BM2_CORE_HABITAT.shp	12
Coastal Waters	Saltwater portion of watershed	MassGIS/ UMass Boston	Major Watersheds	See discussion in Section 3 (Methods)	13

* This raster dataset was developed for Massachusetts Coastal Zone Management (CZM) by the Woods Hole Group, Inc. (WHG) using the SLAMM (Sea Level Affecting Marshes Model) developed by the Warren Pinnacle Consulting, Inc. (Clough, et. al., 2012).

** The raster GRIDCODE value corresponds to the SLAMM Category (see Clough, et. al., 2012, for Category descriptions).

Sources: Woods Hole Oceanographic Institution, UMass Boston

A priority level is assigned to each land cover type to avoid double-counting of ecosystem values of overlapped areas of multiple land cover types.

TABLE 7.5

Mystic River Watershed: Land Cover Changes with SLR (MHHW)

Land Cover Types	Acres (0 ft)	Acres (1 ft)	Acres (3 ft)	Acres (5 ft)
Marine Wetlands	1,298.80	1,298.77	1,298.77	1,298.77
Salt Marsh	46.80	110.29	599.01	3,015.75
Freshwater Wetland	94.30	84.04	62.49	496.33
City Parks	1,214.70	1,216.22	1,214.84	1,067.25
Beach	35.25	50.47	122.00	248.85
Freshwater	786.24	363.34	354.69	321.68
Oyster Bed	0.00	0.00	0.00	0.00
Estuary	86.48	58.51	106.51	137.71
Tidal Flat	6.68	8.32	89.36	279.38
Forest	4,574.30	4,577.44	1,187.90	4,579.43
Grassland/Openland	491.03	486.32	482.04	353.93
Core Habitats	1,822.92	1,864.18	2,099.47	1,762.83
Coastal Waters	5,985.33	5,992.25	5,989.33	5,985.65

Sources: Woods Hole Oceanographic Institution, UMass Boston

TABLE 7.6

Charles and Neponset Rivers Watershed: Land Cover Changes with SLR (MHHW)

Land Cover Types	Acres (0 ft)	Acres (1 ft)	Acres (3 ft)	Acres (5 ft)
Marine Wetlands	671.41	671.41	671.41	671.41
Salt Marsh	108.44	113.49	395.72	4,871.13
Freshwater Wetland	40.80	174.75	315.94	296.28
City Parks	4,217.98	4,210.54	4,137.52	3,914.42
Beach	40.54	70.40	50.83	23.55
Freshwater	752.14	793.99	506.15	375.07
Oyster Bed	0.00	0.00	0.00	0.00
Estuary	115.20	90.98	405.98	574.84
Tidal Flat	5.60	12.38	26.24	247.54
Forest	54,864.48	54,862.22	54,859.79	54,855.14
Grassland/Openland	1,631.93	1,630.35	1,610.43	1,547.98
Core Habitats	18,031.26	17,972.06	17,949.63	17,929.50
Coastal Waters	2,800.69	2,812.78	2,810.81	2,781.10

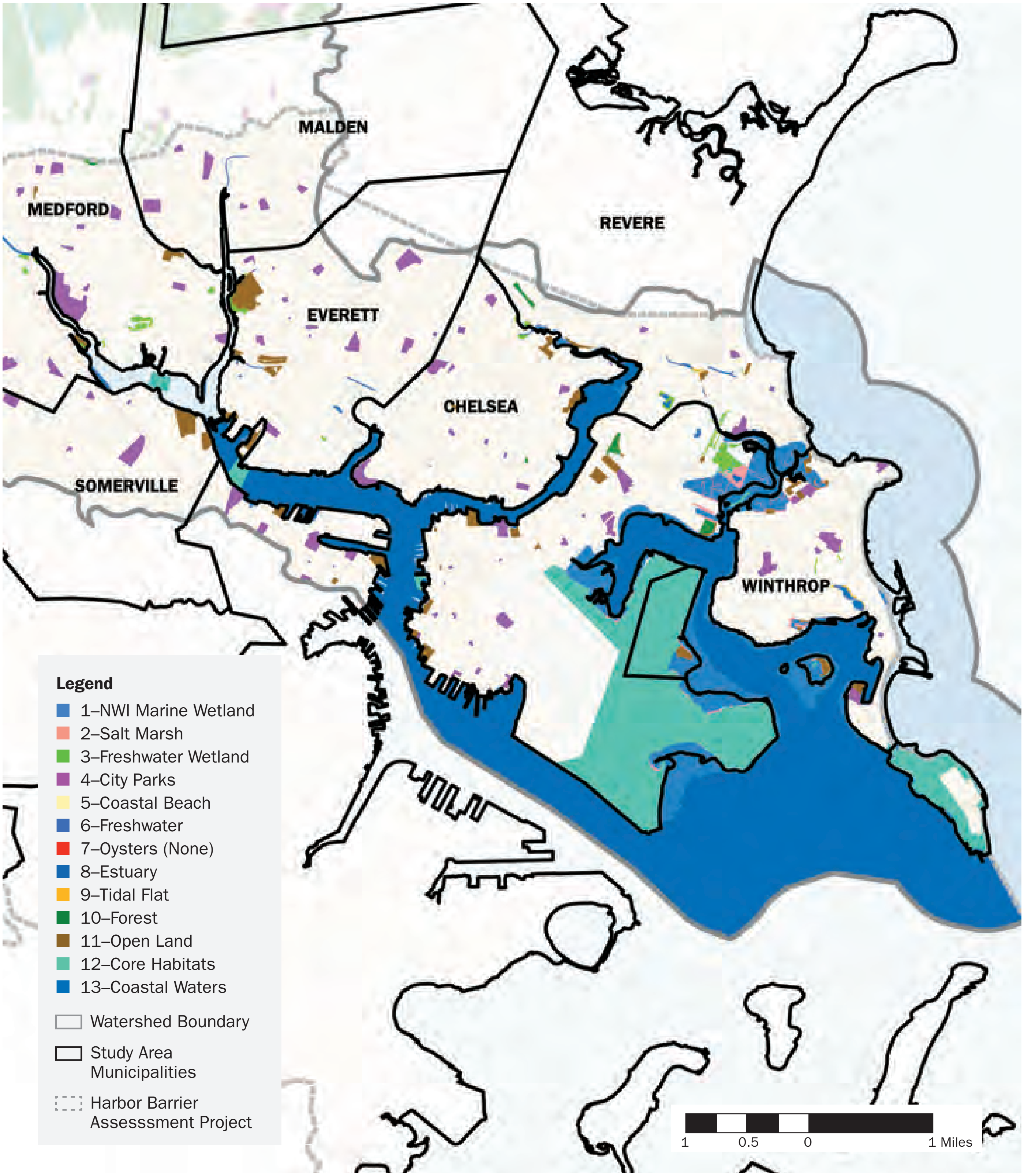
Sources: Woods Hole Oceanographic Institution, UMass Boston

To calculate the areas for different land covers in the four sub-areas, we compiled publicly-available GIS datasets from different sources (Table 7.4). Additionally, several land covers as listed in Table 7.4 were compiled using Sea Level Affecting Marshes Model (SLAMM) results prepared by Woods Hole Group, under contract to Massachusetts Coastal Zone Management (CZM) (Woods Hole Group, 2016). The SLAMM model "simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea level rise." (Clough et al., 2012). The WHG/CZM SLAMM model results we use in this analysis do not consider impervious surfaces. Therefore, the model did not prohibit marshes and wetlands from expanding into currently "developed" areas, and the marshes and wetlands migrate given the elevation landscape, as if the impervious features were absent. For the purposes of this study, modeling the expansion of wetlands and marshes aligns with alternative management approaches that ensure that wetlands and beaches can migrate inland.

A priority level is assigned to each land cover type to avoid double-counting of ecosystem values of overlapped areas of multiple land cover types (i.e., the overlapped portions of lower-priority land areas are not counted if they are overlapped by a higher priority land area). Generally, higher-valued land covers (e.g., wetlands) are ranked higher on the priority list so that the overall ecosystem values are not underestimated. For example, a wetland area may also be in a city park, and by counting only the high-end unit value for a wetland (which includes recreational values), we actually capture the park value.

To assess the effects of SLR on the asset value of ecosystem services, we calculate the total asset value for each of the four SLR scenarios separately, assuming no changes in the unit ecosystem service values and land covers over the next 100 years. The assumption is necessary for a consistent comparison of two "static" scenarios. To estimate the effects on the ecosystem values of the proposed harbor barrier, we make adjustments to the unit values of relevant land covers according to results of the environmental analysis in Section 6. We also estimate the net present values (NPVs) of ecosystem services with and without the proposed barrier. For the NPV analysis, we construct the total annual ecosystem service value by converting the unit asset values (OAV) to annual values using the average of 3% and 7%, or a 5% discount rate.

FIGURE 7.3
Mystic River Watershed

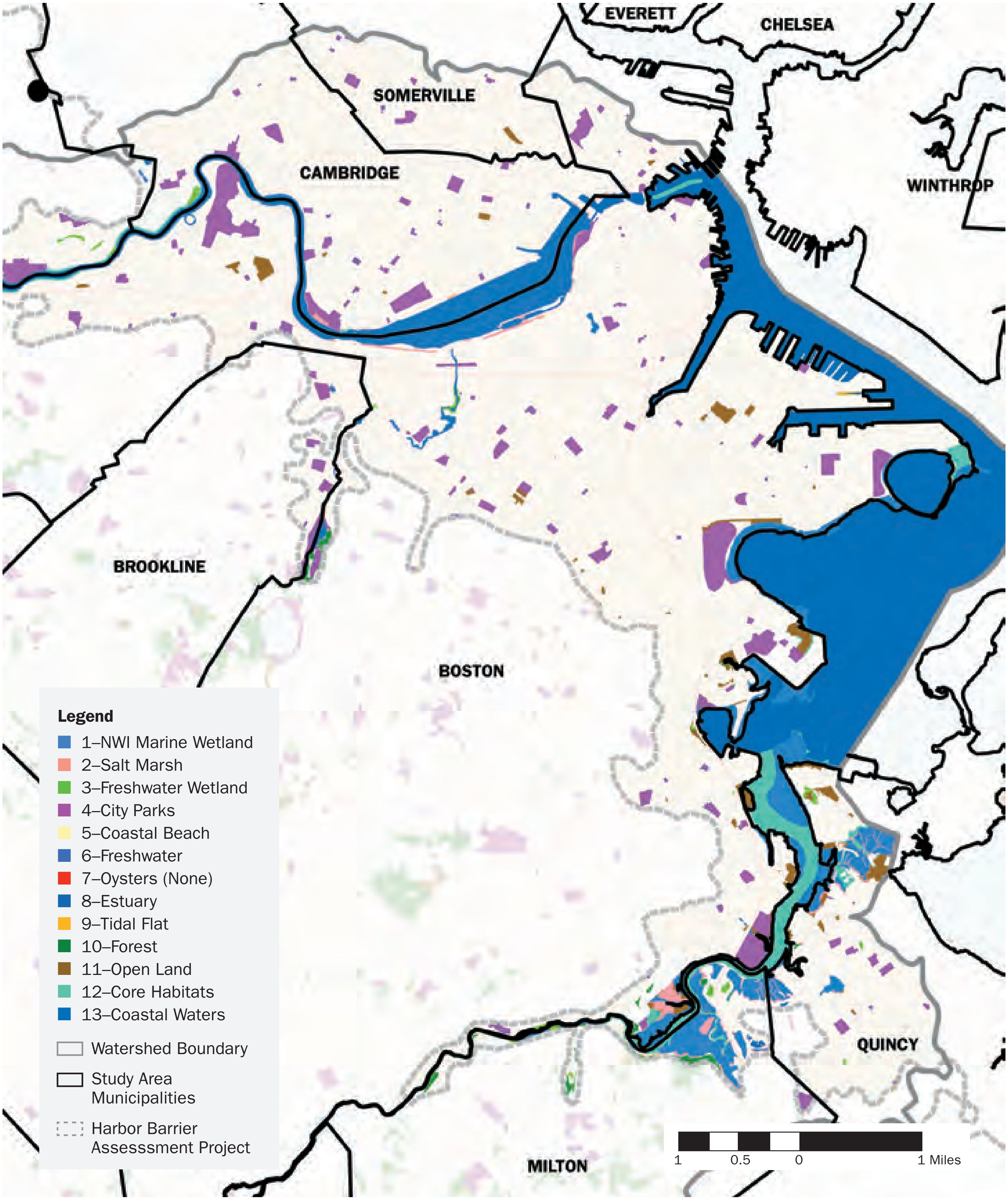


Note: Logan is classified by MassGIS here as "Core Habitats" because the Logan Airport Sustainability Management Plan notes that the airport area "provide(s) habitat for a wide variety of vegetative communities and terrestrial and aquatic wildlife."

Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

FIGURE 7.4

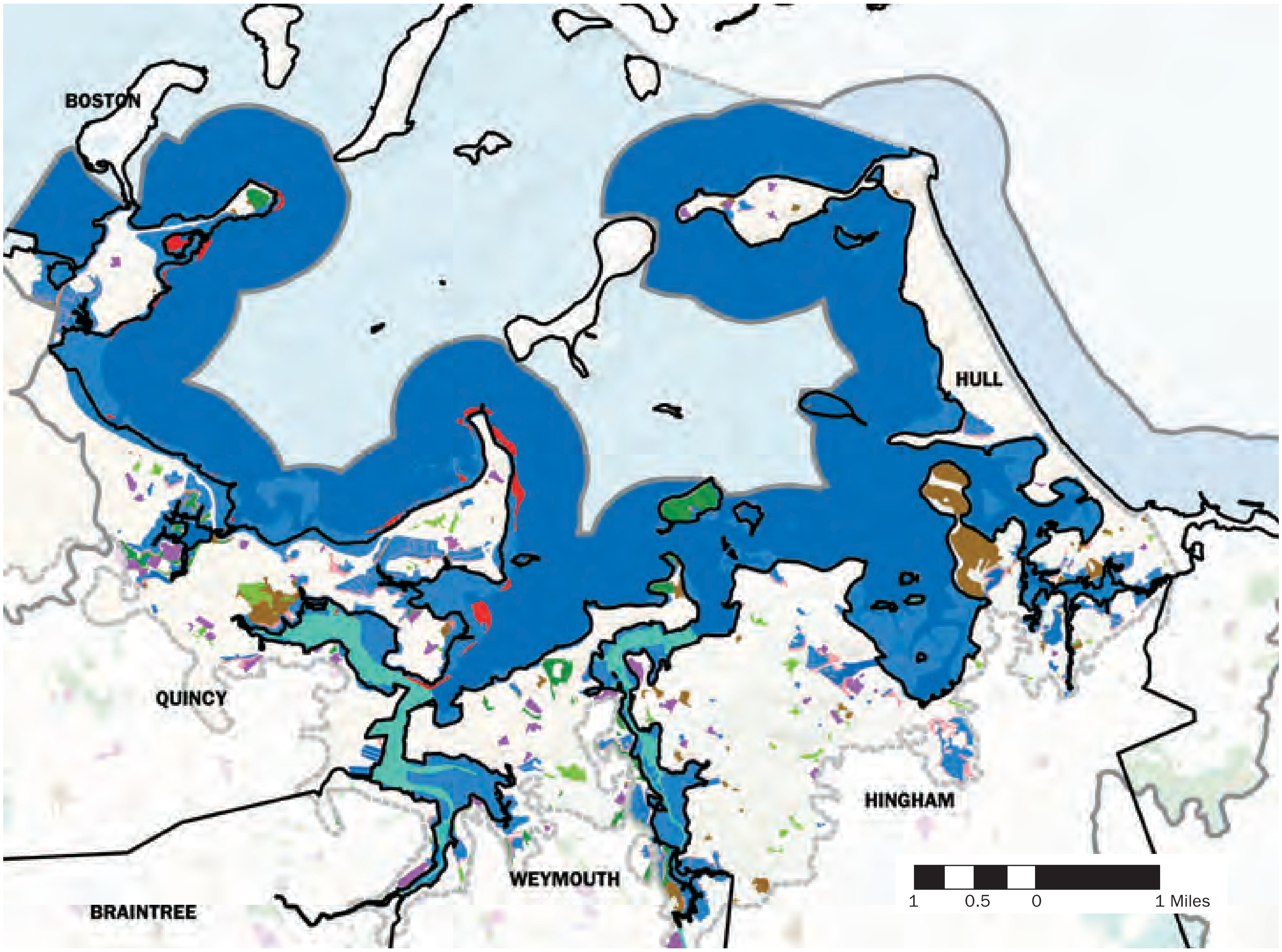
Charles and Neponset Rivers Watershed



Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

FIGURE 7.5

Weir River Watershed

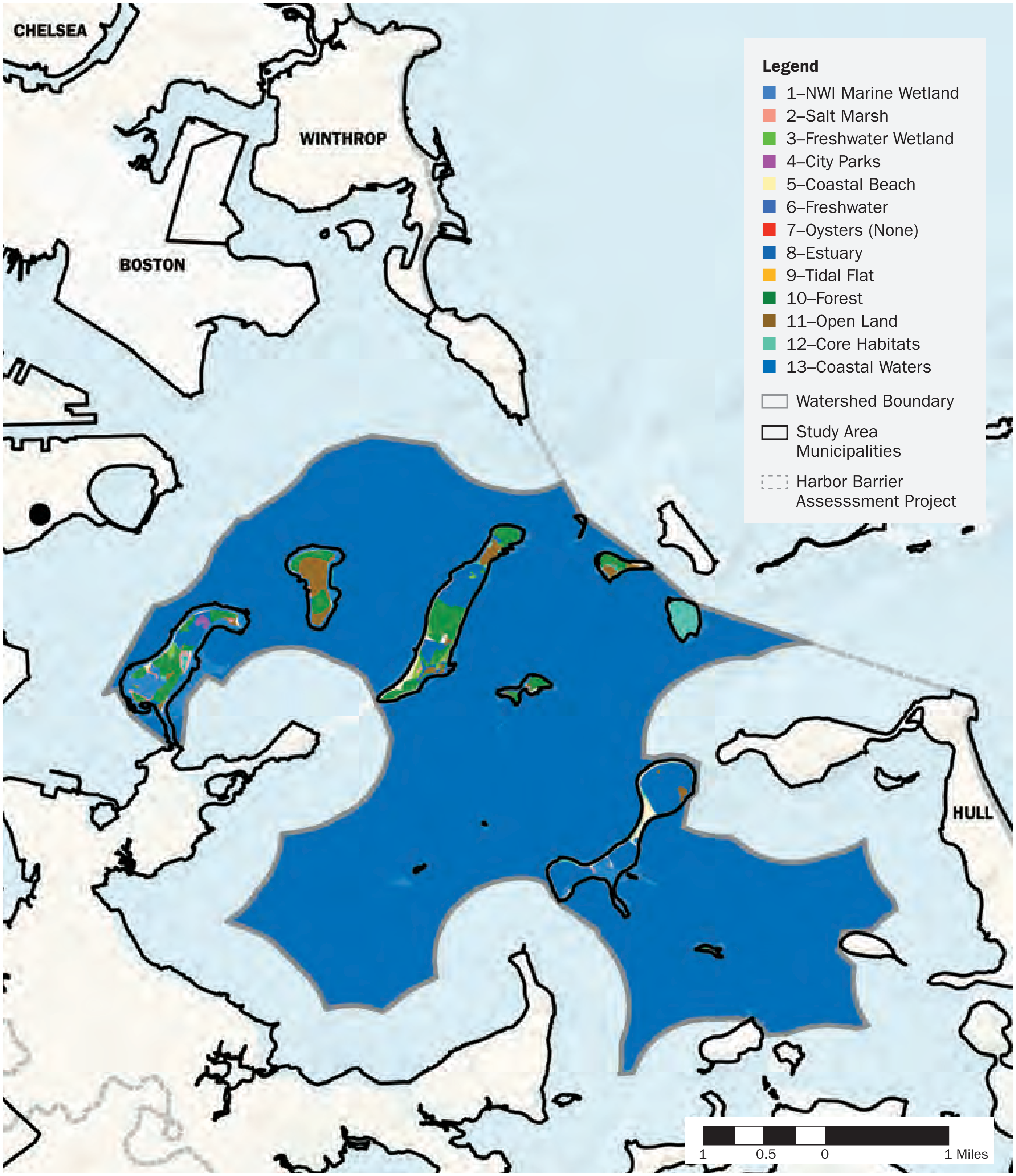


Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

Legend

- 1–NWI Marine Wetland
- 2–Salt Marsh
- 3–Freshwater Wetland
- 4–City Parks
- 5–Coastal Beach
- 6–Freshwater
- 7–Oysters (None)
- 8–Estuary
- 9–Tidal Flat
- 10–Forest
- 11–Open Land
- 12–Core Habitats
- 13–Coastal Waters
- Watershed Boundary
- Study Area Municipalities
- Harbor Barrier Assesssment Project

FIGURE 7.6
Harbor Islands Watershed



Sources: MassGIS, UMass Boston, Woods Hole Group, Esri

Results

Different land covers at the baseline (0 feet SLR) in the four sub-areas—Mystic River Watershed, Charles and Neponset Rivers Watershed, Weir River Watershed, and Harbor Islands are shown in Figures 7.3 to 7.6, respectively. Note that coastal waters are the blue areas in these maps. Results of the area calculation by land cover in the four sub-areas under the four SLR scenarios (0, 1, 3, and 5 feet) are reported in Tables 7.5 to 7.8.

As noted above, the flow of ecosystem service values is converted to an asset value as the sum of discounted annual values over 100 years. The flows of high- and low-end baseline estimates of annual values in the Mystic River Watershed under a sliding-scale discount rate is illustrated in Figure 7.7. As shown in the figure, the discount rate (red dashed line) is 4% in years 1–4, 3% in years 6–25, 2% in years 26–75, and 1% in years 75–100. Figure 7.8 depicts the ecosystem value flows under constant discount rates (3% and 7%).

Ecosystem service asset values for the four sub-areas under different discounting schedules and different SLR scenarios are summarized in Table 7.9, and corresponding percent changes are in Table 7.10. Note that the projected timeline for the four SLR scenarios is 2013 (0 feet), 2030 (1 foot), 2070 (3 feet), and 2100 (5 feet). For comparison, the asset values for each SLR scenario in Table 7.9 are the current values in corresponding years. For example, the low-end estimate of asset value using the 3% discount rate under 3 feet of SLR in 2070 is $3,316 million (in 2016 dollars). The results suggest that, without additional shoreline protection measures and restrictions on marsh migration, the total ecosystem asset values are expected to increase (mainly due to growth in marsh/wetland areas) in the study area under SLR, and significant increases will occur at 3–5 feet of SLR. These results capture the benefits of managed coastal retreat, a policy to allow marsh migration, rather than shoreline armoring (Gittman et al., 2015). As rising sea level is inundating low-lying lands, property owners have typically attempted to hold back the sea by shoreline armoring, which can accelerate erosion and loss of beaches and tidal wetlands. To preserve natural defenses and other ecosystem services, alternative management approaches have been proposed to ensure that wetlands and beaches can migrate inland, as people remove buildings, roads, and other

As rising sea level is inundating low-lying lands, property owners have typically attempted to hold back the sea by shoreline armoring.

TABLE 7.7

Weir River Watershed: Land Cover Changes with SLR (MHHW)

Land Cover Types	Acres (0 ft)	Acres (1 ft)	Acres (3 ft)	Acres (5 ft)
Marine Wetlands	3,990.23	3,990.23	3,990.23	3,990.23
Salt Marsh	255.73	344.31	814.26	1,292.08
Freshwater Wetland	99.92	140.69	116.35	99.47
City Parks	790.60	789.45	766.65	740.11
Beach	137.04	208.60	245.39	417.51
Freshwater	33.22	70.40	68.27	50.46
Oyster Bed	104.69	99.62	99.58	100.48
Estuary	113.75	69.79	84.27	128.96
Tidal Flat	10.00	16.49	62.12	379.29
Forest	5,793.51	5,790.71	5,782.14	5,772.74
Grassland/Openland	522.45	538.75	500.64	460.70
Core Habitats	5,736.91	5,736.52	5,730.39	5,727.88
Coastal Waters	10,167.73	10,172.62	10,168.48	10,162.67

Source: Woods Hole Oceanographic Institution

TABLE 7.8

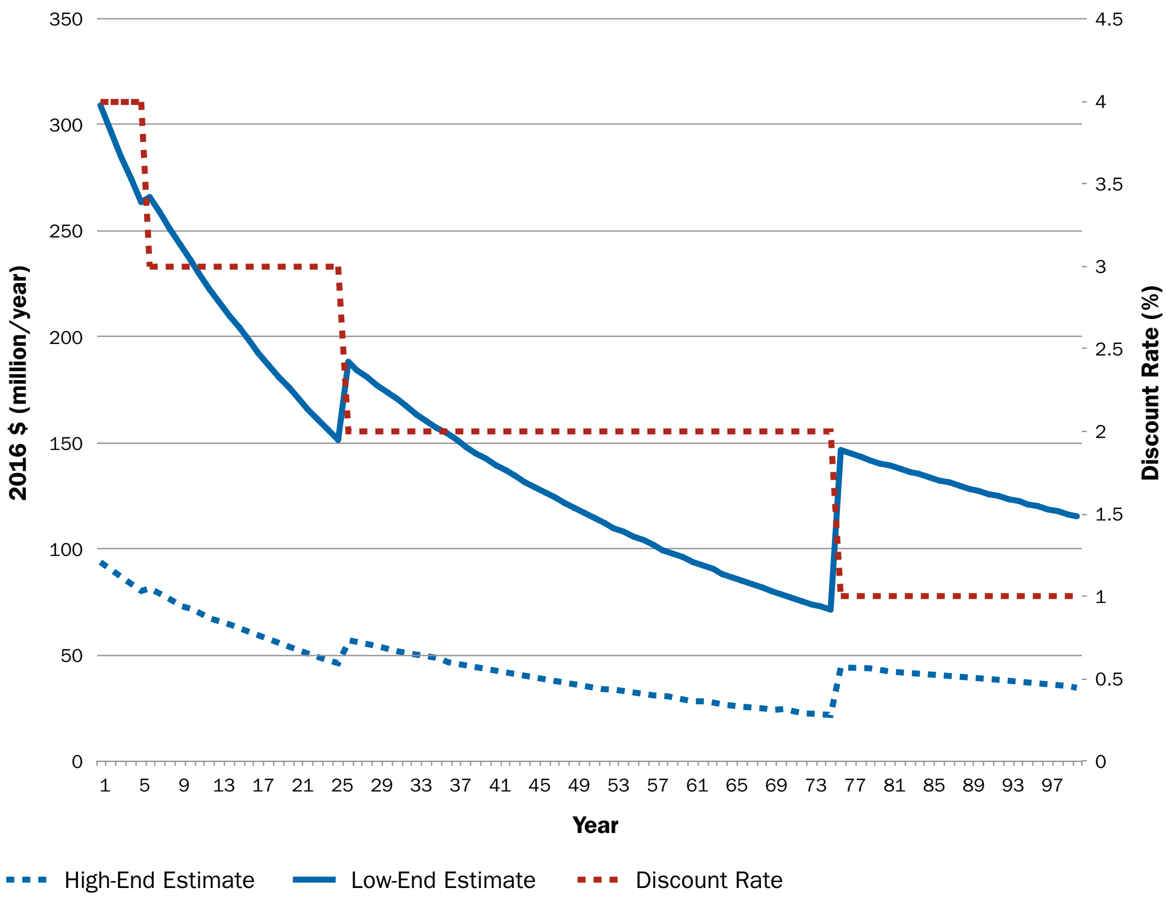
Harbor Islands: Land Cover Changes with SLR (MHHW)

Land Cover Types	Acres (0 ft)	Acres (1 ft)	Acres (3 ft)	Acres (5 ft)
Marine Wetlands	583.86	583.86	583.86	583.86
Salt Marsh	11.72	0.00	45.50	69.03
Freshwater Wetland	11.18	11.18	1.80	1.04
City Parks	5.69	5.69	5.69	5.69
Beach	0.34	0.00	80.89	75.60
Freshwater	0.00	0.00	0.00	0.00
Oyster Bed	0.00	0.00	0.00	0.00
Estuary	0.00	0.00	5.63	18.11
Tidal Flat	5.60	0.00	1.69	17.36
Forest	198.98	217.58	191.40	175.39
Grassland/Openland	73.90	76.52	69.10	58.71
Core Habitats	72.60	109.15	53.92	44.34
Coastal Waters	9,109.77	9,138.04	9,091.35	9,081.71

Source: Woods Hole Oceanographic Institution

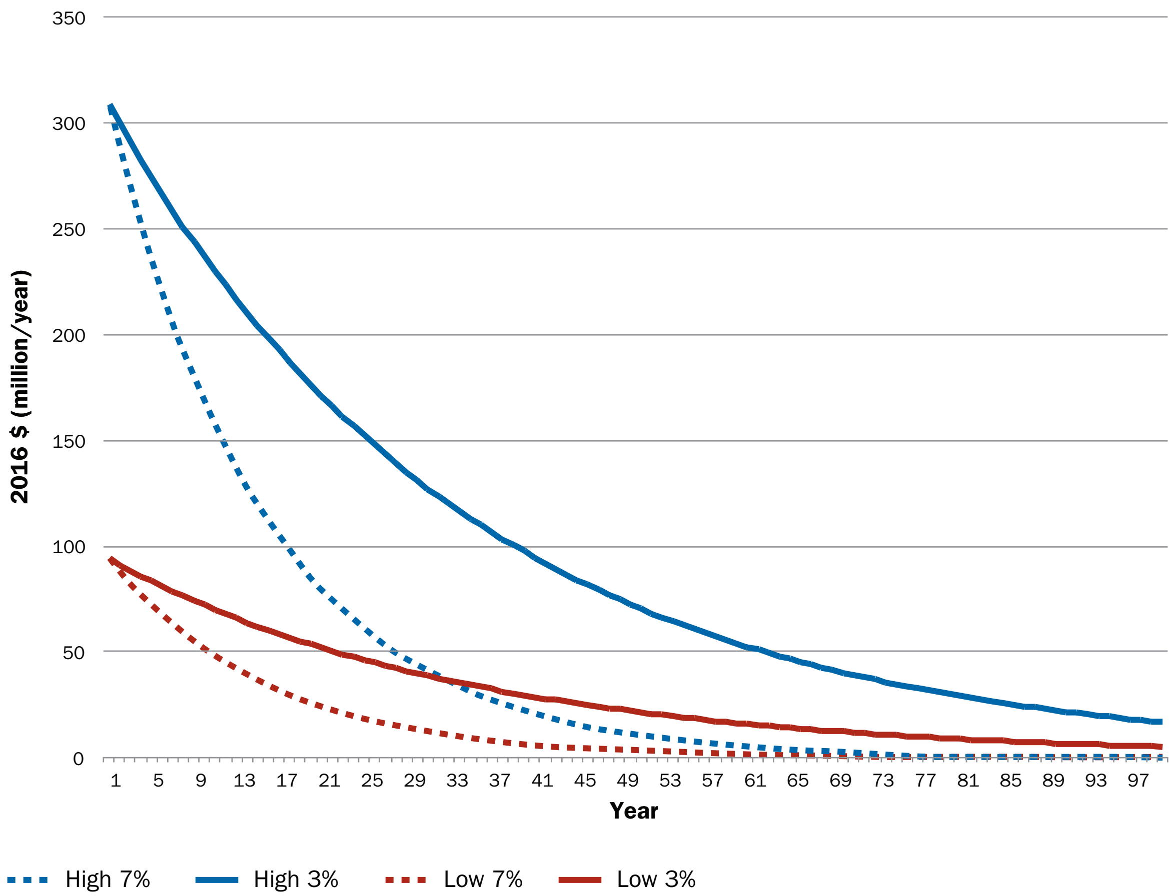
FIGURE 7.7

Flow of Ecosystem Service Values (0 feet SLR), Mystic River Watershed (sliding scale discount rate)



Source: Woods Hole Oceanographic Institution

FIGURE 7.8
Flow of Ecosystem Service Values (0 feet SLR), Mystic River Watershed (constant discount rate)



Source: Woods Hole Oceanographic Institution

structures from land as they become submerged (Titus, 2011).*

Finally, we assess the effects of the proposed harbor barrier on ecosystem asset values. Results of Section 6 have indicated that the barrier would have minor to moderate negative impacts, particularly on water quality, due to reduced flushing and changes in sediment transport. Table 7.11 summarizes relevant results of Section 6 showing the direction and severity of effects of the barrier under conditions of 5 feet of SLR. To estimate the ecosystem values with the barrier, we re-run our models for the scenario of 5 feet of SLR by reducing the unit values of marine wetlands by 5%, estuary by 10%, and coastal waters by 20% and keeping the same unit values for other land covers, assuming that there is no change in the areal extent of each type of land cover. The results are reported in Table 7.12. Generally, the overall reductions in ecosystem asset values in the study area are small (2–3%), although local reductions in the harbor and islands sub-area may be higher (up to 16%).

For the NPV analysis, we estimate the annual flow of ecosystem service values from 2013 to 2140. Figure 7.10 illustrates the annual values for the entire study area, showing also the effects of the barrier to be installed in 2050 (note that the annual value is not discounted). Results of the net present values calculation are summarized in Table 7.13. Again, the overall effects of the proposed harbor barrier are small (below 2%). For example, the low-end estimate of NPV under sliding-scale discounting for the entire study area

* If the marshes were not allowed to migrate in the SLAMM model simulations, marsh areas would reduce with SLR. As a result, the value of ecosystem services would decrease in future years. However, the barrier impacts on ecosystem values discussed below would be similar in terms of percent reduction.

We assess the effects of the proposed harbor barrier on ecosystem asset values. Results have indicated that the barrier would have minor to moderate negative impacts, particularly on water quality, due to reduced flushing and changes in sediment transport.

TABLE 7.9

Asset Value of Ecosystem Services (2016$ millions)

Discount Rate	Sliding Scale		3 Percent		7 Percent	
SLR	Low	High	Low	High	Low	High
Mystic						
0 ft (2013)	4,878	15,297	3,434	10,547	1,812	5,211
1 ft (2030)	4,834	15,125	3,404	10,425	1,799	5,147
3 ft (2070)	4,753	15,751	3,316	10,798	1,702	5,236
5 ft (2100)	7,073	28,413	4,958	19,506	2,582	9,502
Charles and Neponset						
0 ft (2013)	16,000	48,000	11,536	33,560	6,522	17,342
1 ft (2030)	16,196	48,360	11,669	33,813	6,585	17,475
3 ft (2070)	16,449	49,433	11,847	34,554	6,679	17,841
5 ft (2100)	18,801	67,869	13,493	47,119	7,532	23,815
Weir						
0 ft (2013)	6,544	27,530	4,646	18,934	2,515	9,280
1 ft (2030)	6,680	28,122	4,740	19,340	2,560	9,476
3 ft (2070)	6,916	30,092	4,904	20,681	2,646	10,111
5 ft (2100)	7,289	32,447	5,163	22,284	2,775	10,870
Islands						
0 ft (2013)	1,671	4,851	1,221	3,382	716	1,733
1 ft (2030)	1,669	4,814	1,220	3,358	716	1,722
3 ft (2070)	1,706	5,105	1,245	3,555	728	1,813
5 ft (2100)	1,721	5,198	1,255	3,618	732	1,843
Total						
0 ft (2013)	29,093	95,678	20,837	66,423	11,565	33,566
1 ft (2030)	29,379	96,420	21,034	66,936	11,660	33,820
3 ft (2070)	29,824	100,381	21,313	69,587	11,754	35,001
5 ft (2100)	34,883	133,927	24,869	92,527	13,622	46,030

Source: Woods Hole Oceanographic Institution

TABLE 7.10

Percent Change in Ecosystem Asset Value due to SLR* (subtracting the lower SLR scenario value from the higher SLR scenario)

Discount Rate	Sliding Scale		3 Percent		7 Percent	
SLR	Low	High	Low	High	Low	High
Mystic						
0 to 1 ft	–0.91%	–1.13%	–0.86%	–1.15%	–0.72%	–1.24%
1 to 3 ft	–1.68%	4.14%	–2.60%	3.58%	–5.37%	1.73%
3 to 5 ft	48.83%	80.39%	49.53%	80.64%	51.71%	81.49%
Charles and Neponset						
0 to 1 ft	1.23%	0.75%	1.16%	0.75%	0.97%	0.77%
1 to 3 ft	1.56%	2.22%	1.52%	2.19%	1.42%	2.10%
3 to 5 ft	14.30%	37.29%	13.89%	36.37%	12.78%	33.48%
Weir						
0 to 1 ft	2.09%	2.15%	2.01%	2.14%	1.80%	2.12%
1 to 3 ft	3.52%	7.00%	3.47%	6.93%	3.33%	6.70%
3 to 5 ft	5.39%	7.83%	5.27%	7.75%	4.91%	7.51%
Islands						
0 to 1 ft	–0.14%	–0.76%	–0.10%	–0.73%	0.00%	–0.63%
1 to 3 ft	2.25%	6.05%	2.07%	5.87%	1.62%	5.29%
3 to 5 ft	0.84%	1.83%	0.78%	1.78%	0.64%	1.63%
Total						
0 to 1 ft	0.98%	0.78%	0.94%	0.77%	0.83%	0.76%
1 to 3 ft	1.51%	4.11%	1.33%	3.96%	0.80%	3.49%
3 to 5 ft	16.97%	33.42%	16.69%	32.97%	15.89%	31.51%

* Percent changes are between 2 water levels and not cumulative.
Source: Woods Hole Oceanographic Institution

TABLE 7.11

Environmental Effects of Proposed Barrier

Function*	Land Cover/Activity*	Directional* Effects	Percent**	Expected Changes in ESV (percent)
Habitat Quality	Sandy beach	positive	20%	
	Muddy subtidal	positive	20%	
	Sandy subtidal	negative	40%	Estuary (–10%), Wetland (–5%)
	Mixed subtidal	negative	20%	Estuary (–10%), Wetland (–5%)
	Coastal bluff	positive	20%	
Water Quality	Coastal waters	negative	20%	Coastal waters (–20%)
Ecosystem Services	Recreation	positive	20%	
	Fishery	negative	20%	Coastal waters (–20%)

* As described in Chen et al., 2017
** Based on environmental impact ratings in Chen et al., 2017
Source: Woods Hole Oceanographic Institution

TABLE 7.12

Effects of Proposed Barrier on Ecosystem Asset Values (2016$ millions)

Discount Rate	Sliding Scale		3 Percent		7 Percent	
SLR	Low	High	Low	High	Low	High
Mystic						
SLR no Barrier	7,073	28,413	4,958	19,506	2,582	9,502
SLR with Barrier	6,868	27,847	4,808	19,111	2,494	9,299
Change	–206	–566	–150	–395	–88	–203
Change %	**–2.91%**	**–1.99%**	**–3.03%**	**–2.02%**	**–3.41%**	**–2.13%**
Charles and Neponset						
SLR no Barrier	18,801	67,869	13,493	47,119	7,532	23,815
SLR with Barrier	18,693	67,565	13,415	46,908	7,487	23,707
Change	–108	-304	–78	–211	–45	–107
Change %	**–0.58%**	**–0.45%**	**–0.58%**	**-0.45%**	**-0.60%**	**–0.45%**
Weir						
SLR no Barrier	7,289	32,447	5,163	22,284	2,775	10,870
SLR with Barrier	6,888	31,107	4,872	21,356	2,608	10,404
Change	–401	–1,340	–291	–928	–167	–466
Change %	**–5.50%**	**–4.13%**	**–5.63%**	**–4.17%**	**–6.03%**	**–4.29%**
Islands						
SLR no Barrier	1,721	5,198	1,255	3,618	732	1,843
SLR with Barrier	1,454	4,649	1,059	3,229	614	1,635
Change	–266	–550	–197	–389	–118	–208
Change %	**–15.49%**	**–10.57%**	**–15.66%**	**–10.75%**	**–16.13%**	**–11.30%**
Total						
SLR no Barrier	34,883	133,927	24,869	92,527	13,622	46,030
SLR with Barrier	33,902	131,168	24,153	90,604	13,203	45,045
Change	–981	–2,759	–716	–1,923	–419	–985
Change %	**–2.81%**	**–2.06%**	**–2.88%**	**–2.08%**	**–3.07%**	**–2.14%**

Source: Woods Hole Oceanographic Institution

without barrier is $42,309 million. With the barrier installed in 2050, the NPV would be reduced by 1.92% to $41,497 million. If the barrier is to be installed in 2090, the reduction in NPV would be smaller (1.10%), as shown in Table 7.14.

Conclusions

Ecosystems in the study area provide a multitude of services to society with an estimated asset value of $30–$100 billion. Sea level rise will have significant impacts on ecosystem service values. Without shoreline armoring, these values are expected to grow, which reflects the benefits of managed retreat as a policy option (Table 7.9). Based on available data and results of the environmental analysis, the overall effects of a proposed harbor barrier on ecosystem values are expected to be small (less than 3%) (Figure 7.9).

Summary

In this study, we develop estimates of ecosystem service values in Boston Harbor and neighboring areas and investigate how these values may change with sea level rise. In addition, we assess the effects of the proposed harbor barrier on ecosystem service values, using results of a parallel study on environmental impacts. Our results suggest that the ecosystems in the study area provide a multitude of services to society valued at $30–$100 billion. SLR will have significant impacts on ecosystem service values, and without shoreline armoring, these values are expected to grow mainly due to growth in marsh/wetland areas. Based on available data and assumptions, the overall effects of a proposed harbor barrier on ecosystem values are expected to be small (less than 3%).

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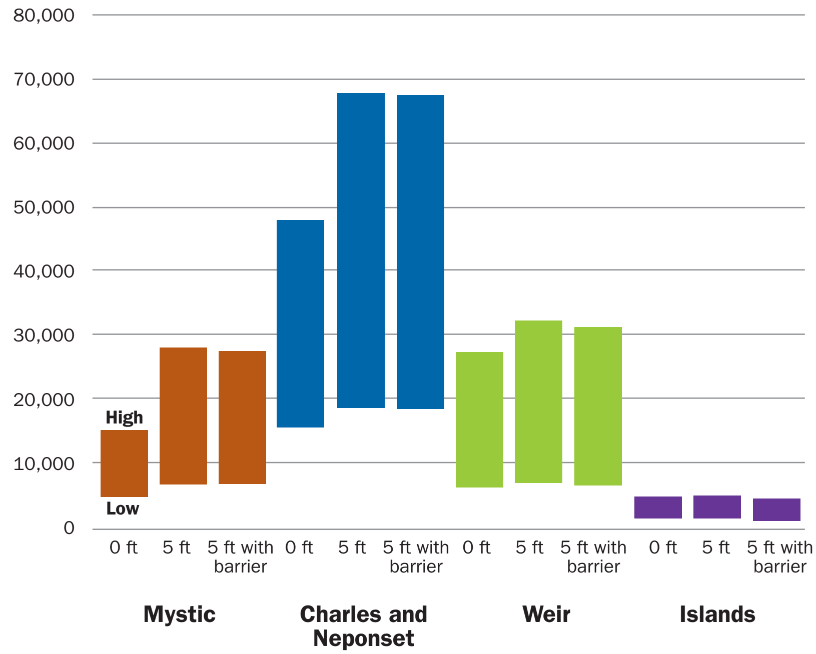
FIGURE 7.9

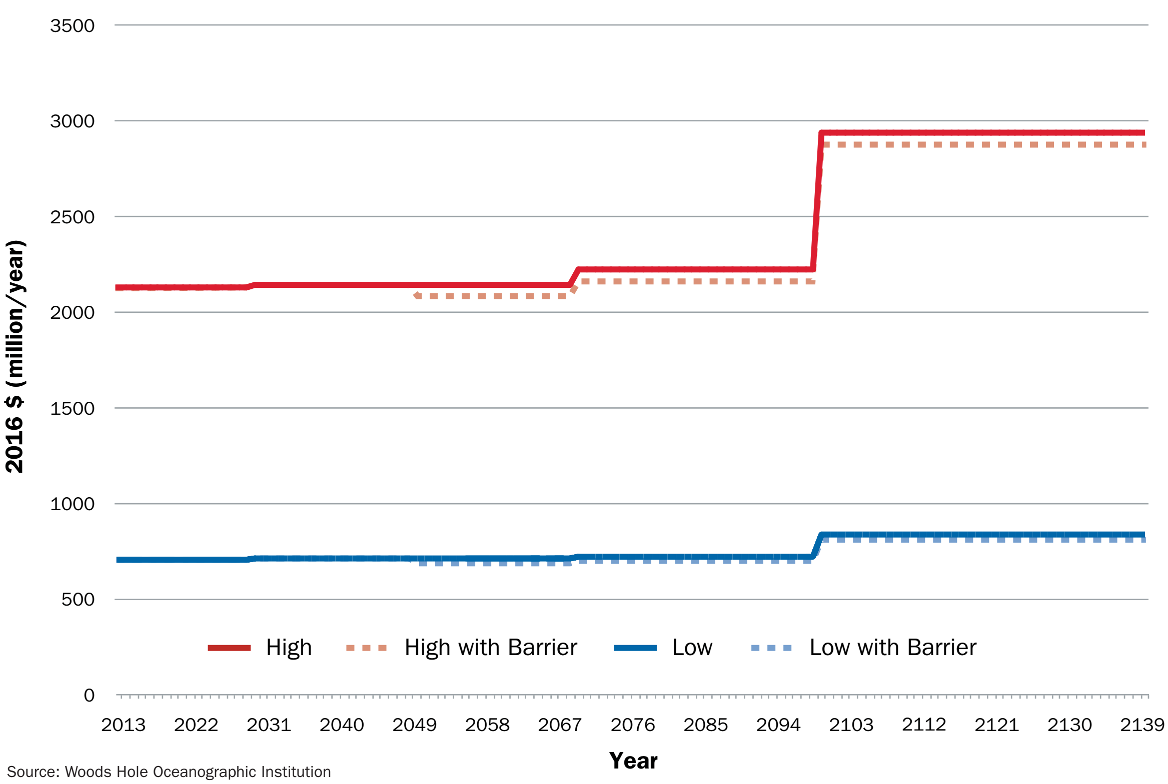
Effects of SLR and Proposed Barrier on Ecosystem Asset Values (2016$ millions, sliding scale discounting)



Source: Woods Hole Oceanographic Institution

FIGURE 7.10

Effects of SLR and Proposed Barrier on Annual Ecosystem Values, 2013–2140 (assuming barrier installation by 2050)



Source: Woods Hole Oceanographic Institution

TABLE 7.13

Effects of Proposed Barrier in 2050 on Net Present Values of Ecosystem Services, 2013–2140 (2016$ millions)

	Mystic		Charles and Neponset		Weir		Islands		Total	
Discount Rate	Low	High	Low	High	Low	High	Low	High	Low	High
Sliding Scale										
NPV no Barrier	7,051	22,953	23,590	68,569	9,209	36,264	2,458	6,371	42,309	134,157
NPV with Barrier	6,880	22,538	23,504	68,353	8,882	35,299	2,231	5,951	41,497	132,141
Change	**2.43%**	**1.81%**	**0.37%**	**0.31%**	**3.56%**	**2.66%**	**9.26%**	**6.60%**	**1.92%**	**1.50%**
3 percent										
NPV no Barrier	3,841	11,665	13,459	37,558	5,302	20,580	1,438	3,688	24,040	73,491
NPV with Barrier	3,785	11,529	13,431	37,488	5,194	20,262	1,363	3,549	23,773	72,829
Change	**1.46%**	**1.17%**	**0.21%**	**0.19%**	**2.03%**	**1.54%**	**5.22%**	**3.75%**	**1.11%**	**0.90%**
7 percent										
NPV no Barrier	1,720	5,093	6,057	16,709	2,384	9,188	653	1,668	10,814	32,658
NPV with Barrier	1,714	5,077	6,054	16,701	2,371	9,151	644	1,652	10,783	32,581
Change	**0.38%**	**0.31%**	**0.05%**	**0.05%**	**0.53%**	**0.40%**	**1.34%**	**0.97%**	**0.29%**	**0.24%**

Source: Woods Hole Oceanographic Institution

TABLE 7.14

Effects of Proposed Barrier in 2090 on Net Present Values of Ecosystem Services, 2013–2140 (2016$ millions)

	Mystic		Charles and Neponset		Weir		Islands		Total	
Discount Rate	Low	High	Low	High	Low	High	Low	High	Low	High
Sliding Scale										
NPV no Barrier	7,051	22,953	23,590	68,569	9,209	36,264	2,458	6,371	42,309	134,157
NPV with Barrier	6,953	22,715	23,540	68,443	9,021	35,710	2,328	6,130	41,842	132,998
Change	**1.39%**	**1.04%**	**0.21%**	**0.18%**	**2.04%**	**1.53%**	**5.31%**	**3.78%**	**1.10%**	**0.86%**
3 percent										
NPV no Barrier	3,841	11,665	13,459	37,558	5,302	20,580	1,438	3,688	24,040	73,491
NPV with Barrier	3,827	11,630	13,451	37,539	5,274	20,498	1,419	3,652	23,971	73,320
Change	**0.38%**	**0.30%**	**0.05%**	**0.05%**	**0.52%**	**0.40%**	**1.33%**	**0.96%**	**0.29%**	**0.23%**
7 percent										
NPV no Barrier	1,720	5,093	6,057	16,709	2,384	9,188	653	1,668	10,814	32,658
NPV with Barrier	**1,720**	**5,092**	**6,057**	**16,708**	**2,383**	**9,186**	**653**	**1,667**	**10,812**	**32,653**
Change	**0.02%**	**0.02%**	**0.00%**	**0.00%**	**0.03%**	**0.03%**	**0.09%**	**0.06%**	**0.02%**	**0.02%**

Source: Woods Hole Oceanographic Institution

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8 *Economic Analysis*

The benefit:cost analysis is based on potential losses avoided in the form of reduced physical damage to structures, building contents and inventory, and displacement costs for residents.

The economic analysis presented in this chapter evaluates the potential risk reduction benefits of a Harbor Barrier system, comparing several project implementation scenarios to understand sensitivity and produce a preliminary estimate of cost-effectiveness of a harbor barrier. The benefit:cost analysis is based on potential losses avoided in the form of reduced physical damage to structures, building contents and inventory, and displacement costs for residents.

As is the case in all the other analyses, the results of the economic analysis are limited by the preliminary nature of the assessment and its many assumptions. We believe the results, however, provide useful insights for the broader decision-making process regarding a harbor barrier. While the analysis does show that a barrier might have some utility before the end of the century under very limited conditions, it also points out some larger questions the City of Boston should be addressing.

Analysis Approach

This summary of the analysis approach presents three components of the preliminary benefit:cost review for the Harbor Barrier Feasibility Study:

- Loss and exposure categories considered.
- Expected losses avoided attributable to a Harbor Barrier. Analysts evaluated the potential losses avoided, and the expected benefits of a Harbor Barrier, from sixteen different flood event scenarios correlating to specific flood event exceedance probabilities. These were calculated at varying sea level intervals associated with the 4.5 RCP emissions scenario from the Boston Research Advisory Group (Douglas et al., 2016) report used in Climate Ready Boston (2016). Flood hazard data from Woods Hole Group were used to estimate potential flood impacts across the study area. RCP 4.5 was chosen because we only could analyze one scenario for the economic analysis; this is a moderate one.
- A preliminary comparison of expected Harbor Barrier benefits (losses avoided) over time when compared to costs over time under multiple barrier, cost, and shoreline flood risk reduction scenarios

This analysis differs from Climate Ready Boston (2016) in both the approach and data used due to the size of the study area and project constraints. Principally, the Harbor Barrier Feasibility Study aggregated parcel information to the census tract level to assess expected losses, while Climate Ready Boston evaluated site-specific expected losses. While the full details of the analysis approach and limitations are in Appendix D, see Table 8.1 for key analysis considerations.

The feasibility study performed through this effort is highly conceptual. Detailed evaluations of closure success rate, final design elevations of the barrier, and on-land flood assumptions have not yet been developed. As such, potential losses avoided presented in the tables below assume the Harbor Barrier would be completely effective at mitigating or avoiding all losses associated with each flood scenario within the barrier's benefitting area up to an assumed level of protection of the 0.1% annual chance event with 5 feet of sea level rise. The potential effect of shore-based solutions, design elevation, and functional life of a barrier system is incorporated into the Sensitivity Analysis at the end of this chapter.

> While the analysis does show that a barrier may have some utility before the end of the century under very limited conditions, it also points out some larger questions the City of Boston should be addressing.

Loss and Exposure Categories

Analysts estimated impacts across the study area as a result of flooding under 16 flood events that correlated to the 10-percent, 2-percent, 1-percent, and 0.1-percent annual exceedance probabilities in each of four sea level rise intervals based on the 4.5 RCP rate. Analysts used regression analysis to understand the annual exceedance probability that each of these 16 events correlated to at each sea level rise interval.

Refer to Table 8.2 for detailed descriptions of each impact category explored in this analysis.

Expected Losses within Harbor Barrier Study Areas (Example Flood Events)

The study included two Harbor Barrier configurations, an Inner Harbor Barrier configuration and an Outer Harbor Barrier configuration (see Section 4 for more information on barrier configurations) which could be expected to provide benefit to two distinct study areas. Table 8.3 through

TABLE 8.1

Key Economic Analysis Considerations

Analysis Element	Key Considerations
Hazard Data	• The analysis uses 16 flood events provided by Woods Hole Group. Probabilities of each of these flood events being met or exceeded in any given year vary in the analysis based on sea level rise assumptions for that given year. • The analysis relies on a single rate of sea level rise that correlates 0-feet of sea level rise to the year 2000, 1-foot to the year 2030, 3-feet to the year 2070, and 5-feet to the year 2100. Change in flood event probabilities as a result of sea level rise for years in between these four intervals is interpolated annually
Potential Losses Avoided	• Include impacts to structures, their contents, and displacement costs for residents exposed to flood impacts • Do not include business interruption (lost sales and revenues from business closure), nor damage to infrastructure or regional impacts from interruptions in transportation, electrical, or water and wastewater services. As these impacts represent potential significant economic value, the potential losses avoided in this analysis are conservative estimates of risk reduction benefits gained from implementation of a Harbor Barrier.
Analysis Approach	• Based on aggregated parcel level and flood depth data at the census tract level • Does not consider site-specific evaluations of flood hazard data or built environment context. The aggregated analysis approach to estimating potential losses avoided resulted in outcomes with trends that differ from Climate Ready Boston (2016).* For example, Climate Ready Boston concluded with higher building damage and greater flood risk present in South Boston than other City neighborhoods. Climate Ready Boston notes that these results are likely due to large, high-value development located on the waterfront in South Boston.
Built environment	• Based on present-day built environment and population conditions • Does not account for future development, redevelopment, or population growth. While current projections are that population and the built environment will continue to grow into the future, such factors are likely to be heavily affected by decisions made by the City and its constituents related to climate adaptation planning and additional investments and market signals over the coming decades.

* The aggregated analysis uses median structure square footage and height information across a census tract. In the case where there is a large census tract with a mix of structure types and sizes, the potential losses avoided are tempered by the aggregated structure information. Large developments on the waterfront at risk of frequent flooding from high-probability events are not captured to the same degree that a site-specific analysis would accomplish. This yielded conservatively low results in areas dominated by waterfront high rises.

Source: Arcadis

TABLE 8.2

Expected Loss and Exposure Category Descriptions*

Loss Category	Description
Direct Physical Damage to Buildings	Structure damage expected due to flooding based on 2016 RS Means Replacement Costs associated with specific building types and characteristics. Damages to buildings calculated using USACE depth-damage curves gathered from the North Atlantic Coast Comprehensive Study (NACCS) Physical Depth Damage Function Summary Report (USACE, 2015); depth damage curves define the relationship between the depth of flooding in a structure and the percent of damage that occurs. The percent damage is applied to the replacement value of the building for an estimate of direct physical damage.
Direct Physical Damage to Contents and Inventory	The 2016-dollar value of structure contents and inventory damaged due to flooding. Contents and inventory damage are also estimated through depth-damage curves from the USACE West Shore Lake Pontchartrain Hurricane and Storm Damage Risk Reduction Study (USACE, 2014). Contents and inventory estimated as a share above the structure replacement cost based on building type, characteristics, and use.
Displacement (also known as Relocation) Costs to Businesses and Occupants	Displacement is a function of direct physical damage and flood depth, and includes relocation and rental costs associated with displacement, method sourced from Climate Ready Boston (2016).

* Direct physical damages to infrastructure and business, transportation, and service interruption losses are not contemplated in this analysis.

Source: Arcadis

TABLE 8.3

Summary of Expected Single-Event Losses for the 1% Annual Exceedance Probability Coastal Flood Event for Each SLR Interval (in thousands) within the Study Areas

Study Area	SLR Scenario	1% Building Losses	1% Contents and Inventory	1% Displacement	1% Total Losses Avoided
Assoc. with Outer Harbor Barrier	1-foot	$1,896,000	$1,916,000	$129,000	$3,941,000
	3-foot	$7,537,000	$8,933,000	$976,000	$17,446,000
	5-foot	$12,992,000	$15,255,000	$1,877,000	$30,125,000
Assoc. with Inner Harbor Barrier	1-foot	$1,048,000	$1,233,000	$41,000	$2,322,000
	3-foot	$5,291,000	$6,889,000	$627,000	$12,807,000
	5-foot	$9,932,000	$12,354,000	$1,332,000	$23,618,000

Source: Arcadis

Table 8.7 summarize expected losses for single-event damages (using the 1% chance event as an example) for study areas correlating to the Inner and Outer Harbor Barrier configurations. Several communities or neighborhoods within Boston are expected to be consis-tently at a higher risk of flood damage due to coastal flooding and sea level rise; these include Weymouth, Quincy, and Revere, as well as South Boston, East Boston, and Downtown Boston. These communities have long stretches of low-lying coastlines compared to their neighbors. There are a few communities that are not expected to be impacted by coastal flood risk in the 1-foot SLR scenario, but in the 3- and 5-foot SLR scenarios —Cambridge, Medford, and the South End. This typically occurs when a topographic threshold is breached, and flood-waters are able to expand in lower-lying inland areas.

In the following calculations, modeled flooding to areas inland of the metro area's three dams for near-term sea level rise scenarios is expected to be caused by rainfall and riverine flooding (which would not be reduced by an Inner or Outer Harbor Barrier), and not coastal flooding. As such, areas expected to be flooded inland of the metro area's three dams for said flood events have been excluded from this analysis, despite the fact that such losses could be expected to occur within the study area. The Harbor Barrier could not mitigate such losses. Additionally, neither existing nor planned local flood protection and mitigation projects are accounted for in the hazard data or the expected losses avoided presented in this section.

Refer to Appendix C for a detailed display of expected losses by community within the study area.

Neither existing nor planned local flood protection and mitigation projects are accounted for in the hazard data or the expected losses avoided presented in this section.

TABLE 8.4

Expected Losses per SLR Interval for the 1% Annual Exceedance Probability Coastal Flood Event, 2016 Dollars (in thousands) within the Outer Harbor Barrier Study Area by Community

Community	5-foot	3-foot	1-foot
Braintree	$102,000	$80,000	$31,000
Boston	$14,845,000	$7,976,000	$1,712,000
Brookline	$51,000	$340	Not applicable
Cambridge	$3,370,000	$643,000	Not applicable
Chelsea	$1,093,000	$936,000	$253,000
Everett	$822,000	$703,000	$156,000
Hingham	$234,000	$178,000	$87,000
Hull	$744,000	$576,000	$238,000
Malden	$1,017,000	$718,000	$44,000
Medford	$2,029,000	$1,566,000	Not applicable
Milton	$55,000	$47,000	$35,000
Newton	$1,000	$300	Not applicable
Quincy	$2,119,000	$1,582,000	$594,000
Revere	$1,766,000	$1,262,000	$460,000
Somerville	$963,000	$450,000	$28,000
Weymouth	$196,000	$175,000	$80,000
Winthrop	$716,000	$553,000	$222,000

Source: Arcadis

Flooded Critical Facilities

Damages to critical facilities and infrastructure are captured by the economic analysis if those services are housed within a structure. Damages to underground networks, which have higher replacement values, are not covered by the analysis. Loss of service of critical facilities and essential services are an important consideration in a feasibility assessment, and can contribute significantly to an economic analysis with sufficient data and clear consequences of loss (outside of the scope of this study). Table 8.8 shows the critical facilities that would be flooded in the area without the Outer Harbor Barrier with a 1% storm with 0 and 5 feet of SLR.

POTENTIAL BENEFITS OF A HARBOR BARRIER

Estimating potential benefits of a Harbor Barrier configuration to compare with estimated project costs requires calculations of annualized losses

TABLE 8.5

Expected Losses per SLR Interval for the 1% Annual Exceedance Probability Coastal Flood Event, 2016 Dollars (in thousands) within the Outer Harbor Barrier Study Area by City of Boston Neighborhood

Community	5-foot	3-foot	1-foot
Allston	$315,000	$16,000	Not applicable
Back Bay	$1,314,000	$67,000	Not applicable
Charlestown	$746,000	$600,000	$129,000
Downtown	$3,109,000	$2,062,000	$294,000
East Boston	$2,185,000	$1,884,000	$519,000
Fenway	$1,620,000	$24,000	$3,000
Jamaica Plain	$136,000	Not applicable	Not applicable
North Dorchester	$579,000	$310,000	$140,000
Roxbury	$642,000	$185,000	Not applicable
South Boston	$2,053,000	$1,669,000	$545,000
South Dorchester	$705,000	$413,000	$82,000
South End	$1,441,000	$746,000	Not applicable

Source: Arcadis

TABLE 8.6

Expected Losses per SLR Interval for the 1% Annual Exceedance Probability Coastal Flood Event, 2016 Dollars (in thousands) within the Inner Harbor Barrier Study Area by Community

Community	5-foot	3-foot	1-foot
Boston	$10,778,000	$7,442,000	$1,732,000
Brookline	$51,000	$340	Not applicable
Cambridge	$3,370,000	$643,000	Not applicable
Chelsea	$1,093,000	$936,000	$253,000
Everett	$819,000	$702,000	$155,000
Malden	$895,000	$640,000	Not applicable
Medford	$2,029,000	$1,566,000	Not applicable
Revere	$510,000	$387,000	$141,000
Somerville	$963,000	$450,000	$28,000
Winthrop	$58,000	$43,000	$13,000

Source: Arcadis

TABLE 8.7

Expected Losses per SLR Interval for the 1% Annual Exceedance Probability Coastal Flood Event, 2016 Dollars (in thousands) within the Inner Harbor Barrier Study Area by City of Boston Neighborhood

Community	5-foot	3-foot	1-foot
Allston	$291,000	$16,000	Not applicable
Back Bay	$1,077,000	$67,000	Not applicable
Charlestown	$564,000	$595,000	$146,000
Downtown	$2,349,000	$2,062,000	$311,000
East Boston	$1,411,000	$1,878,000	$554,000
Fenway	$1,390,000	$24,000	$3,000
Jamaica Plain	$419,000	Not applicable	Not applicable
North Dorchester	$303,000	$256,000	$148,000
Roxbury	$564,000	$185,000	Not applicable
South Boston	$1,275,000	$1,613,000	$570,000
South Dorchester	Not applicable	Not applicable	Not applicable
South End	$1,135,000	$746,000	Not applicable

Source: Arcadis

avoided within the study area for each flood event expected to be mitigated by the barrier. Annualized values represent monetary loss that can be expected due to risk (consequence times probability) over any given one-year period. As evidenced in Figure 8.1, risk associated with lower impact, higher probability events is often higher than risk associated with larger, more intense storms with lower probability. This is because the expected frequency of impact for higher probability events is likely to lead to increased costs over time.

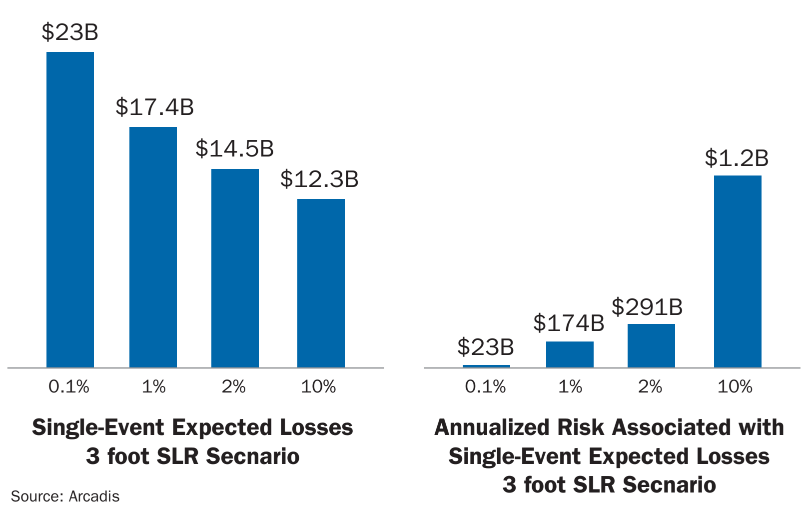
As stated previously, this evaluation includes information for 16 flood event scenarios: four sea level rise scenarios, with four exceedance probabilities each. As sea level rise occurs over time, it is reasonable to expect that flood events become more frequent and the probability of occurrence changes. For example, a storm with a 10-foot flood elevation may equate to the 1% annual chance event in 2030 but is equivalent to the 10% annual chance event in 2070 due to sea level rise. These changing probabilities have a significant effect on annualized values, which are greater for more frequent flood events due to the cumulative impacts of flooding over time.

The evolution of probability of event occurrence over time is accounted for through a regression analysis; analysts gathered water surface elevations for each of the sixteen flood scenarios from the Boston Harbor Tide Gauge and created a curve for each sea level rise scenario that calculates event probability over time. Table 8.9 presents an example of how flood probabilities could be expected to change over time using the 3-foot sea level rise interval. This approach provides additional events to consider within a sea level rise scenario to generate expected losses avoided.

An important assumption of the evaluation is that regression analysis that applies to the

FIGURE 8.1

Consequence and Probability Example for Boston Harbor



Source: Arcadis

TABLE 8.8

Number of Flooded Critical Facilities with 1% Flood

Municipality	Type	0 ft SLR	5 ft SLR	% increase
Boston	City Hall	0	1	
	Dam	0	2	
	Amtrak Station	0	2	
	Toll Plaza	0	4	
	Hospital	0	5	
	Power Plant	0	7	
	Commuter Rail Station	0	8	
	Long–Term Care Facility	0	8	
	College	0	27	
	Community Health Center	1	13	
	Fire Station	1	13	
	Police Station	2	16	
	School	2	40	
	T Station	2	60	
	Seaport	4	10	
	MassDEP Major Facility	7	71	
	MassDEP 21E Site	12	75	
	TOTALS	**31**	**362**	**1,068%**
Braintree	MassDEP Major Facility	0	1	
	Power Plant	0	1	
	TOTALS	**0**	**2**	**n/a**
Brookline	MassDEP 21E Site	0	1	
	School	0	1	
	T Station	0	2	
	TOTALS	**0**	**4**	**n/a**
Cambridge	Fire Station	0	1	
	Power Plant	0	2	
	Police Station	0	2	
	Long Term Care Facility	0	2	
	Community Health Center	0	3	
	T Station	0	3	
	College	0	4	
	School	0	11	
	MassDEP Major Facility	3	29	
	MassDEP 21E Site	3	30	
	TOTALS	**6**	**87**	**1,350%**

Source: UMass Boston

Boston Harbor tide gauge can be applied throughout both the Inner and Outer Harbor Barrier configuration study areas.

Present Value and Sensitivity Analysis

Calculating the present value (PV) of potential losses avoided allows for the comparison of future benefits (losses avoided) to current project costs and is standard accounting practice for valuing return on investments. To do this, analysts apply a discount rate to annualized benefits expected over the life of a Harbor Barrier configuration to account for the fact that project costs and benefits in several decades' time should be valued at a lower rate than costs and benefits expected today. There is an added element of complexity in a forward-looking analysis such as this one, as the scale of benefits are expected to change over time due to sea level rise, which affects the expected probability and magnitude of flooding.

The PV analysis provided for the Harbor Barrier evaluation discounts benefits and costs for several project scenarios. These scenarios provide alternatives for different discount rates, high- and low-estimate project costs, and assumptions regarding potential shore-based protections implemented before the barrier is constructed. This sensitivity analysis helps identify key variables that influence the costs and benefits of a barrier system. The results of the sensitivity analysis show that the cost-effectiveness of a Harbor Barrier System is highly sensitive to the discount rate, but also responsive to the effectiveness of potential shore-based solutions. The sensitivity of this analysis further demonstrates the number of unknowns regarding a Harbor Barrier configuration at this point in time, and that further research and consideration of how to implement a barrier to work in tandem with shore-based solutions is needed.

A key sensitivity not addressed in this analysis is the rate of sea level rise. In the analysis, sea level rise is expected to occur according to the schedule provided in Table 8.10 the moderate rate as described in Section 3. Benefits are interpolated between timeframes according to this schedule. This is an assumption of the analysis that can be addressed over time as the rate of actual sea level rise is further observed or ranges of rates of sea level rise are integrated into more detailed analyses.

Sensitivities and Analysis Limitations

DISCOUNT RATES

The Federal Office of Management and Budget identifies a discount rate of 7% for use when calculating the benefits and costs associated with projects requiring federal funding, but 3% is another common discount rate used to generate net present value that has been used by the United States Department of Housing and Urban Development (HUD). A 7% discount rate provides a more conservative estimate of discounted benefits.

PROJECT COST ESTIMATES

Analysts used high and low preliminary cost estimates developed for this project in Section 4 to estimate PV of design and capital costs expected for each barrier system as well as the annual O&M costs (without inflation). It is assumed that the design and construction of a completed harbor barrier configuration would take approximately 20 years and costs are distributed equally over that period.

Shore-Based Solutions and Construction Timeline

The presence of district-scale shore-based solutions is a consistent assumption in the economic analysis. Using the approach to annualize values demonstrated in Table 8.9, analysts determined that if district-scale solutions are constructed by 2040 and function until 2100, the present value of losses avoided by the shore-based solutions within the study area that is associated with the Outer Harbor Barrier would be nearly $74 billion. The study team assumed that a Harbor Barrier could be designed and constructed by 2050. Losses avoided as a result of shore-based solutions between the years 2040 and 2050 could reach $26 billion net present value dollars based on discounted summed annualized expected losses avoided. These loss avoidance calculations for shore-line solutions do not consider any flooding expected to be more frequent than monthly during any part of the century and do not consider benefits higher than an assumed level of protection that correlates to 14 feet NAVD88 at the Boston Harbor tide gauge. The analysis assumes that property which is flooding monthly is no longer usable and removes such damages from the analysis. The analysis does not consider long term economic or revenue impacts associated with chronic flooding.

As a result, the Harbor Barrier economic analysis assumes that the potential consequence

TABLE 8.8

Number of Flooded Critical Facilities with 1% Flood (CONTINUED)

Municipality	Type	0 ft SLR	5 ft SLR	% increase
Chelsea	Community Health Center	0	3	
	MassDEP Major Facility	0	7	
	School	0	8	
	Long Term Care Facility	1	1	
	MassDEP 21E Site	2	16	
	TOTALS	**3**	**35**	**1,067%**
Everett	School	0	1	
	MassDEP Major Facility	0	9	
	TOTALS	**0**	**10**	**n/a**
Hingham	Seaport	0	1	
	Dam	0	1	
	Long Term Care Facility	0	2	
	School	1	1	
	TOTALS	**1**	**5**	**400%**
Hull	Community Health Center	0	1	
	Seaport	0	1	
	MassDEP 21E Site	0	3	
	Dam	1	1	
	Fire Station	1	1	
	School	1	2	
	TOTALS	**3**	**9**	**200%**
Malden	College	0	1	
	Police Station	0	1	
	School	0	1	
	MassDEP Major Facility	0	6	
	MassDEP 21E Site	2	7	
	TOTALS	**2**	**16**	**700%**
Medford	T Station	0	1	
	City Hall	0	1	
	Dam	0	1	
	Police Station	0	2	
	Fire Station	0	3	
	School	0	4	
	MassDEP 21E Site	0	17	
	MassDEP Major Facility	1	7	
	TOTALS	**1**	**36**	**3,500%**
Milton	Dam	0	1	
	TOTALS	**0**	**1**	**n/a**

TABLE 8.8

Number of Flooded Critical Facilities with 1% Flood (CONTINUED)

Municipality	Type	0 ft SLR	5 ft SLR	% increase
Quincy	Seaport	0	1	
	T Station	0	1	
	Police Station	0	1	
	College	0	1	
	Community Health Center	0	2	
	Long Term Care Facility	0	3	
	MassDEP Major Facility	0	3	
	Power Plant	1	1	
	School	1	5	
	Fire Station	2	3	
	MassDEP 21E Site	2	5	
	TOTALS	**6**	**26**	**333%**
Revere	Power Plant	0	1	
	School	0	5	
	T Station	1	1	
	MassDEP 21E Site	1	5	
	MassDEP Major Facility	1	7	
	TOTALS	**3**	**19**	**533%**
Somerville	Police Station	0	1	
	T Station	0	1	
	School	0	1	
	Fire Station	0	1	
	College	0	1	
	Dam	1	1	
	MassDEP Major Facility	1	9	
	MassDEP 21E Site	4	27	
	TOTALS	**6**	**42**	**600%**
Weymouth	MassDEP 21E Site	0	1	
	MassDEP Major Facility	0	1	
	Power Plant	0	1	
	School	0	1	
	TOTALS	**0**	**4**	**n/a**
Winthrop	MassDEP Major Facility	0	1	
	Fire Station	1	1	
	School	1	2	
	TOTALS	**2**	**4**	**100%**

of inaction in the near to mid-term is significant enough to reasonably expect that the Harbor Barrier would be constructed to complement shore-based adaptation measures, as opposed to providing a single line of flood defense. To fail to do so would likely pose an existential threat to many waterfront properties within the study area, based on the expected frequency of flooding. Therefore, the analysis assumes that the Harbor Barrier provides an outer, second layer of defense to the study area, and it is assumed to only mitigate losses that exceed the level of protection expected at the shore (equivalent events exceeding a flood elevation of 12 ft NAVD88 or 14 ft NAVD88 at the Boston Harbor tide gauge, depending on the scenario evaluated below).

The closure analysis in Section 5 evaluates the functionality timeline of a Harbor Barrier System by comparing the implementation timeframe for a barrier system to the time when the frequency of closure exceeds 50 times per year. As previously mentioned this is a very high estimate. Most barriers of this scale are designed to close only once every decade or so (see Section 2). The closure analysis estimates that a Harbor Barrier configuration is not needed until 2100 if shore-based protection is provided to the equivalent of 14 feet NAVD88 at the Boston Harbor tide gauge by at least 2070. There remains the possibility that some events greater than the equivalent of 14 feet NAVD at the Boston Harbor tide gauge could occur between 2070 and 2100; this event is essentially equal to the 0.1% annual chance exceedance probability with 3 feet of sea level rise. Therefore this lifetime was extended to 2070 to 2130.

The City of Boston and the region at large have not clarified risk tolerance. As such, sensitivity scenarios included in the economic analysis include two alternate timings (based on potential regional risk tolerance) and shoreline level of protection scenarios, as follow:

SHORE-BASED SOLUTIONS AND CONSTRUCTION TIMELINE SCENARIO 1

- Universal shoreline adaptation within the study area to a level of protection reaching the equivalent of 12 feet NAVD88 at the Boston Harbor tide gauge by 2050.
- A Harbor Barrier configuration is constructed by 2050 as the region decides to pursue implementation of a barrier within the next ten years followed by a design and construction period when costs are equally distributed over the 20 year construction period beginning in 2030.

TABLE 8.9

Water Surface Elevations at the Boston Tide Gauge and Example Redistributed Exceedance Probabilities for the 3-Foot Sea Level Rise Scenario, Feet NAVD88

Sea Level Rise Scenario	Exceedance Probability within sea level rise interval	Water Surface Elevation (ft-NAVD88)	Redistributed Exceedance Probability based on 3-foot SLR Scenario (2070 Expectations of Probability)
0 feet (2013)	10%	8.1	14666.7142% (every 2 days)
	2%	8.9	3027.3006% (2–3 times a month)
	1%	9.4	2485.3976% (2–3 times a month)
	0.1%	9.9	1129.1646% (every month)
1-foot (2030)	10%	9	513.0014% (every other month)
	2%	9.8	421.1715% (every three months)
	1%	10.2	233.0665% (two times a year)
	0.1%	11	48.1064% (every other year)
3-foot (2070)	10%	11.8	*9.9295%* (1 in 10 years chance)
	2%	12.5	*2.4964%* (1 in 50 years chance)
	1%	13.1	*0.7645%* (1 in 100 years chance)
	0.1%	14.1	*0.1064%* (1 in 900–1,000 years chance)
5-foot (2100)	10%	13.5	0.3473% (1 in 250–300 years chance)
	2%	14.4	0.0589% (1 in 1,700 years chance)
	1%	14.8	0.0267% (1 in 3,500 years chance)
	0.1%	15.9	0.0031% (1 in 30,000 years chance)

Sources: Arcadis, Woods Hole Group

- The barrier would be functional to approximately five feet of sea level rise, or roughly 2100 (see Figure 5.20). After that period some additional means would likely be necessary to control flooding, as the closure analysis estimates that the gates would be required to close too frequently to continue functioning as intended (based on shoreline level of protection).

SHORE-BASED SOLUTIONS AND CONSTRUCTION TIMELINE SCENARIO 2

- Universal shoreline adaptation within the study area to a level of protection reaching the equivalent of 14 feet NAVD88 at the Boston Harbor tide gauge by the time a Harbor Barrier configuration is in place in 2070. This correlates to approximately the 0.1% annual chance exceedance probability with three feet of sea level rise. Selected as upper bound because recent shoreline adaptation concepts in East Boston and Charlestown identified this as the goal for shoreline protection by 2070.
- A Harbor Barrier configuration would be constructed by 2070, with design and construction costs equally distributed over the 20 year planning period (beginning in 2050).
- The barrier would be functional to approximately seven feet of sea level rise, or roughly 2130. After that period some additional means or significant modification to the barrier would likely be necessary to control flooding, as the closure analysis estimates that the gates would be required to close too frequently to continue functioning as intended (based on shoreline level of protection).

TABLE 8.10

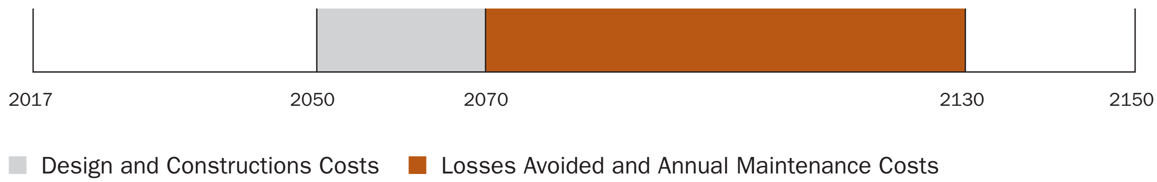
Sea Level Rise Timing Assumed in the Analysis

Sea Level Rise Scenario	Timing Assumed in Present Value Analysis
1-foot	2030
3-foot	2070
5-foot	2100

Source: Arcadis

FIGURE 8.2

Scenario 2. Barrier Construction Timeline and Functional Period Assuming Shore-Based Solutions Built to 14 NAVD88 by 2070



Source: Arcadis

The barrier system functional life is dependent on a number of assumptions and could possibly continue to provide benefits for less frequent events after the year 2100 for Scenario 1 and 2130 for Scenario 2.

For both scenarios, analysts estimated maintenance costs would be incurred annually, without escalation, over the expected functional life of the barrier. Losses avoided, or project benefits, are also discounted over this time period. Refer to Figure 8.2 for a visual example of how the economic analysis accounts for construction costs and project benefits over time (Scenario 2).

The barrier system functional life is dependent on a number of assumptions and could possibly continue to provide benefits for less frequent events after the year 2100 for Scenario 1 and 2130 for Scenario 2. The diminishing effectiveness of the barrier over time, as well as the possible residual benefits post-functional life have been acknowledged by the study team but have not been evaluated under the scope of this feasibility study. As such, this analysis does not consider those residual benefits expected after the end of the barrier's functional life. Furthermore, significant investment in an additional capital project would likely be required after the functional life of a barrier is complete and it would be misleading to include residual benefits of the barrier without also assuming there would be additional costs.

Annualized losses between 1 foot and 3 feet, and 3 feet and 5 feet of sea level rise are interpolated based on an assumed constant rate of increase in sea level between the years correlating to the sea level rise interval (2030, 2070, 2100). Flood losses were not calculated for 7 feet of sea level rise. As such, for Scenario 1, Harbor Barrier benefits are expected to begin in the year 2050; annualized losses avoided for that year are interpolated between 1 foot and 3 feet of sea level rise, with annualized losses avoided between the years 2050 and 2070 interpolated between those two time periods. For Scenario 2, the analysis assumes losses avoided would increase between the years 2070 and 2100, and, due to data limitations, remain constant between the years 2100 and 2130.

Effectiveness of Shore-Based Solutions

Estimating these benefits requires assumptions regarding the effectiveness of shore-based solutions. Analysts considered two scenarios for shore-based solution effectiveness:

EFFECTIVENESS OF SHORE-BASED SOLUTIONS SCENARIO A: TOTAL EFFECTIVENESS OF SHORELINE SOLUTIONS.

- Assumes that in the occurrence of a flood event greater than the shoreline adaptation level of protection (the equivalent of 12 or 14 feet NAVD88 at the Boston Harbor tide gauge), the shoreline solutions will perform perfectly and provide protection up to the design elevation (the equivalent of 12 or 14 feet NAVD88 at the Boston Harbor tide gauge). As such, the economic analysis captures only the incremental loss above the equivalent of 12 or 14 feet NAVD88 at the Boston Harbor tide gauge as benefits provided by a barrier alignment. This forms the lower bound of the range of potential benefits for the Harbor Barrier.

EFFECTIVENESS OF SHORE-BASED SOLUTIONS SCENARIO B: TOTAL FAILURE OF SHORELINE SOLUTIONS.

- Assumes that in the occurrence of a flood event greater than the equivalent of 12 or 14

feet NAVD88 at the Boston Harbor tide gauge with the barrier in place, the shoreline solutions will not perform and benefits of the Harbor Barrier would be similar to those if there were no shoreline protection solutions at all. This is the upper bound of the range of potential benefits for the Barrier.

Neither the upper nor the lower bound of the effectiveness scenarios are likely occurrences; nevertheless, the range is necessary because the effectiveness of the shore-based solutions is highly dependent on the nature of the solution, and these will vary across the study area landscape. The nature of loss is dependent on the behavior of the shore-based solution and the number of times overtopping occurs. It's important to note that the scenario assumes that shore–based solutions would not be adapted to higher levels of protection beyond the equivalent of 12 feet NAVD88 at the Boston Harbor tide gauge through 2100 or 14 feet NAVD88 at the Boston Harbor tide gauge through 2130 (depending on the selected Shore-Based Solutions and Construction Timeline Scenario). This also assumes total flood mitigation of the shoreline across the study area by the time the Harbor Barrier is in place. Current planning at the shore in South Boston, for example, is focused on designs that could be adapted in the future to the 1% annual chance exceedance probability event at 5 feet of sea level rise (approximately 15 ft. NAVD88), and this is not considered in the analysis.

Sensitivity Analysis Results

The sensitivity variables (shore-based solutions and construction timeline, discount rates, project cost estimates, shore-based solution effectiveness) combined with the potential of an Inner or Outer Harbor Barrier configuration present 32 scenarios of cost-effectiveness for a barrier solution. The cost-effectiveness scenarios provide a benefit-cost ratio (BCR) which divides the expected present value benefits by expected present value costs for a project. A BCR of one or above indicates a project's benefits outweigh its costs. Cost-effectiveness evaluation results for the 32 planning scenarios explored in this analysis are presented in Tables 8.11 to 8.14.

All scenarios consider the Harbor Barrier as a complementary of defense, using benefits solely attributable to the Barrier in managing events greater than assumed shoreline levels of protection. Potential cost effectiveness of the Harbor Barrier varies widely based on assumptions used. Results are very similar for both the IHB and the OHB. Under all the scenarios for the 7% discount rate except for one the benefit-cost ratio (BCR) is less than 1.0. The one exception is when it equals 1.05, the low cost estimate for the OHB, in place from 2050 to 2100 with ineffective shore-based adaptation. For the 3% discount rate,

TABLE 8.11

Present Value Analysis for Shore-Based Solutions and Construction Timeline Scenario 1 and Effectiveness of Shore-Based Solutions Scenario A

	7 Percent Discount Rate					3 Percent Discount Rate			
Barrier System	Cost Range	PV Costs	PV Benefits	Net PV	Benefit-Cost Ratio	PV Costs	PV Benefits	Net PV	Benefit-Cost Ratio
Outer Harbor Barrier	Low Estimate	$2.0 bil	$658 mil	–$1.4 bil	.33	$5.0 bil	$8.4 bil	$3.4 bil	1.69
	High Estimate	$3.0 bil	$658 mil	–$2.3 bil	.22	$7.3 bil	$8.4 bil	$1.1 bil	1.15
Inner Harbor Barrier	Low Estimate	$1.6 bil	$519 mil	–$1.1 bil	.32	$4.0 bil	$6.6 bil	$2.6 bil	1.65
	High Estimate	$2.2 bil	$519 mil	–$1.7 bil	.24	$5.4 bil	$6.6 bil	$1.2 bil	1.23

Note: The Present Value Analysis result for these eight planning scenarios assumes total effectiveness of shore-based solutions (incremental benefit of the Harbor Barrier) when flood elevations exceed the equivalent of 12 feet NAVD88 at the Boston Harbor tide gauge (4 flood event scenarios).

Source: Arcadis

TABLE 8.12

Present Value Analysis for Shore-Based Solutions and Construction Timeline Scenario 1 and Effectiveness of Shore-Based Solutions Scenario B

	7 Percent Discount Rate					3 Percent Discount Rate			
Barrier System	Cost Range	PV Costs	PV Benefits	Net PV	Benefit-Cost Ratio	PV Costs	PV Benefits	Net PV	Benefit-Cost Ratio
Outer Harbor Barrier	Low Estimate	$2.0 bil	$2.1 bil	$103 mil	1.05	$5.0 bil	$27 bil	$22 bil	5.42
	High Estimate	$3.0 bil	$2.1 bil	–$838 mil	.72	$7.3 bil	$27 bil	$19.7 bil	3.69
Inner Harbor Barrier	Low Estimate	$1.62 bil	$1.57 bil	–$56 mil	.97	$4.0 bil	$20 bil	$16 bil	4.28
	High Estimate	$2.2 bil	$1.57 bil	–$618 mil	.72	$5.4 bil	$20 bil	$14.6 bil	3.70

Note: The Present Value Analysis result for these eight planning scenarios assumes total failure of shore-based solutions when event elevations exceed the equivalent of 12 feet NAVD88 at the Boston Harbor tide gauge (4 flood event scenarios).

Source: Arcadis

the benefit:cost ratios are above or close to 1.0 when the shore-based adaptations are ineffective for storms greater than 14 feet NAVD88. If they are effective, the benefit:cost ratios are a maximum of 0.30. For the case of the shoreline adapted to 12 feet NAVD88, the benefit:cost ratios are greater than for the barrier constructed in 2070. They are actually all greater than 1.0 (1.15–1.69) if the shore-based systems are effective. If they are ineffective, the BCRs range from 3.69 to 5.42.

Since this analysis differs from Climate Ready Boston (2016) in both the approach and data used due to the size of the study area and project constraints, the expected benefits for some subareas of Boston in this analysis could be as much as 50 % less than the benefit values using the methodology of CRB (2106). Even if this was the case in all subareas, if shore-based adaptation is effective, the BCRs are still less than 1.0 in most cases.

While our scenario analysis captures much of the integrated nature of shore-based and harbor-wide solutions, a more detailed additional cost analysis might consider the entire flood protection system as a holistic system with multiple layers of defense and include a discussion of risk tolerance (see US Army Corps of Engineers, 2017). It is also not clear at this time to what extent the study area will receive shoreline solutions.

TABLE 8.13

Present Value Analysis for Shore-Based Solutions and Construction Timeline Scenario 2 and Effectiveness of Shore-Based Solutions Scenario A

		7 Percent Discount Rate				3 Percent Discount Rate			
Barrier System	Cost Range	PV Costs	PV Benefits	Net PV	Benefit-Cost Ratio	PV Costs	PV Benefits	Net PV	Benefit-Cost Ratio
Outer Harbor Barrier	Low Estimate	$521 mil	$41 mil	–$480 mil	0.08	$2.8 bil	$833 mil	–$2 bil	0.30
	High Estimate	$764 mil	$41 mil	–723 mil	0.05	$4.1 bil	$833 mil	–$3.3 bil	0.20
Inner Harbor Barrier	Low Estimate	$420 mil	$33 mil	–$387 mil	0.08	$2.3 bil	$680 mil	–$1.6 bil	0.30
	High Estimate	$566 mil	$33 mil	–$533 mil	0.06	$3.0 bil	$680 mil	–$2.3 bil	0.23

Note: The Present Value Analysis result for these eight planning scenarios assumes total effectiveness of shore-based solutions (incremental benefit of the Harbor Barrier) when flood elevations exceed the equivalent of 14 feet NAVD88 at the Boston Harbor tide gauge (4 flood event scenarios).

Source: Arcadis

TABLE 8.14

Present Value Analysis for Shore-Based Solutions and Construction Timeline Scenario 2 and Effectiveness of Shore-Based Solutions Scenario B

		7 Percent Discount Rate				3 Percent Discount Rate			
Barrier System	Cost Range	PV Costs	PV Benefits	Net PV	Benefit-Cost Ratio	PV Costs	PV Benefits	Net PV	Benefit-Cost Ratio
Outer Harbor Barrier	Low Estimate	$521 mil	$174 mil	–$347 mil	0.33	$2.8 bil	$3.5 bil	$733 mil	1.26
	High Estimate	$764 mil	$174 mil	–$591 mil	0.23	$4.1 bil	$3.5 bil	–$575 mil	0.86
Inner Harbor Barrier	Low Estimate	$420 mil	$135 mil	–$285 mil	0.32	$2.3 bil	$2.8 bil	$496 mil	1.22
	High Estimate	$566 mil	$135 mil	–$430 mil	0.24	$3.0 bil	$2.8 bil	-$285 mil	0.91

Note: The Present Value Analysis result for these eight planning scenarios assumes total failure of shore-based solutions when event elevations exceed the equivalent of 14 feet NAVD88 at the Boston Harbor tide gauge (4 flood events).

Source: Arcadis

Depending on the study area's risk tolerance, the combined benefits of the shoreline solutions and the barrier could be enough in the future to deem the integrated solution cost-effective, assuming that it is not possible to adapt shore-based solutions to satisfy the region's risk tolerance.

From the perspective of economic analysis, a future re-assessment of the Harbor Barrier should also incorporate the impacts of a range of rates of sea level rise; evaluate the residual benefits over time as barrier closure frequency inhibits potential effectiveness; and estimate the possible costs, benefits, and externalities of converting a harbor barrier to a lock system or to a system only closed during low frequency, high intensity events.

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US Army Corps of Engineers, 2017. Risk Assessment for Flood Risk Management Studies, ER 1105-2-101, 17 July.

US Army Corps of Engineers, (USACE, 2014). West Shore Lake Pontchartrain Hurricane and Storm Damage Risk Reduction Study, August.

9 *Impacts on Recreational and Commercial Harbor Use*

Commercial and recreational harbor uses are important to the economy and culture of the region.

The goal of this analysis is to understand the potential impacts of an Inner or Outer Harbor Barrier on recreational boating and fishing, as well as commercial shipping and fishing. These are not only the most common activities in the harbor, but are economically and culturally important to the city and region.

The main purposes of this analysis are to determine:

- the effects that a barrier might have on these selected human uses in Boston Harbor, and
- the extent to which a barrier could accommodate or disrupt the continuation of these uses.

The following analysis is an initial examination of how a barrier could affect these uses. We also identify additional future studies that are needed to understand the range of impacts in more detail.

Methodology

We employed a two-step methodology to determine the impacts of the two barrier options on human uses in Boston Harbor.

STEP 1: BASELINE DATA

We collected all available baseline data that depict existing usage and value for recreational boating and fishing, and commercial shipping and fishing. These data include the intensity and economic value of use when available. The baseline data are important for determining who is currently utilizing these waterways and to what extent, and how common uses could be impacted by a barrier. The baseline data also helped to identify key stakeholders for subsequent interviews in Step 2 of this methodology. We collected the baseline information from the following organizations and/or sources:

- Northeast Ocean Data Portal (including provided data from the 2012 Northeast Recreational Boater Survey, Automatic Tracking System (AIS), and National Marine Fisheries Service (NMFS))
- Massport
- Boston Harbor Now

STEP 2: INTERVIEWS, FOCUS GROUPS, AND BOOTH ENGAGEMENT

We conducted interviews and focus group discussions with identified user groups (e.g., commercial shippers and fishermen, recreational boaters and fishermen) and regulatory bodies/agencies (e.g., Massport, Metropolitan Area Planning Council) to determine how the potential barriers could impact the current uses that occur in the harbor. We also hosted a booth at the Massachusetts Marine Trades Association (MMTA) Business of Boating Conference in January 2018 to share details on the project and solicit additional feedback on a potential barrier from individual recreational boaters (75–100 recreational boaters were in attendance). During these discussions, we utilized the current baseline data to determine how the barrier could affect the continuation of those uses.

We conducted interviews and focus group discussions with identified user groups and regulatory bodies/agencies to determine how the potential barriers could impact the current uses that occur in the harbor.

Engaged parties in this analysis include:

- Recreational boaters
- Massachusetts Marine Trades Association
- Staff from Massport
- The Massport Port Operators Group
- The Metropolitan Area Planning Council
- United States Coast Guard
- Harbor pilots
- Commercial shipping stakeholders
- Fishing industry experts

Effects of an Outer Harbor Barrier on Current Human Uses in Boston Harbor

Stakeholders identified potential effects of an inner or outer harbor barrier, which include both the anticipated benefits and impediments of the uses described above. In general, all uses would likely experience greater protection from storms as a result of the Outer Harbor Barrier (OHB), because the barrier would cause less turbulent conditions within the harbor, and would reduce flooding and damage to docks and infrastructure. The Outer Barrier would provide this kind of protection to all of Boston Harbor.

If the barrier were closed, all vessels would not be able to enter or leave Boston Harbor, so most of these uses would be impacted by a closed barrier. That said, the influence during storms is expected to be limited since most vessels would not transit during stormy conditions. Additionally, vessels in search of refuge from a storm might seek out

Boston Harbor because of barrier protection. Vessels would need to be aware of when the barrier is closing, to allow time to enter or exit the harbor. This would require an operational system to inform local vessel traffic. Such a system should be integrated with the existing local vessel traffic management systems.

Below are the most recent baseline data we collected for commercial shipping and fishing, and recreational boating and fishing juxtaposed with expected impacts of an Outer Harbor Barrier.

COMMERCIAL SHIPPING

Boston Harbor is the region's largest commercial port. Martin Associates (2012) estimated that $4.6 billion of economic value (direct, indirect, and induced) was related to the activity at the Port of Boston. More than 1,600 businesses use the Port of Boston to import and export their projects. The main commercial shipping boats that utilize the harbor consist of: cargos, tug-tows, tankers, and passenger vessels (e.g., ferries, cruise ships). Below are the data provided by Boston Pilots for the number of foreign-flagged vessels and/or vessels over 350 tons from October 2016–September 2017 that visited Boston Harbor:

TABLE 9.1

Number of Foreign Flagged Vessels and/or Those Vessels Over 350 Tons from October, 2016–September, 2017 that Visited Boston Harbor

Type of Vessel	Number of Trips
Bulk	101
Bunkers only	2
Containership	183
Drydocking	3
Heavy Lift	2
LNG Carrier	29
Navy	5
Other	1
Passenger	146
PCC/PCTC	70
Research	1
Sail Training	13
Tankship	270
Tug	20
Yacht	38
Total	**884**

Source: UMass Boston Urban Harbors Institute

Additionally, 114 cruise ships entered Boston Harbor in 2016, ranging from 600 feet to 1,100 feet in length. Figures 9.2A–D display the density of commercial traffic for cargo (collected vessel movements), tanker, and passenger vessels in 2013 for areas around Boston Harbor.

IMPACT OF OUTER HARBOR BARRIER ON COMMERCIAL SHIPPING

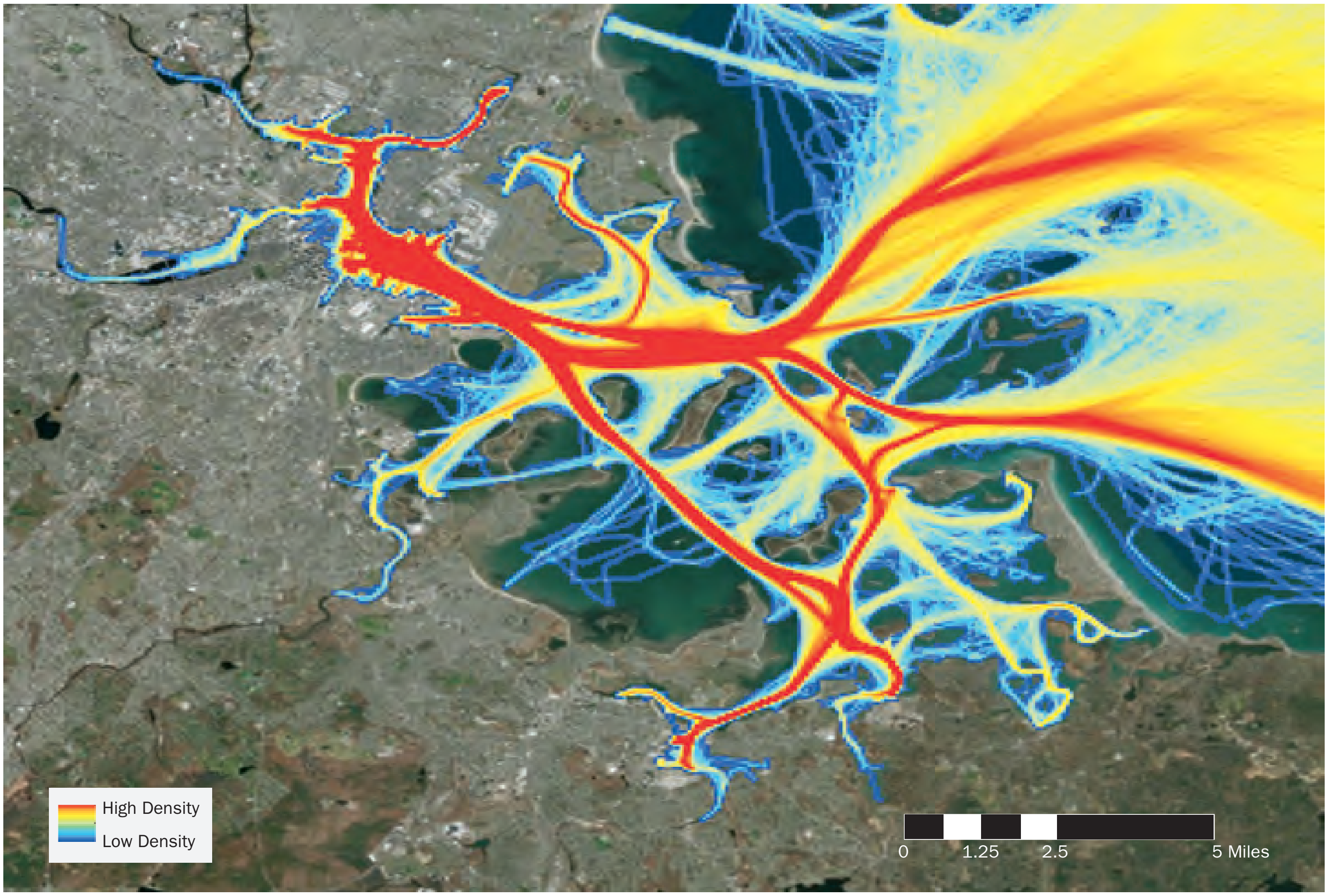
The barrier openings would be designed to accommodate the current main shipping lanes (as displayed by the baseline data) in and out of Boston Harbor. That said, the fairway design (i.e., width of the shipping lane) might need to be somewhat modified to ensure there is enough distance between the vessel and the barrier gates. This modification could slightly alter shipping times, and could require the use of guidance vessels for large tankers to ensure safe navigation.

The closing of the barrier could cause commercial traffic to transit away from Boston and to a different port, resulting in an economic loss (yet to be quantified). This would be critical if the barrier closes many times per year, but might be limited if closures only occur during extreme events when vessels would not be visiting.

Depending on the vessel size and type, the relatively large flow velocities through the barrier openings could impact the vessel's ability to navigate through the barrier openings, possibly leading to situations that are unsafe for the vessel and the barrier. Vessel traffic in and out of Boston Harbor is currently timed based on the tides, which would become even more important if the water velocity increases because of the barrier. A navigational study/stimulation for commercial ships should be conducted to better understand this impact.

The southern barrier opening would have a slightly greater velocity than the northern opening (5 knots compared to 3 knots) as it has a smaller opening, which could result in more vessel operators choosing the northern opening to enter and exit Boston Harbor. This might cause congestion between commercial ships and recreational vessels in the northern opening and safety/navigation issues. On the other hand, vessels could time their passage not to coincide with large flow velocities, which might or might not influence vessel congestion levels.

FIGURE 9.1
All Commercial Vessel Density In and Outside of Boston Harbor



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

COMMERCIAL FISHING

In general, commercial finfishing does not occur within Boston Harbor due primarily to shipping activity and shallow water depths. That said, a number of vessels land their fish in Boston Harbor. Specifically, the Boston Fish Pier is home to 11 seafood processing businesses and 22 fishing vessels, and in 2015, approximately 14 million pounds of commercial fish were landed in Boston Harbor, worth $16.2 million.

Figure 9.4 is a map that represents commercial fishing vessel activity for groundfish (e.g., scallops, monkfish, herring, surf clam/ocean quahog, squid, and mackerel).

Lobstering is the most common fishery that occurs within the Boston Harbor area, generally in the following locations (Massport and USACE, 2013):

- Mystic River
- Chelsea River
- Main Ship Channel (from Ted Williams Tunnel Seaward to Spectacle Island)
- Main Ship Channel (President Roads Anchorage and President Roads Ship Channel)
- Main Ship Channel (Broad South North Entrance Channel)

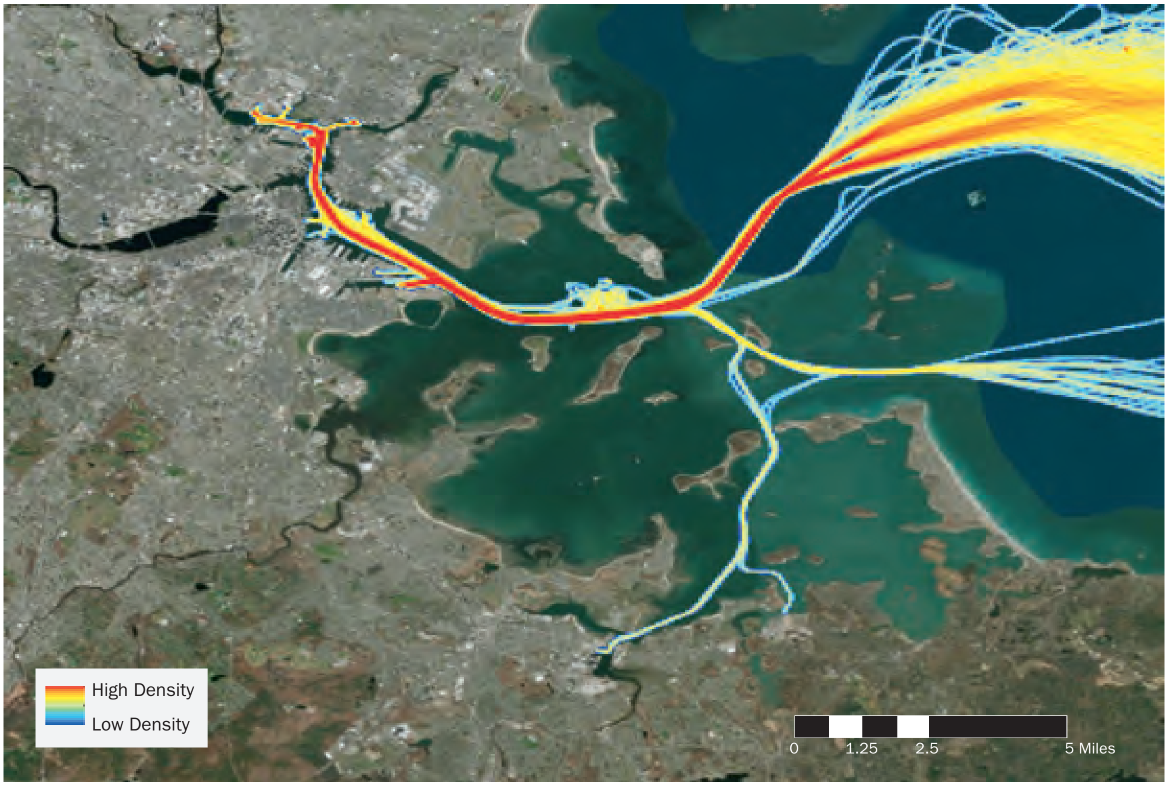
IMPACT OF OUTER HARBOR BARRIER ON COMMERCIAL FISHING

Any environmental changes as a result of the barrier (e.g., circulation, turbidity) could affect the health and/or distribution of lobsters and other fish that are harvested, thereby affecting the commercial fishing industry. Environmental changes and disruption might be a larger issue during the barrier construction phase (e.g., dredging, benthic disturbance) than during the operational phase.

The effects of the barrier on the behavior of lobsters and fish are unknown: they might gravitate towards the barrier (similar to fish populations

FIGURE 9.2A

2013 Cargo Vessel Density In and Outside of Boston Harbor

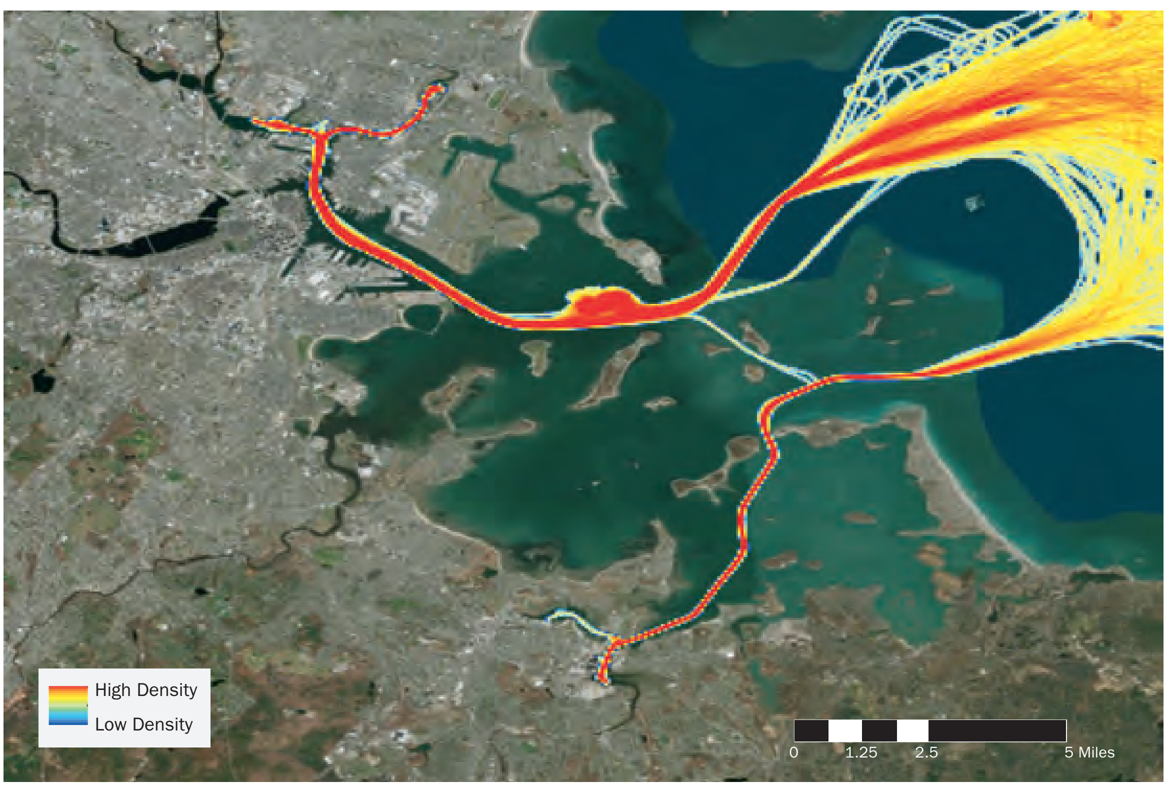


Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

The density and color scales are not uniform across figures 9.2A–9.2D.

FIGURE 9.2B

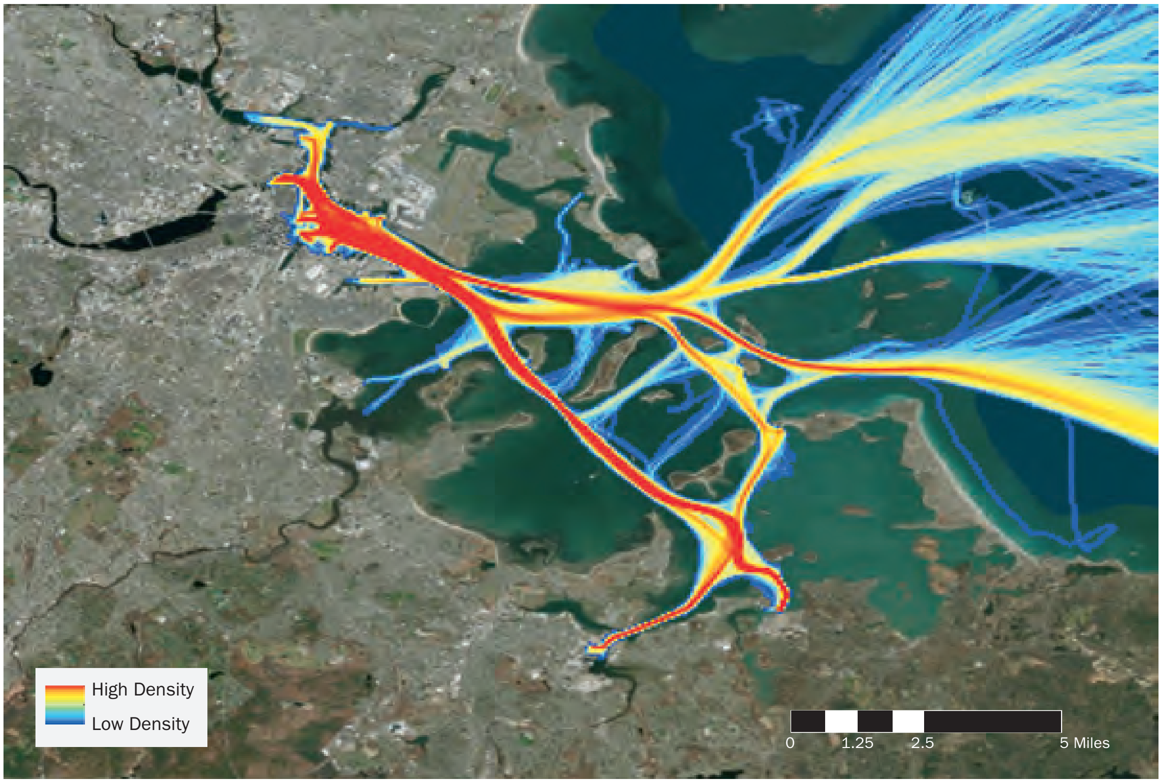
Tanker Vessel Density In and Outside of Boston Harbor



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

FIGURE 9.2C

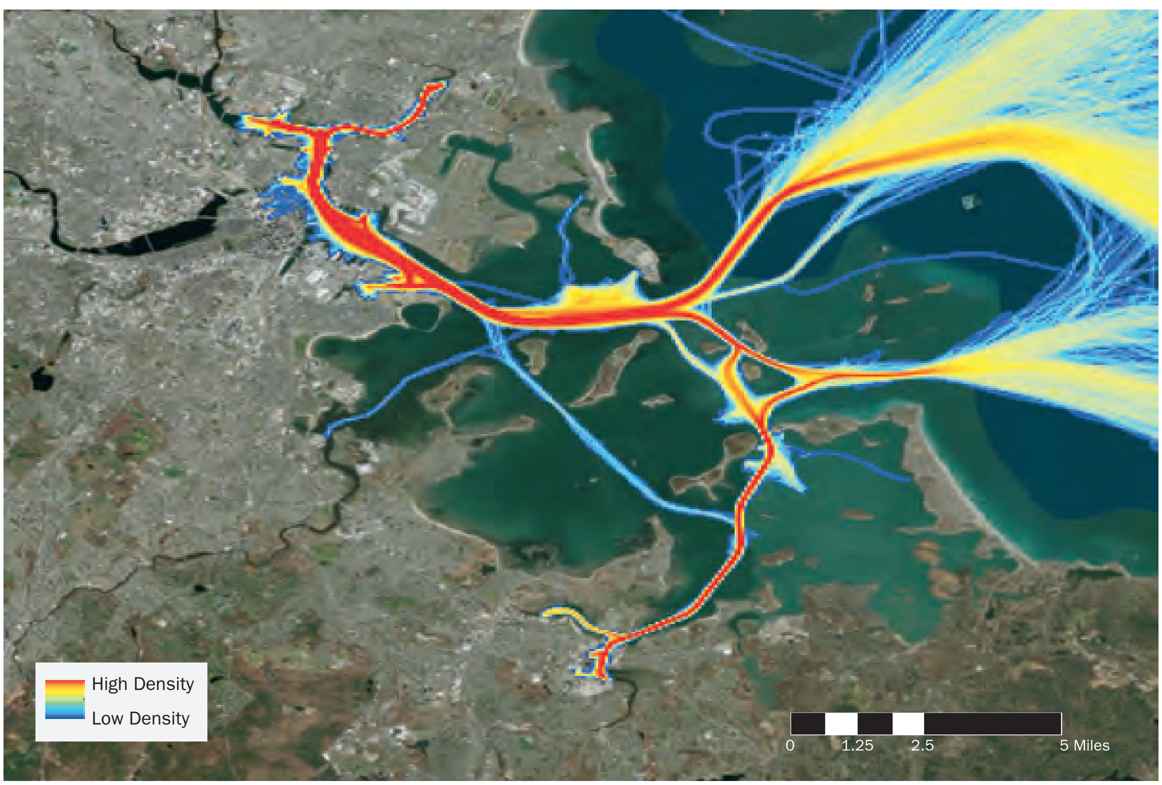
2013 Passenger Vessel Density In and Outside of Boston Harbor



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

FIGURE 9.2D

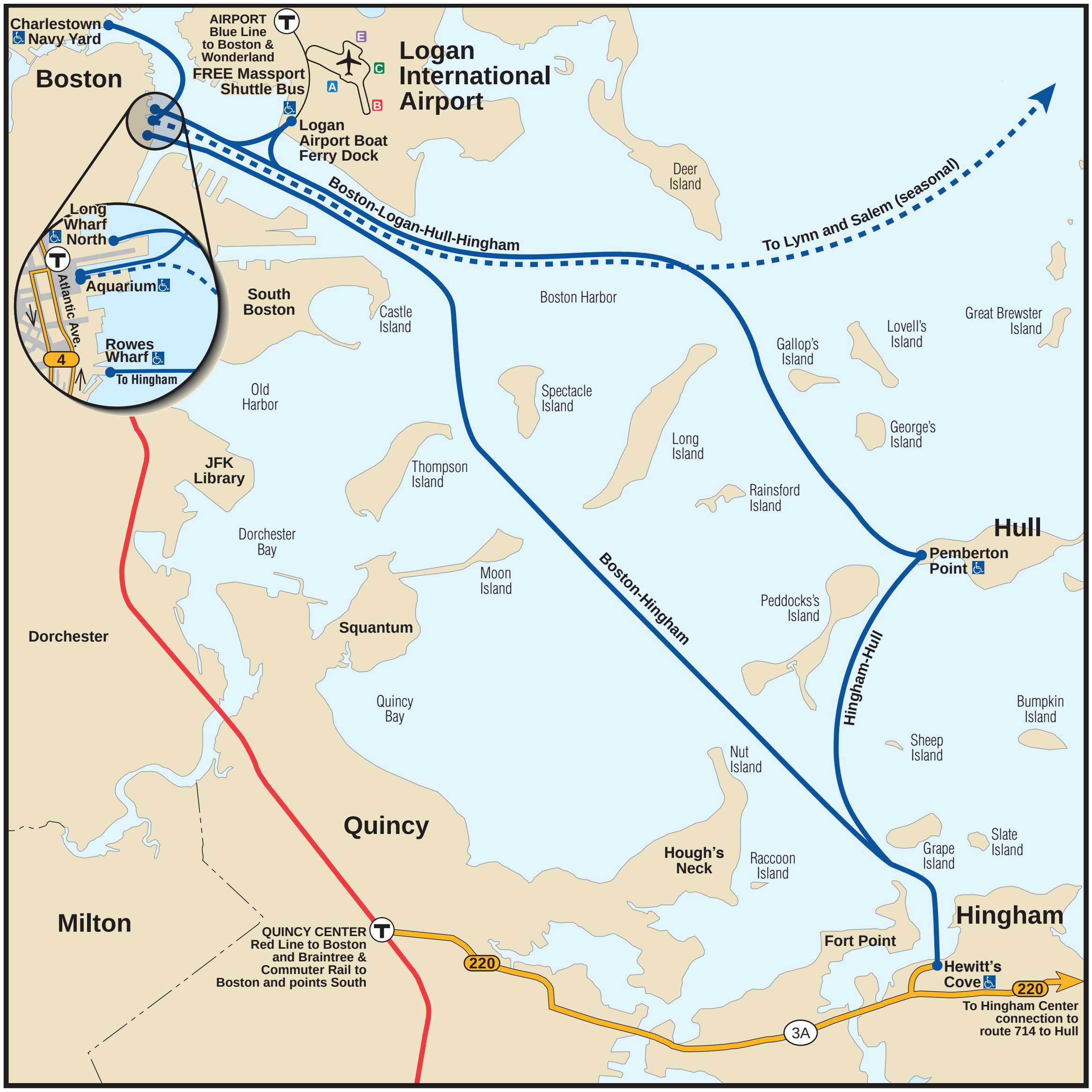
Tug Tow Density In and Outside of Boston Harbor



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

FIGURE 9.3

MBTA Commuter Boat Routes



Source: MBTA

that are attracted to wind turbines) or may be deterred by the barrier. Any changes in the behavior of these populations could impact the commercial fishing industry in positive or negative ways. Further analyses of similar structures elsewhere would be needed to reach concrete conclusions.

RECREATIONAL BOATING

There are 34 islands in the Boston Harbor Islands National and State Park, which attract over a half million visitors each year. Many recreational activities occur on or around these islands. From boating in its own right to swimming, picnicking, fishing, hiking, or camping on the islands, many in the region take advantage of Boston Harbor and the islands as a playground. Figure 9.5 shows some of these different activities that occur on the islands. Visitors can access the islands by ferry (routes are displayed in the map) or on their own boat. The ferries typically operate from May through October. Some ferries are more active than others, but they typically run at least a few times a day.

Additionally, there are other areas within the harbor that are used recreationally for boating. According to the Massachusetts boat registration list and the United States Coast Guard documented vessel list, in 2014, over 10,000 boats were registered in the communities surrounding Boston Harbor, or were listed by boaters as their vessel's documented home port, as can be seen in Table 9.2.

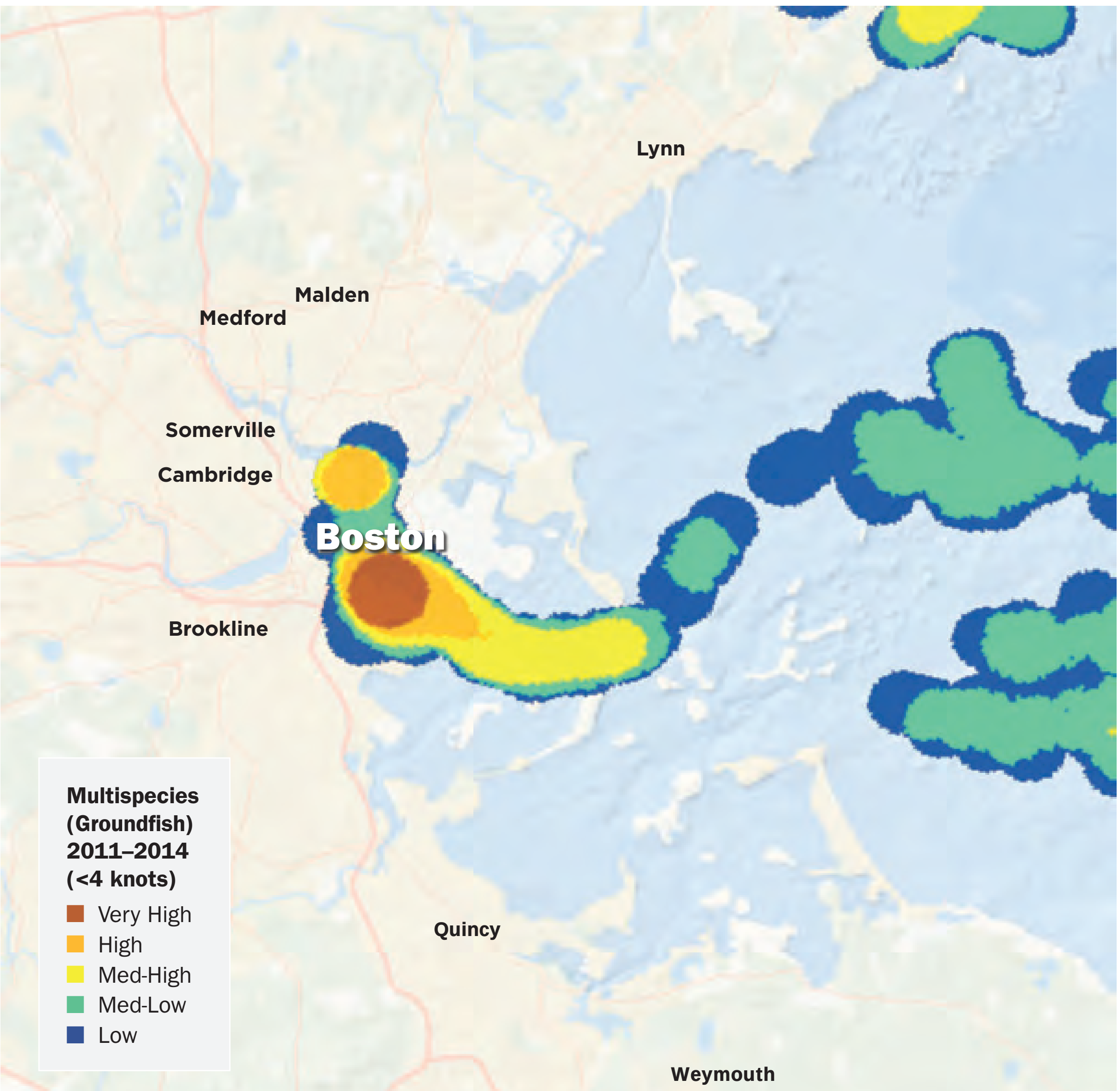
Data about recreational boating patterns and usage were collected through the 2012 Northeast Recreational Boater Survey, as displayed in the maps below (Starbuck et al., 2013). This survey sampled 12,000 recreational boaters in the Northeast and collected both economic and spatial data on recreational boating in the region. The yellow dots on the map below represent 55 boating facilities in Boston Harbor, including marinas, yacht clubs, community boating facilities, and others.

IMPACT OF OUTER HARBOR BARRIER ON RECREATIONAL BOATING

Depending on the size of the boat, the increase in water velocity could restrict recreational boat traffic through the barrier openings. Interviewees hypothesized that the increase in velocity to 4–5 knots would likely affect personal motor boats and sailboats and cause operational challenges. More analysis should be conducted to

FIGURE 9.4

Commercial Fishing Vessel Activity for Multispecies Groundfish In and Outside of Boston Harbor (2011–2014)



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Portal Group

FIGURE 9.5

Ferry Routes and Recreational Harbor Use

Sources: Boston Harbor Now, National Park Service, Massachusetts Department of Conservation and Recreation

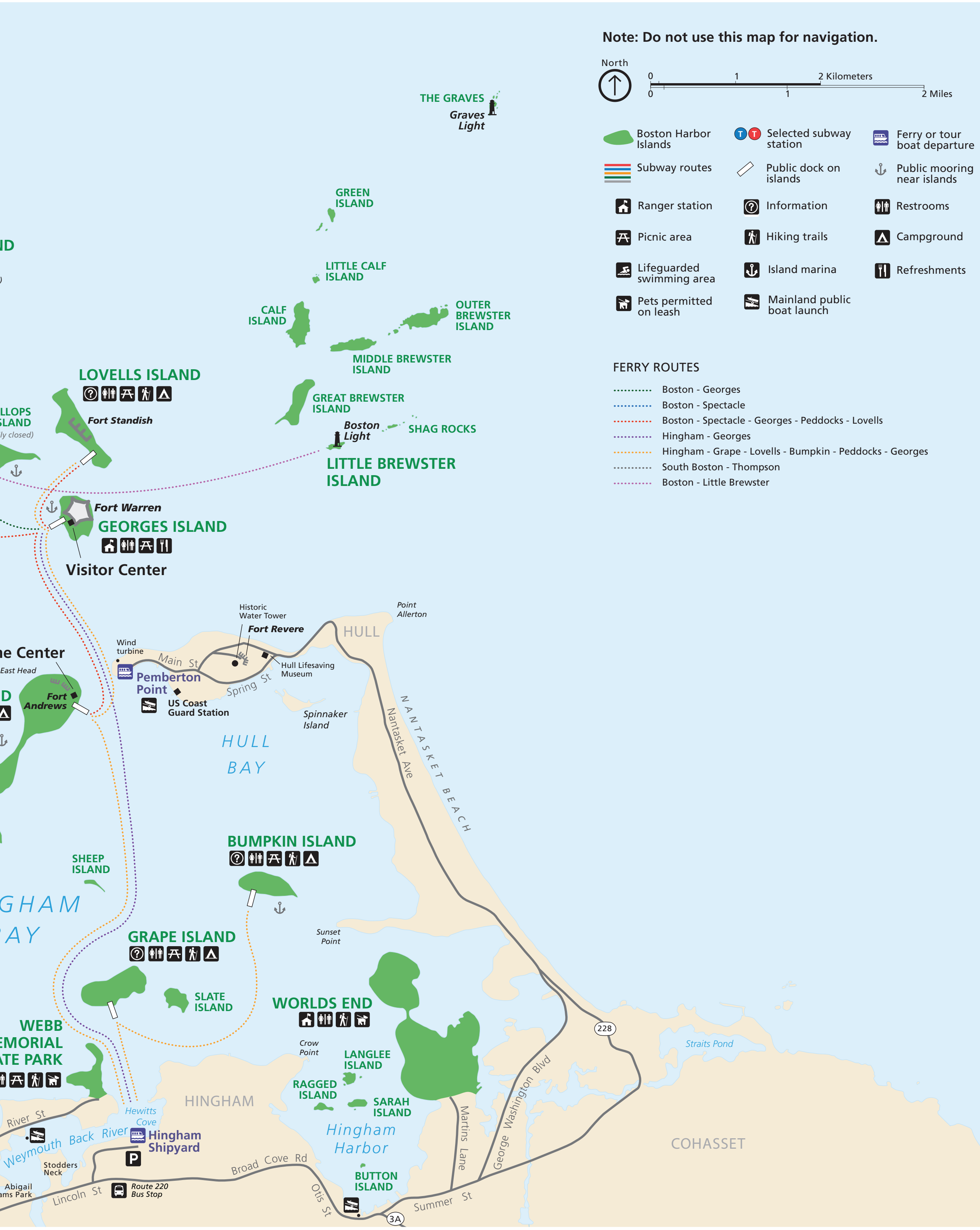

Note: Do not use this map for navigation.
North
0 1 2 Kilometers
0 1 2 Miles
Boston Harbor Islands
Selected subway station
Ferry or tour boat departure
Subway routes
Public dock on islands
Public mooring near islands
Ranger station
Information
Restrooms
Picnic area
Hiking trails
Campground
Lifeguarded swimming area
Island marina
Refreshments
Pets permitted on leash
Mainland public boat launch
FERRY ROUTES
Boston - Georges
Boston - Spectacle
Boston - Spectacle - Georges - Peddocks - Lovells
Hingham - Georges
Hingham - Grape - Lovells - Bumpkin - Peddocks - Georges
South Boston - Thompson
Boston - Little Brewster
THE GRAVES
Graves Light
GREEN ISLAND
LITTLE CALF ISLAND
CALF ISLAND
OUTER BREWSTER ISLAND
MIDDLE BREWSTER ISLAND
GREAT BREWSTER ISLAND
Boston Light
SHAG ROCKS
LITTLE BREWSTER ISLAND
LOVELLS ISLAND
Fort Standish
Fort Warren
GEORGES ISLAND
Visitor Center
Historic Water Tower
Fort Revere
Point Allerton
HULL
Wind turbine
Main St
Hull Lifesaving Museum
Pemberton Point
Spring St
US Coast Guard Station
Spinnaker Island
HULL BAY
NANTASKET BEACH
Nantasket Ave
East Head
Fort Andrews
BUMPKIN ISLAND
SHEEP ISLAND
GRAPE ISLAND
SLATE ISLAND
Sunset Point
WORLDS END
Crow Point
LANGLEE ISLAND
RAGGED ISLAND
SARAH ISLAND
WEBB MEMORIAL STATE PARK
HINGHAM
Hewitts Cove
Hingham Shipyard
River St
Weymouth Back River
Stodders Neck
Broad Cove Rd
Lincoln St
Route 220 Bus Stop
Otis St
BUTTON ISLAND
Hingham Harbor
Martins Lane
George Washington Blvd
Summer St
228
3A
Straits Pond
COHASSET

TABLE 9.2

Number of Boats Registered in Massachusetts

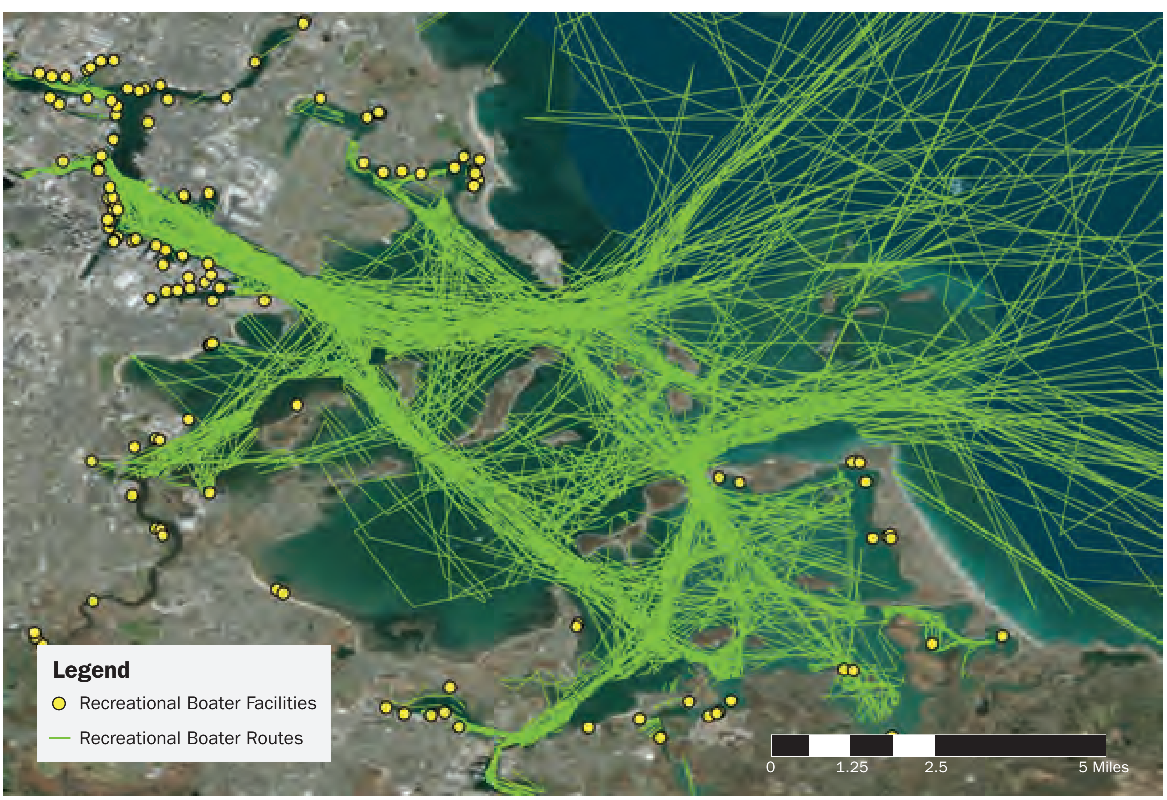
Size Vessel	Boston	Quincy	Winthrop	Hull	Cambridge	Hingham	Weymouth	Chelsea	Somerville
0–<16’	758	400	130	158	141	319	401	27	92
16–25’	1,049	658	29	233	157	650	514	36	107
26–40’	345	336	184	74	67	321	211	23	38
41–55’	7	26	18	1	7	33	11	2	0
56–75’									
76–90’								1	
TOTAL	**2,159**	**1,420**	**361**	**466**	**372**	**1,323**	**1,137**	**89**	**237**

Size Vessel	Brookline	Revere	Medford	Milton	Newton	Everett	Malden	Braintree	TOTAL
0–<16’	59	139	155	129	216	86	130	209	**3,549**
16–25’	96	140	191	209	276	89	108	308	**4,850**
26–40’	27	57	74	58	79	12	43	59	**2,008**
41–55’	3	3	9	2	3	0	1	2	**128**
56–75’									**—**
76–90’									**1**
TOTAL	**185**	**339**	**429**	**398**	**574**	**187**	**282**	**578**	**10,535**

Sources: UMass Boston Urban Harbors Institute, Massachusetts Boat Registration List, US Coast Guard Documented Vessel Database

FIGURE 9.6

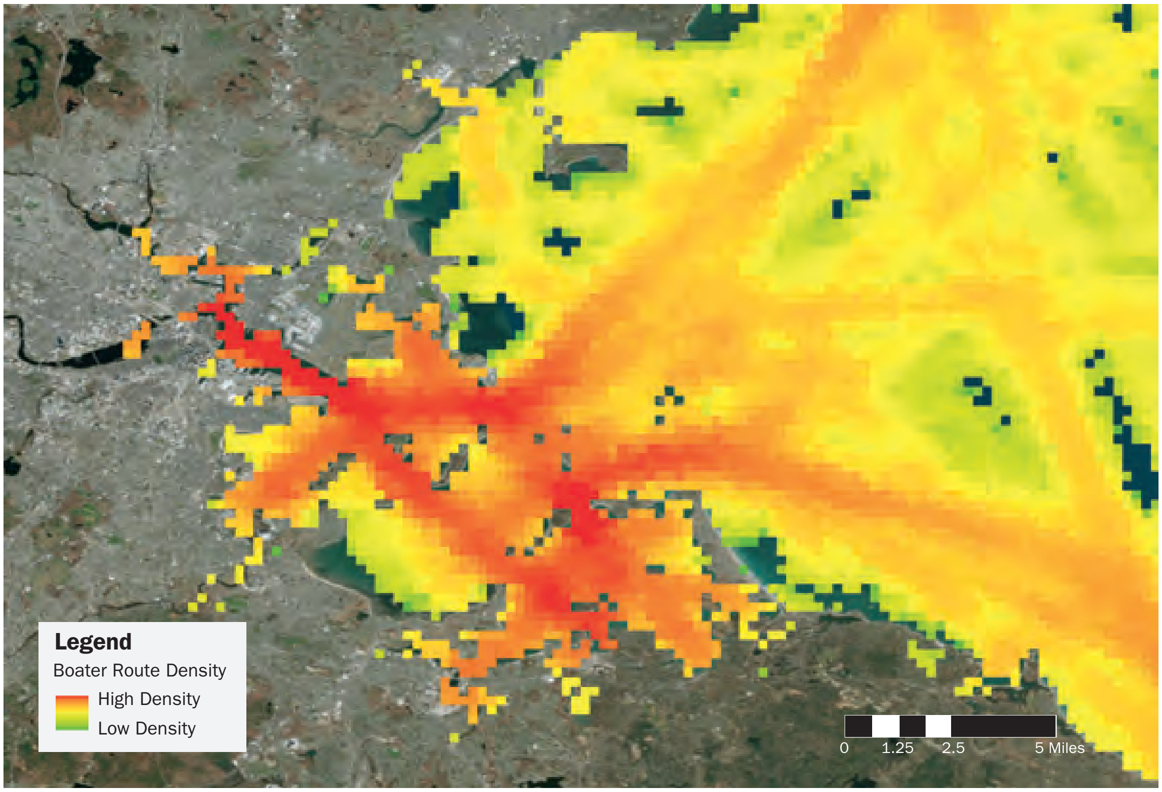
Recreational Boater Routes and Facilities In and Outside of Boston



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

FIGURE 9.7A

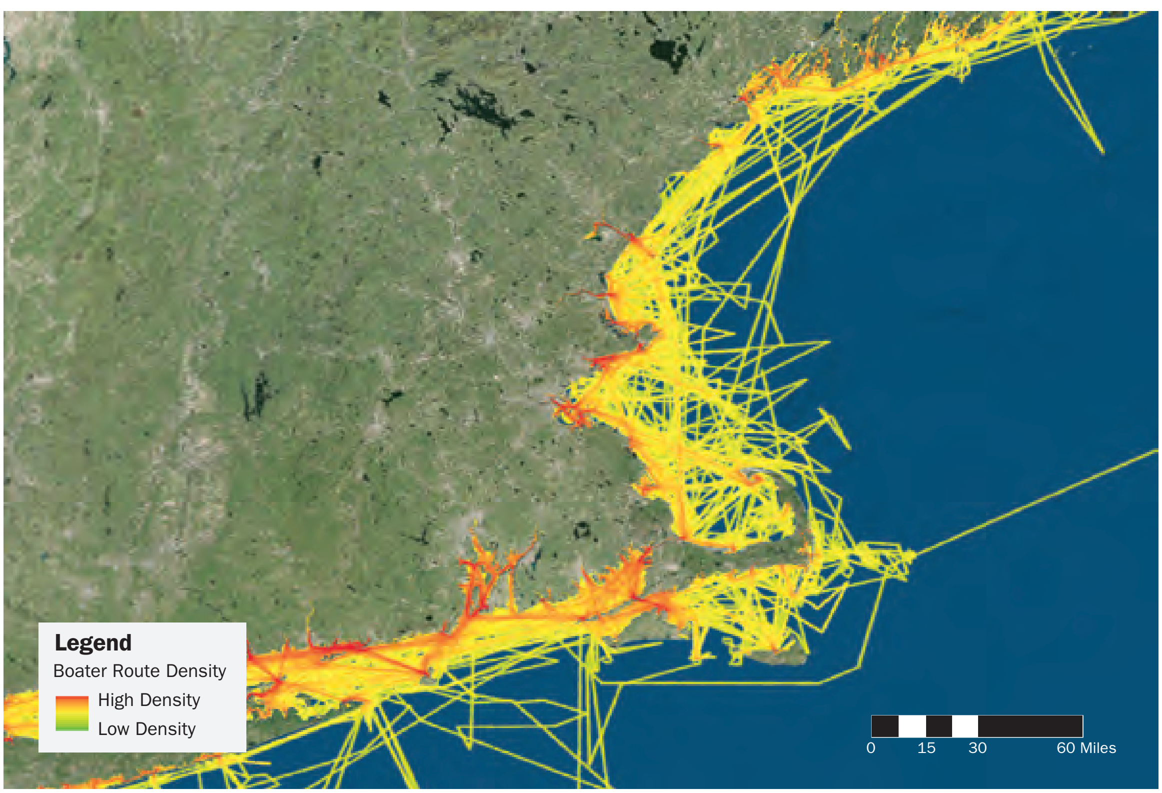
Recreational Boater Density in New England



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

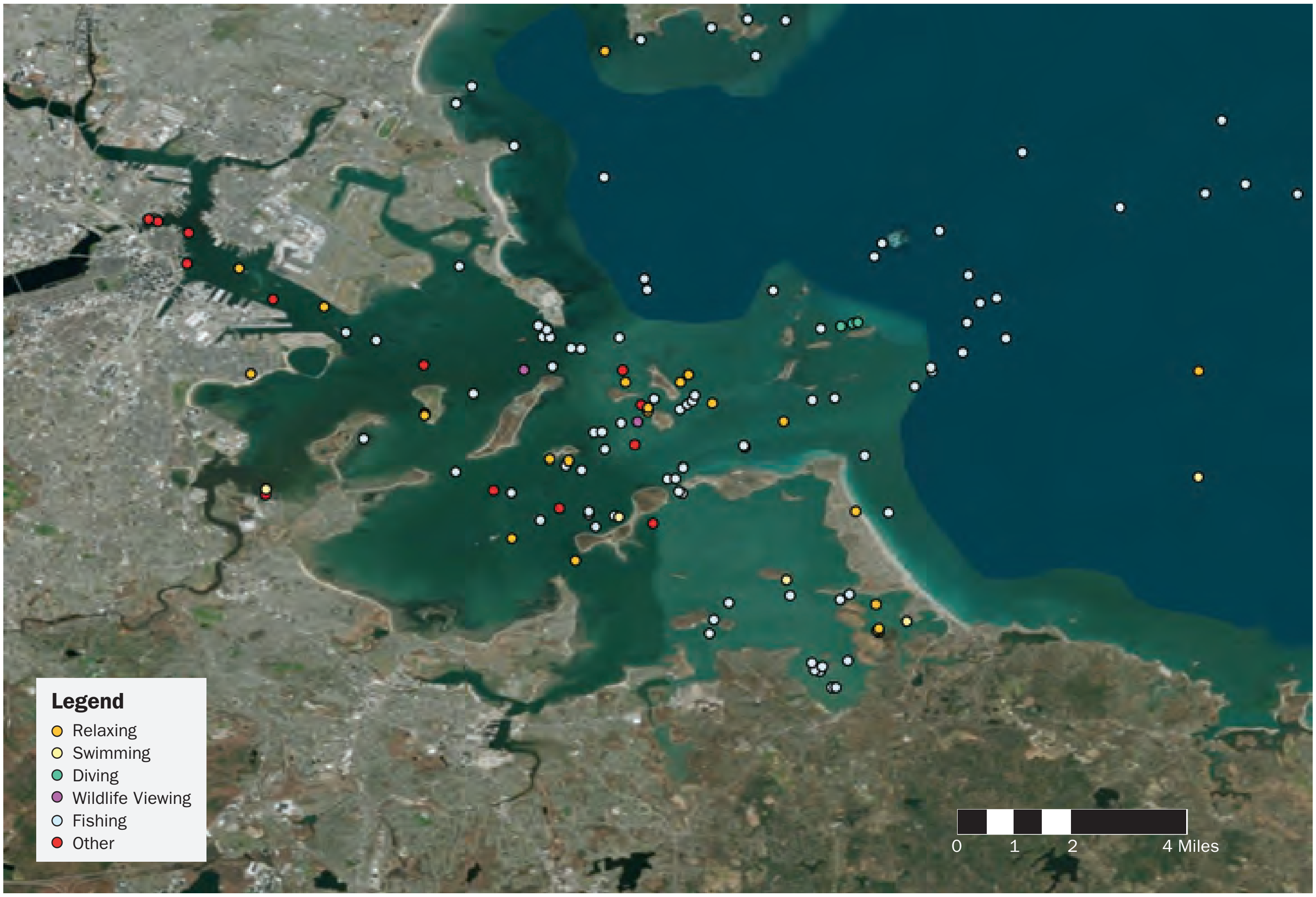
FIGURE 9.7B

Recreational Boater Density in New England



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

FIGURE 9.8
Recreational Activities In and Outside of Boston Harbor



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

determine the maximum current velocity tolerated by vessels.

The two barrier openings would be designed to accommodate the main navigational channels, which are the main routes used by recreational boaters to enter and exit Boston Harbor (as displayed by the baseline data). This would likely create minimal disruption to the main recreational boater routes. That said, recreational boaters often also navigate and recreate between the Boston Harbor Islands (especially between Georges and Gallops Islands). Given that the barrier would have only two openings, boaters would no longer be able to weave in and out of the islands, so their routes could be altered and recreational opportunities could change.

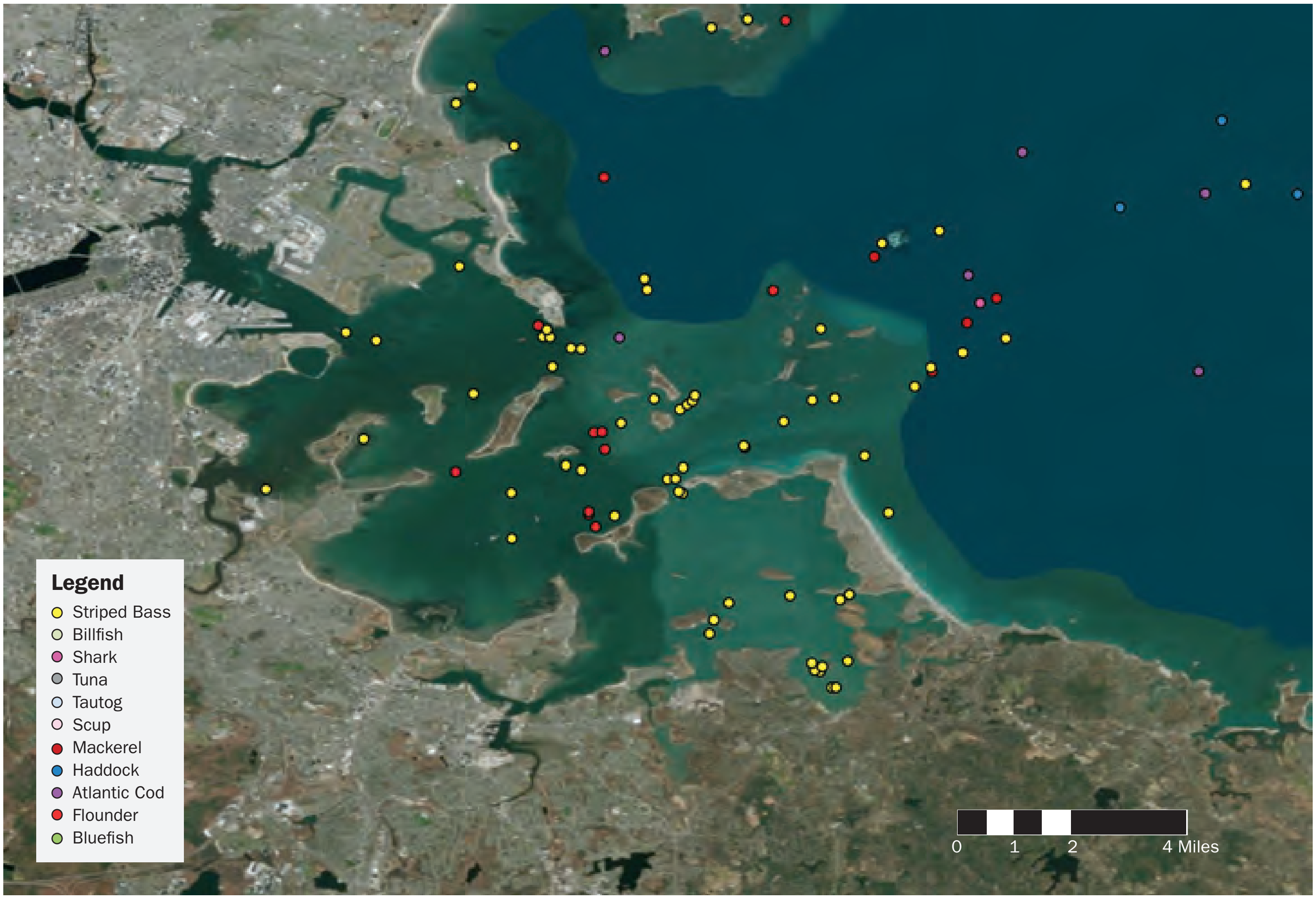
The greater velocity at the southern opening might cause more vessel operators to choose the northern opening to enter and exit Boston Harbor, leading to congestion and safety/navigation issues, similar to the concern mentioned above with commercial shipping. Vessels could time their passage not to coincide with large flow velocities, which may or may not influence vessel congestion levels.

Stakeholders also mentioned visual and aesthetic impacts that a barrier might have on harbor users. Given that the barrier could be upwards of 30 feet tall above present mean low water, scenic viewing could be impacted. On the other hand, the barrier could be an attraction and a welcomed sight to some boaters.

Recreational boaters were concerned that a barrier, if constructed, would reduce tidal exchanges and harbor flushing, thereby negatively impacting the water quality in Boston Harbor. Water quality is important to boaters for a variety of reasons, as boaters prefer to navigate on clean waters,

FIGURE 9.9

Fish Species Targeted while Regional Fishing In and Outside of Boston Harbor



Sources: UMass Boston Urban Harbors Institute, Northeast Ocean Data Portal

and some swim and/or fish off the vessels. See Section 6 for an analysis of potential water quality impacts.

RECREATIONAL FISHING AND OTHER ACTIVITIES

The 2012 Northeast Recreational Boater Survey also collected data on where recreational boaters took part in activities during their trip (e.g., fishing, diving, relaxing, wildlife viewing), and, if fishing, the type of fish targeted. Figure 9.8 displays where recreational activities occurred within Boston Harbor, with the green circles representing fishing locations.

Figure 9.9 shows the type of fish targeted while recreational fishing. The purple circles represent fishing for striped bass, which is the most common target fish species in this map. Note: The 2012 Northeast Recreational Boater Survey only captured a small percentage of

Recreational boaters were concerned that a barrier, if constructed, would reduce tidal exchanges and harbor flushing, thereby negatively impacting the water quality in Boston Harbor. Water quality is important to boaters for a variety of reasons, as boaters prefer to navigate on clean waters, and some swim and/or fish off the vessels.

recreational trips; therefore, these data only cover a portion of the activities and boating traffic.

IMPACT OF OUTER HARBOR BARRIER ON RECREATIONAL FISHING AND OTHER ACTIVITIES

Similar to commercial fishing, recreational fishing could be impacted by environmental changes that affect fish habitat, abundance, and distribution. Any changes in the fish populations (especially striped bass, as they are most often targeted for recreational purposes) may positively or negatively affect recreational fishing.

As seen from the baseline data, a number of recreational fishermen target fish near the planned openings to the barrier. As vessel traffic intensities may change near the barrier openings, recreational fishing may be disrupted, or may cause safety concerns. That said, recreational fishermen likely already avoid traffic lanes of the larger vessels. More research would be needed to determine recreational fishing use near the barrier openings, and any potential impacts.

Additionally, communities located on the outskirts of Boston Harbor (e.g., Hull, Winthrop) might experience impacts from the OHB, including increased wave energy. It is imperative that any future studies investigate how a barrier could impact these communities and how they utilize the ocean for commercial and recreational purposes.

Effects of an Inner Harbor Barrier on Current Human Uses in Boston Harbor

The anticipated effects outlined above for the OHB would likely be mostly similar for the Inner Harbor Barrier (IHB), with the following differences:

- If the IHB is closed, vessels would only be restricted from entering and leaving the downtown Boston area.
- Slightly increased water flow velocities at the entrance to the IHB due to the narrower opening may cause navigational concerns for vessels. More specifically, there are a number

of recreational sailing clubs near the entrance to the port, and an increase in water flow velocity could create safety concerns.

- The opening to the IHB would be slightly narrower than the current ship channel, which could create more congestion for commercial and recreational vessels transiting into and out of the Port of Boston.
- Few commercial and recreational fishermen operate near the planned location of an IHB. That said, fishermen vessels will still transit through the IHB opening, and would be impacted by its opening and closing and any water velocity changes (depending on the extent).

> We anticipate that the proposed barriers would provide added protection to human uses occurring within the harbor, including commercial shipping and fishing, and recreational boating and fishing, as they would protect shoreside infrastructure and vessels from storm turbulence and flooding.

Conclusions

Many commercial and recreational activities occur within Boston Harbor. This analysis determined that the proposed inner and outer harbor barriers could have both positive and negative impacts on these activities. Generally speaking, we anticipate that the proposed barriers would provide added protection to human uses occurring within the harbor, including commercial shipping and fishing, and recreational boating and fishing, as they would protect shoreside infrastructure and vessels from storm turbulence and flooding.

The study team chose configurations for the OHB and IHB that would minimize impact to current commercial and recreational uses of Boston Harbor. The openings to the barriers would generally accommodate the main federal navigation channels, minimizing impacts to commercial and recreational vessels entering and exiting Boston Harbor. That said, the barrier openings might be slightly narrower than the present day navigation channels, which could influence the fairways (e.g., widths) at those locations. Also, vessels would not be able to enter or exit when the barriers are closed, and would have to plan travel in advance of closing.

The anticipated increased water flow velocities in the barrier openings could cause navigational and safety issues for both recreational and commercial vessels near the barrier openings, but the extent is not yet determined. Additionally, there could be greater vessel congestion near the gates, especially at the northern barrier opening as its water velocity is expected to be more manageable than the southern barrier opening. The OHB could also impact the abundance, distribution, and/or behavior of fish populations, which could in turn impact both commercial and recreational fisheries.

These unknowns about a barrier's impacts on the uses of Boston Harbor would be important next questions to investigate should further studies be conducted on a potential harbor barrier.

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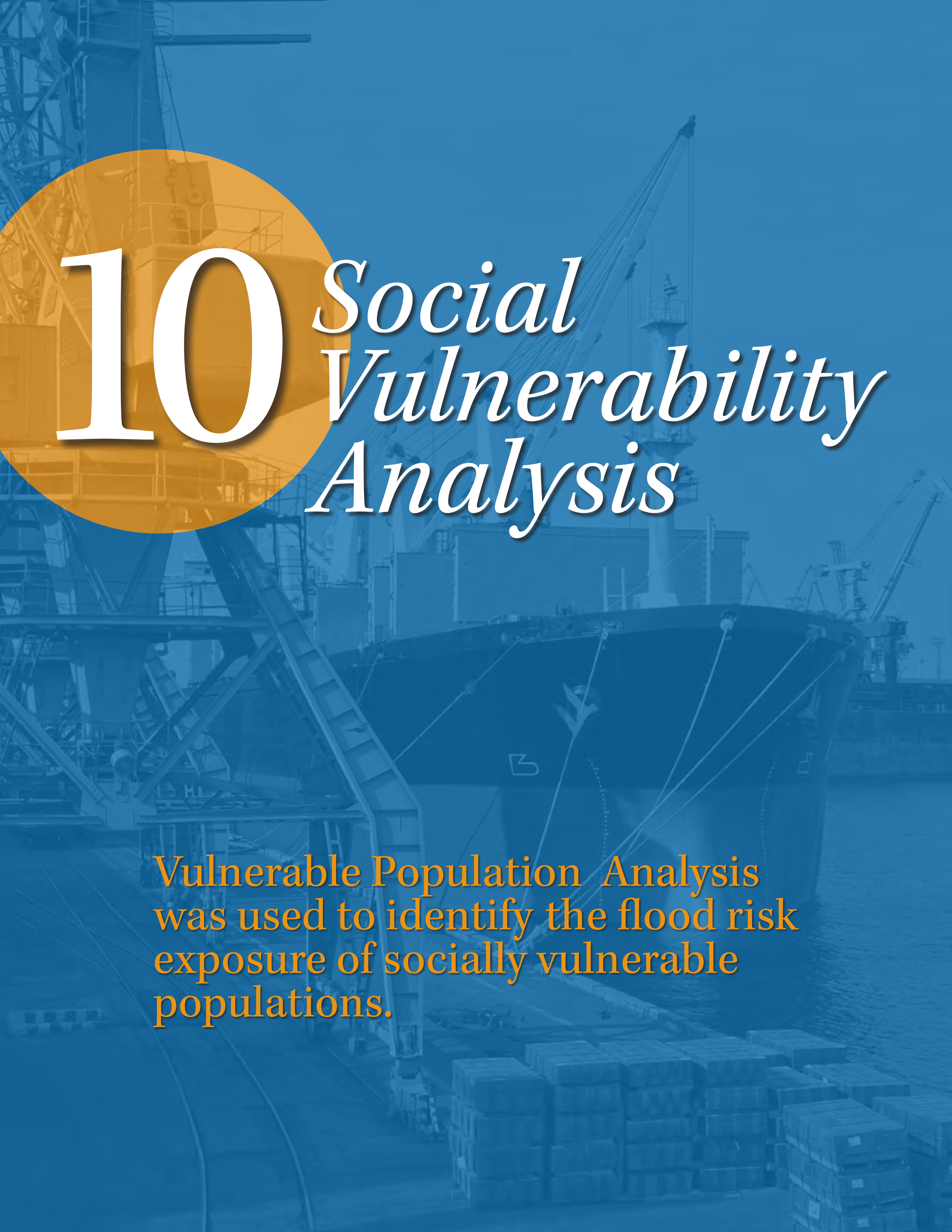


10 Social Vulnerability Analysis

Vulnerable Population Analysis was used to identify the flood risk exposure of socially vulnerable populations.

This analysis reports on populations in Boston Harbor municipalities benefiting from direct flood protection as a result of the two possible barrier alignments: the Outer Harbor Barrier (OHB), which stretches from Winthrop to Hull, and the Inner Harbor Barrier (IHB), from Logan Airport to the South Boston Waterfront.

The Vulnerable Populations Analysis considers two exposure categories:

- **People Exposed:** Considers the number of people who live in residential or mixed-use structures exposed to flood impacts and who would be protected by a barrier. The number of people exposed does not extend to those impacted by loss of service of transportation, energy, or water and wastewater services to avoid double-counting of exposure.
- **Vulnerable Populations:** Considers seven categories of vulnerable populations that may be exposed to flooding, including older adults, children, people of color, people with limited English proficiency, people with low or no incomes, people with disabilities, and people with medical illnesses.

Climate Ready Boston (2016) previously explored these seven categories. Vulnerable populations are not mutually exclusive, and one person can and often does meet multiple categories of social vulnerability.

Approach and Methodology for City of Boston

The Vulnerable Populations Analysis uses parcels exposed to flooding identified in the economic analysis to determine the location and concentration of residents in the City of Boston characterized by the seven social vulnerability factors. Data sources include:

- US 2010 Census population estimates per census tract,
- Parcel inventory, and
- Statistics on vulnerable populations as determined using U.S. Census and American Community Survey (ACS) data compiled by Dr. Atyia Martin.

The Vulnerable Populations Analysis has two steps: estimate the number of residents exposed to flooding at the 0 and 5-foot 1% annual chance event flood scenarios and who would be protected by a barrier, and identify the distribution of exposed residents among socially vulnerable populations.

EXPOSED RESIDENTS

We first identified exposed residents by estimating the number of residents per parcel throughout the study area, using the parcel inventory and US 2010 Census data provided by census tract. Note that this analysis did not use aggregated parcel information similar to the economic analysis, but rather used parcel-level information for building size and use. We estimated residential population per parcel by taking the following steps:

The Vulnerable Populations Analysis has two steps: estimate the number of residents exposed to flooding at the 0 and 5-foot 1% annual chance event flood scenarios and who would be protected by a barrier, and identify the distribution of exposed residents among socially vulnerable populations.

1. Assigned census tract to parcels.
2. Identified the total amount of residential space existing within a census tract. We identified residential and mixed-use parcels using structure use codes provided in the assessing data. For mixed-use parcels three stories tall or higher, we assumed that the first two floors are commercial space and did not include that square footage in the analysis.
3. Identified the total amount of residential space exposed within a census tract for the 1% annual chance event for 0 and 5-foot sea level rise scenarios, using parcels identified in the economic analysis. We followed the same approach to identify residential and mixed-use parcels, and their square footage, within the entire census tract to maintain consistency.
4. Divided the exposed residential square footage within a census tract by the total residential square footage in the census tract. This calculation yielded the percentage of residential square footage exposed to flooding.
5. Multiplied the percentage of residential area exposed by the total population within a building's census tract. This provides an estimate of the number of people exposed within a census tract.

VULNERABLE POPULATIONS

Dr. Atyia Martin's (former Chief Resilience Officer, City of Boston) vulnerable populations data reports

The aggregated results, based on residential structures in the area, highlight concentrations of various vulnerable populations within areas at risk of flooding that could possibly benefit from a harbor barrier system, and will serve to inform the applicability of various resilience initiatives.

the percentage of seven vulnerable populations who reside in a census tract for the City of Boston. Therefore, the Vulnerable Populations Analysis is executed with census-tract granularity. We applied the tract-specific percent population factor for each of the seven vulnerable populations to the total number of people identified as exposed in the census tract to the 1% annual chance event for the 0 and 5-foot sea level rise scenarios. This estimates the presence, distribution, and concentration of vulnerable populations exposed to coastal flooding throughout the City of Boston.

Results for the City of Boston

Table 10.1 presents the summary of vulnerable populations exposed to the 1% chance event for the 0 and 5-foot sea level rise scenarios within the City of Boston. As described later in this section, the methodology employed here has some limitations, and these results should only be viewed as indicative of the stresses that are faced by the population, perhaps not the actual numbers of people who are highly vulnerable. When reviewing exposure of vulnerable populations, it is also critical to consider that these categories are not mutually exclusive, and that one person may meet multiple categories of social vulnerabilities. Nevertheless, the aggregated results, based on residential structures in the area, highlight concentrations of various vulnerable populations within areas at risk of flooding that could possibly benefit from a harbor barrier system, and will serve to inform

TABLE 10.1

Vulnerable Populations Exposure, City of Boston, 1% Event (0 and 5-foot sea level rise scenarios)

Barrier System	SLR Scenario	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
Outer Barrier	0-feet*	6,450	2,430	1,040	560	630	1,980	3,570	2,740
	5-foot	151,460	59,010	17,430	14,240	14,410	50,880	62,100	59,260
Inner Barrier	0-feet*	6,050	2,270	970	500	580	1,900	3,430	2,590
	5-foot	142,190	55,380	15,900	13,090	13,300	48,970	58,860	56,000

*Analysts did not consider persons exposed to flooding inland of the metro area's three dams for the 0 and 1-foot sea level rise scenarios, as these are likely caused by rainfall and riverine flooding and will not be reduced by the Inner or the Outer Harbor Barrier.

Source: Arcadis

TABLE 10.2

Fraction of Population by Vulnerability Category

SLR Scenario	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
Outer								
0-feet*		0.38	0.16	0.09	0.10	0.31	0.55	0.42
5-foot		0.39	0.12	0.09	0.10	0.34	0.41	0.39
Inner								
0-feet*		0.38	0.16	0.08	0.10	0.31	0.57	0.43
5-foot		0.39	0.11	0.09	0.09	0.34	0.41	0.39
Total Pop % in Boston as a whole	617,516	0.38	0.17	0.10	0.11	0.29	0.53	0.39

Source: CRB (2016)

the applicability of various resilience initiatives. Refer to Appendix C for detailed results per neighborhood.

As can be seen, there are no large differences between the exposed populations protected by IHB and the OHB. This is partly explained by limitations in the analysis as well as by the protection the IHB would provide, not only to residents directly on the coast, but also to residents inland who are impacted by flood pathways originating on the coast, including many of the same areas in Boston protected by the OHB.

Table 10.2 shows the allocation of vulnerable populations (by fraction) who are exposed to flooding in a 1% chance event in the two sea level rise scenarios, compared to the total percentages of vulnerable populations in Boston regardless of living in a flooded area. As can be seen, there were no significant differences in the proportion of exposed populations in flooded areas compared to Boston as a whole.

Assumptions and Limitations

This analysis employs a different methodology than that used by Climate Ready Boston (2016); thus, the exposed populations identified through each analysis vary. Each analysis uses different structure inventory information, and the Climate Ready Boston analysis identified the number of residents per structure exposed to flooding based on an average square footage per person, which results in higher estimates of exposed residents. However, neither analysis includes a review of people who work or visit areas exposed to flooding. Furthermore, while it is reasonable to assume that residents of structures exposed to flood risk will also be exposed to system outages such as public transportation and essential services

> While it is reasonable to assume that residents of structures exposed to flood risk will also be exposed to system outages such as public transportation and essential services including energy, water, and wastewater, this analysis does not consider impacts to people who live outside of flood inundation zones but are affected by interruption of those services.

> This analysis did not look at different factors that would allow socially vulnerable populations to recover from a storm or take into account the disparate challenges that different groups have after an emergency event.

including energy, water, and wastewater, this analysis does not consider impacts to people who live outside of flood inundation zones but are affected by interruption of those services. Therefore, this analysis of exposed populations may be considered conservative. Estimated populations exposed to the 1% annual chance event with 5 feet of sea level rise are also conservative, as the analysis considers a static population and does not account for future development and population growth.

The Vulnerable Populations Analysis is completely dependent upon the exposed population generated in the economic analysis and data provided by Dr. Atyia Martin. All assumptions that apply to those studies also apply to this analysis.

Each social vulnerability category is not mutually exclusive, and one person can be represented in multiple categories. The vulnerable populations analysis is not meant for use in determining the total number of socially vulnerable people exposed to coastal flooding, but instead to identify the locations and concentrations of such populations in the context of risk areas.

Other Boston Harbor Municipalities

We conducted a separate social vulnerability analysis for towns and cities surrounding the City of Boston including Revere, Winthrop, Chelsea, Cambridge, Everett, Somerville, Milton, Malden, Medford, Quincy, Braintree, Hingham, and Hull. The analysis utilized the same methodology as used for the City of Boston.

We obtained U.S. Census and ACS data from 2010–2014 for the same categories as Boston except for medical illness which was not accessible.

For each census tract, we determined the number of exposed residents for the 2013 1% chance flood event (0 feet SLR) and 2100 (5 feet SLR). Utilizing the Census and ACS data from 2010–2014 on vulnerable populations, we then applied the tract-specific percent population factor for each of the six vulnerable populations to the total number of exposed residents in the census tract to estimate the presence of vulnerable populations exposed to coastal flooding.

RESULTS

The tables below, based on residential structures in the area, convey concentrations of various vulnerable populations within areas at risk of coastal flooding (for 0 feet and 5 feet SLR) that could possibly benefit from a harbor barrier system. Table 10.3 contains the results for all cities and towns in the study area (combined), while Tables 10.4 to 10.7 display the results by city and town. When reviewing exposure to vulnerable populations, it is important to note that these categories are not mutually exclusive, and that one person may meet multiple categories of social vulnerability.

This analysis did not look at different factors that would allow socially vulnerable populations to recover from a storm or take into account the disparate challenges that different groups have after an emergency event. Instead, the focus was on exposure to flooding caused by storm events.

REFERENCES

Climate Ready Boston, 2016. Final Report, City of Boston, December.

TABLE 10.3

Vulnerable Populations Exposure, Cities and Towns Surrounding City of Boston Combined, 1% Event (0 and 5-foot sea level rise scenarios)

Barrier System	SLR Scenario	Total Persons Exposed*	Number of Vulnerable People Exposed					
			Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
Outer Barrier	0-feet	26,250	4,601	4,129	3,185	4,636	6,232	3,314
	5-foot	140,840	28,640	16,714	12,641	26,642	53,026	23,309
Inner Barrier	0 feet	4,250	996	460	532	1,232	1,320	1,217
	5-foot	98,560	19,780	9,941	8,674	19,521	39,622	15,984

* Number of vulnerable and non-vulnerable persons exposed

Source: UMass Boston Urban Harbors Institute

TABLE 10.4

Vulnerable Populations Exposure by City and Town for the Outer Barrier, 1% Event (0-feet sea level scenario)

Town	County	Total Persons Exposed*	Number of Vulnerable People Exposed					
			Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
Revere	Suffolk	2,490	527	281	359	660	797	705
Winthrop	Suffolk	5,500	1160	845	575	686	350	315
Chelsea	Suffolk	1,320	391	99	118	485	499	479
Everett	Middlesex	0	0	0	0	0	0	0
Somerville	Middlesex	10	1	1	1	1	1	1
Milton	Norfolk	350	106	49	21	20	25	8
Quincy	Norfolk	9,840	2,002	1,632	1,241	2,018	2,892	1,648
Braintree	Norfolk	30	8	5	3	4	5	2
Hingham	Plymouth	1,460	406	238	119	114	70	26
Hull	Plymouth	5,250	0	979	748	648	1,593	130
TOTAL		26,250	4,601	4,129	3,185	4,636	6,232	3,314

* Number of vulnerable and non-vulnerable persons exposed

Source: UMass Boston Urban Harbors Institute

TABLE 10.5

Vulnerable Populations Exposure by City and Town for the Inner Barrier, 1% event (0-feet sea level scenario)

Town	County	Total Persons Exposed*	Number of Vulnerable People Exposed					
			Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
Revere	Suffolk	2,470	523	279	357	655	790	700
Winthrop	Suffolk	450	82	81	57	90	30	37
Chelsea	Suffolk	1,320	391	99	118	485	499	479
Everett	Middlesex	0	0	0	0	0	0	0
Somerville	Middlesex	10	1	1	1	1	1	1
Milton	Norfolk	0	0	0	0	0	0	0
Quincy	Norfolk		0	0	0	0	0	0
Braintree	Norfolk	0	0	0	0	0	0	0
Hingham	Plymouth	0	0	0	0	0	0	0
Hull	Plymouth	0	0	0	0	0	0	0
TOTAL		4,250	996	460	532	1,232	1,320	1,217

* = Number of vulnerable and non-vulnerable persons exposed

Source: UMass Boston Urban Harbors Institute

TABLE 10.6

Vulnerable Populations Exposure by City and Town for the Outer Barrier, 1% Event (5-feet sea level scenario)

Town	County	Total Persons Exposed*	Number of Vulnerable People Exposed					
			Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
Revere	Suffolk	6,960	1,352	809	906	1,939	1,993	2,003
Winthrop	Suffolk	8,950	1,813	1,415	110	1,297	611	550
Chelsea	Suffolk	7,920	2,094	644	919	2,548	4,967	3,449
Everett	Middlesex	4,150	997	459	462	959	1,864	1,372
Somerville	Middlesex	8,730	1,509	840	756	1,451	3,155	1,641
Cambridge	Middlesex	43,930	8,453	3,845	2,951	8,411	17,860	3,929
Malden	Middlesex	10,310	2,408	1,168	1,137	2,335	5,566	3,274
Medford	Middlesex	16,480	3,139	2,162	1,433	2,077	4,584	2,253
Milton	Norfolk	450	136	63	27	26	32	11
Quincy	Norfolk	23,540	4,742	3,635	2,771	4,584	8,225	4,597
Braintree	Norfolk	460	124	80	47	42	59	31
Hingham	Plymouth	2,590	721	421	210	202	125	46
Hull	Plymouth	6,370	1,152	1,173	912	771	3,985	153
TOTAL		140,840	28,640	16,714	12,641	26,642	53,026	23,309

* Number of vulnerable and non-vulnerable persons exposed

Source: UMass Boston Urban Harbors Institute

TABLE 10.7

Vulnerable Populations Exposure by City and Town for the Inner Barrier, 1% Event (5-feet sea level scenario)

Town	County	Total Persons Exposed*	Number of Vulnerable People Exposed					
			Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
Revere	Suffolk	5,440	1,026	620	906	1,567	1,568	1,586
Winthrop	Suffolk	880	154	153	110	173	58	69
Chelsea	Suffolk	7,920	2,094	644	919	2,548	4,967	3,449
Everett	Middlesex	4,150	997	459	462	959	1,864	1,372
Somerville	Middlesex	9,450	1,509	840	756	1,451	3,155	52
Cambridge	Middlesex	43,930	8,453	3,895	2,951	8,411	17,860	3,929
Malden	Middlesex	10,310	2,408	1,168	1,137	2,335	5,566	3,274
Medford	Middlesex	16,480	3,139	2,162	1,433	2,077	4,584	2,253
Milton	Norfolk	0	0	0	0	0	0	0
Quincy	Norfolk	0	0	0	0	0	0	0
Braintree	Norfolk	0	0	0	0	0	0	0
Hingham	Plymouth	0	0	0	0	0	0	0
Hull	Plymouth	0	0	0	0	0	0	0
TOTAL		98,560	19,780	9,941	8,674	19,521	39,622	15,984

* Number of vulnerable and non-vulnerable persons exposed

Source: UMass Boston Urban Harbors Institute

11 *Comparison to Shore-Based Adaptation*

The benefits of a Harbor Barrier should be compared to shore-based adaptation strategies to understand the options the region has for the future.

The prospect of a harbor-wide barrier for Boston raises the question of how such a structure would fit into the city's larger long-term goals and strategies of climate resilience planning. Climate Ready Boston (CRB) is the City of Boston's initiative to begin preparing for future impacts of climate change and develop resilient solutions for the city. A city-wide report (CRB, 2016) suggests five principles for climate resilience planning:

1. Generate Multiple Benefits
2. Incorporate Local Involvement in Design and Decision-Making
3. Create Layers of Protection by Working at Multiple Scales
4. Design in Flexibility and Adaptability
5. Leverage Building Cycles

The report also outlines layers and specific strategies for directing efforts toward climate change planning. Promoting social justice and income equality are also among the important adaptation planning goals embedded in the principles and in Layer 2: Prepared and Connected Communities. The recent report Resilient Boston (City of Boston, 2017) also recommends that the City "develop neighborhood-based climate resilience plans that benefit households citywide and promote environmental justice" as part of an overall goal to have a "Connected, Adaptive City."

Here we investigate shore-based adaptation strategies compared to harbor-wide barrier systems assuming all municipalities in the harbor implement shore-based strategies. Shown in Figure 11.1 from CRB (2016) are examples of a variety of physical and policy shore-based adaptation actions that can be employed under the general categories of protection, accomodation, and retreat actions using green and gray, engineered and policy strategies. One of these strategies is "District-scale flood protection" which, according to CRB (2016),

> "are infrastructure investments at or near the waterfront that can reduce flood risk for a specific area within Boston. In each case, some type of flood barrier would need to be constructed, connecting two points of high ground in order to reduce flood risk in low-lying areas. Generally, these defenses would be more cost effective in narrow low-lying areas where floodwaters can enter and inundate large inland areas and less cost-effective in broad, low-lying exposed areas."

Thus, we consider district-scale solutions as one option of a shore-based adaptation strategy.

The shore-based solutions can be employed at the regional scale or the individual asset scale, and if designed correctly, can provide multiple layers of effectiveness and safety. In addition, they can provide management of high tide nuisance flooding—which harbor-wide barriers do not. Most of these adaptation strategies also provide many co-benefits such as recreation, access, open-space, and urban heat island cooling. These co-benefits may be particularly important in communities suffering from environmental and social injustice. Harbor-wide barrier systems may provide considerably fewer co-benefits (example limited co-benefits are possible increases in habitat and less wave damage and erosion) and, in fact, given the high costs, impacts on harbor users described in Section 9, and other impacts on the environment, might actually result in maladaptation for some sectors—meaning they could actually increase the negative impacts of climate change on some sectors.

We consider district-scale solutions as one option of a shore-based adaptation strategy. The shore-based solutions can be employed at the regional scale or the individual asset scale, and if designed correctly, can provide multiple layers of effectiveness and safety.

Another advantage of the shore-based solutions is that they provide a flexible, adaptive management approach to coastal protection where management responses can be implemented over time as SLR and flooding increases. The responses may include policy measures such as zoning and building codes, augmenting flood proofing of individual buildings or entire properties, adding elevation to floodwalls or berms so that they will provide more protection, deploying temporary flood barriers that can be installed in advance of impending floods, and, as a last resort, relocating structures or undertaking a full "managed retreat."

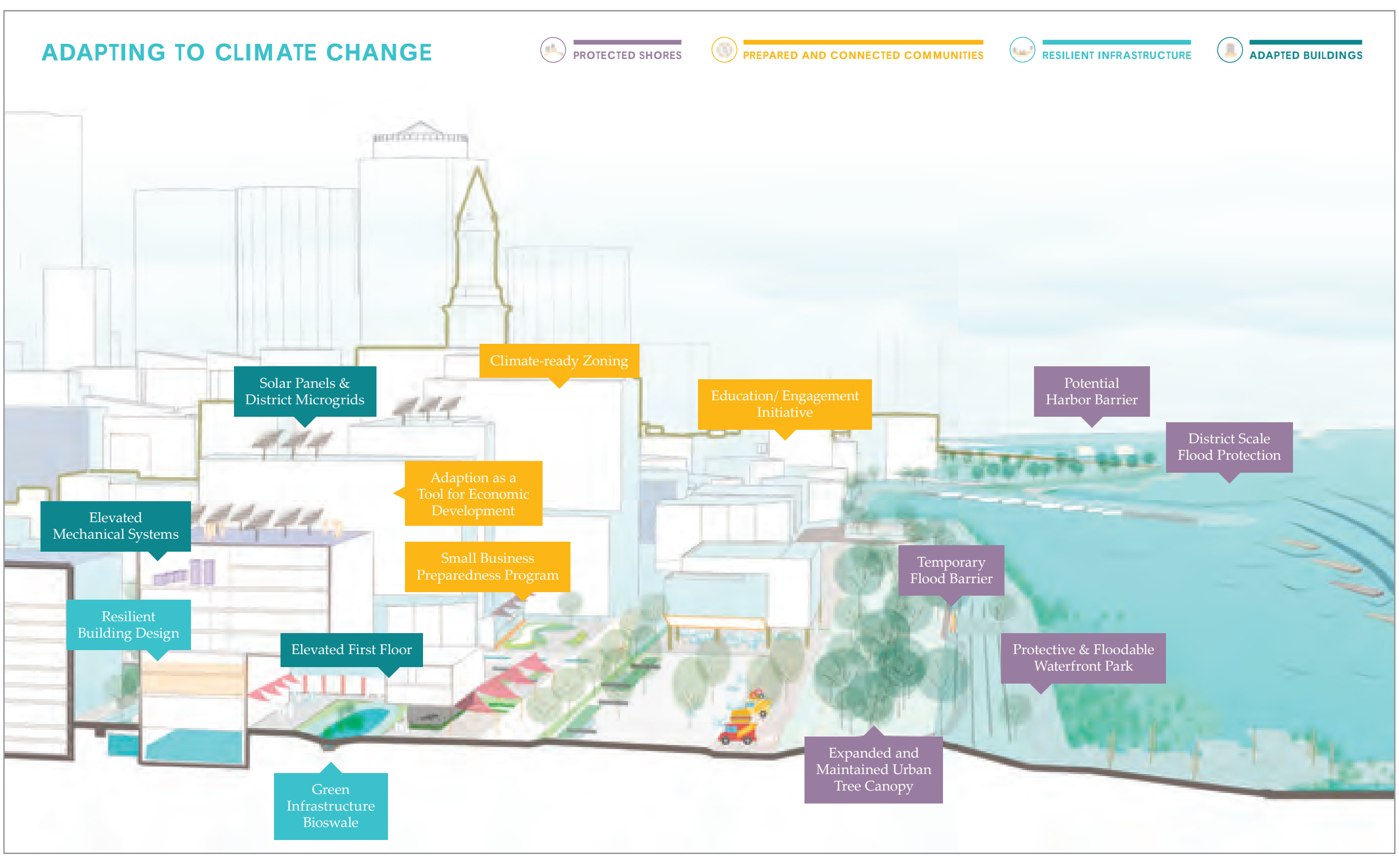
Harbor-wide barriers, in comparison are much less flexible. While it is possible to add elevation to the walls of a harbor-wide flood barrier system, it is not possible to build flexibility into the gate system, the major component of the cost. Conversion to a lock system would also be extremely expensive with possible maladaptation. In addition, if a gate was closed for an extended period of time due to malfunctioning, it would impact shipping and boating as well as ecosystems. In addition, the risk of singularly relying on a barrier, even if technology could be developed to ameliorate the concerns around closure frequency, is that if completion is delayed or it is not as effective as designed, then the City and the region might be left completely exposed, or in the words of CRB (2016), having “catastrophic” results (page 104). Thus CRB (2016) recommends that even if a harbor-wide barrier system is implemented, strategies such as shore-based systems will also be necessary as multiple levels of safety.

Benefit-cost Analysis

It is also valuable to compare the benefit-cost ratios of the harbor-wide barrier systems to shore-based barrier systems. Cost-effectiveness evaluation results for the 32 planning scenarios explored in this analysis for the barrier are presented in Section 8. All scenarios consider the Harbor Barrier as a complementary line of defense, using benefits solely attributable to the Barrier in managing events greater than assumed shoreline levels of protection. Potential cost effectiveness of the Harbor Barrier varies widely based on assumptions used. Results are very similar for both the IHB and the OHB. Under all the scenarios for the 7% discount rate except for one, the benefit-cost ratio (BCR) is less than 1.0. The one exception is when it equals 1.05, the low cost estimate for the OHB, in place from 2050 to 2100 with total failure of shore-based solutions.

Climate Ready Boston (2017) estimates benefit:cost ratios for a shore-based flood protection system for the Greenway/Border Street area of East Boston, assuming a discount rate of 7% and a time period of 20 years. The benefit:cost ratios are 3.22 to 5.3. These far exceed the ratios for the barrier assuming a 7% discount rate. In fact, for the most likely case that shore-based systems are effective, the barrier ratios

FIGURE 11.1
Coastal Flood Management Options



Source: Climate Ready Boston, 2016

TABLE 11.1

Comparison of Benefits Analyses of East Boston and Harbor-wide Barrier

Assumption	CRB (2017) East Boston	HWB Report
Discount Rate	7 %	7 %
Time Period	20 years	~50-60 years
Damages Included	Business interruption, relocation, lost productivity, mental stress, and damages to buildings and contents. Note damages to buildings and contents are approximately 80% of total damages.	Damages to buildings and contents and displacement costs
Assets Protected	Possibly average lower value than HWB report	Range of values
Level of Aggregation of Damage Analysis	Moderate	Coarse
Benefits beyond 20 year time period	While not explicitly considered, shoreline barrier system continues to provide benefits beyond 20 years	While not explicitly considered, barrier system continues to provide benefits beyond 50– to 60–year functional life
Impacts of Staging of Construction	Barriers staged over time—lowers discounted investment costs	One time large investment
Confidence in Results	The project level of protection, short-term implementation timeframe, and near-term losses avoided (benefits) are reasonably accurate due to the methodologies, and can be accounted for in a benefit-cost analysis with a high degree of confidence.	There are uncertainties in this analysis (e.g., engineering costs, SLR estimates, future damages avoided) due to the aggregated level of analysis and the distant time period of the analysis.

Source: UMass Boston

are all less than 0.33. In addition, the longer lifetimes used in the barrier analyses compared to the shore-based systems favor a higher ratio for the barrier analysis. The similarities in the assumptions in the CRB (2017) and the analysis of the harbor-wide barrier systems in this report are listed in Table 11.1. While the CRB (2017) analysis includes only one area in East Boston and may not be representative of other sites, it indicates that shore-based solutions may be more cost-effective than a harbor-wide barrier system. This finding is reinforced by the benefit-cost ratio of 4.3 to 7.9 calculated for a shore-based protection project for Charlestown MA over a 20-year period with a 7% discount rate (CRB, 2017). While this analysis also used a 3% discount rate to calculate benefit-cost ratios, the Climate Ready Boston report did not report benefit:cost ratios for the proposed projects in East Boston and Charlestown using a 3% discount rate.

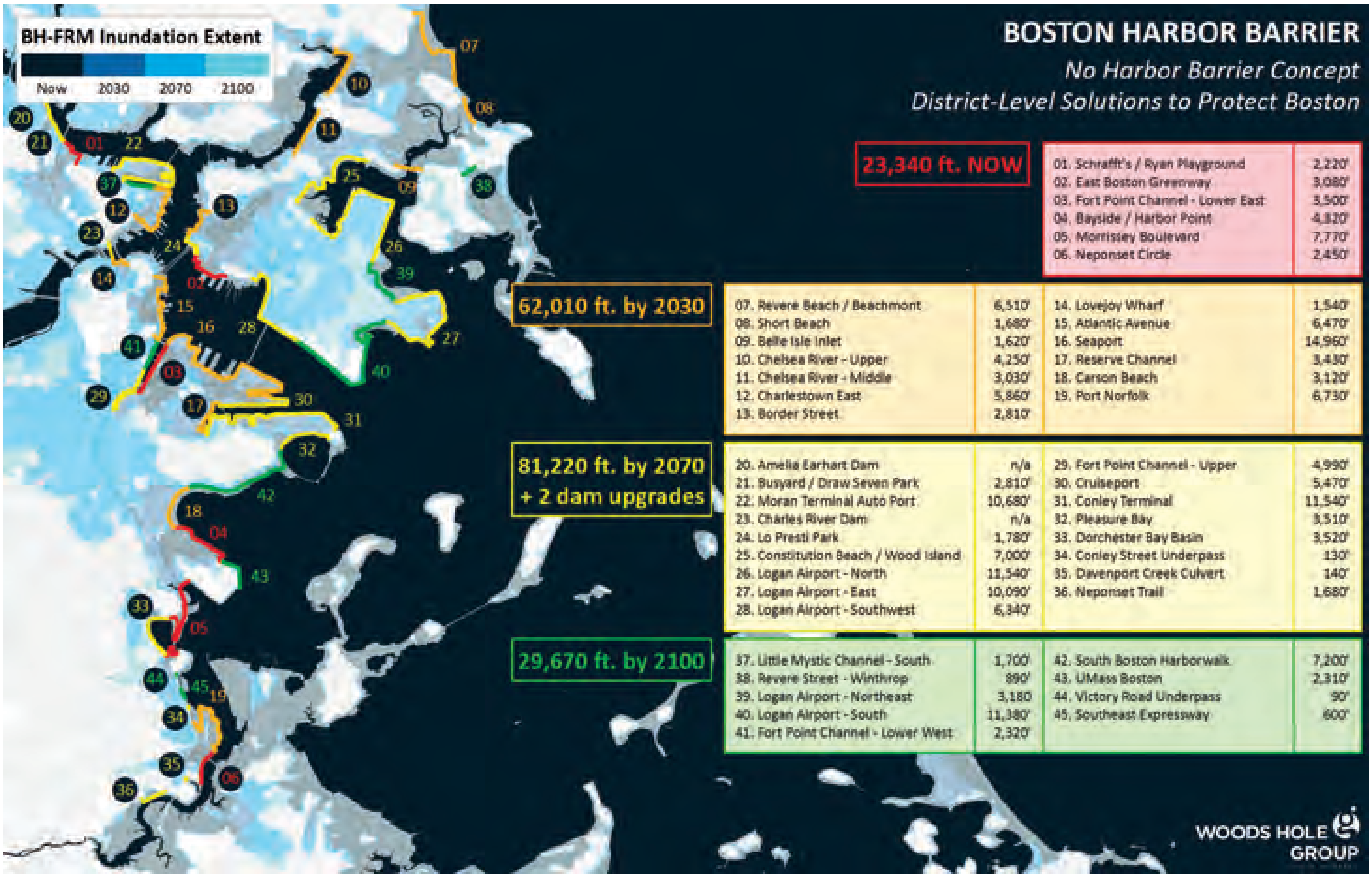
Cost Scenario Analysis

Another approach is to compare the costs of using an Inner or Outer Harbor Barrier to protect Boston to the costs of using shore-based solutions drawn from the entire set of biophysical and policy solutions illustrated in Figure 11.1. Figure 11.2 shows the areas where a barrier or other shoreline solutions would be needed over time to protect Boston (it does not include the other municipalities in Boston Harbor), assuming a planning scenario of 1 foot of SLR by 2030, 3 feet by 2070, and approximately 5 feet by 2100 (note that Figure 11.2 covers a slightly smaller area than the shoreline protections depicted in Figure 4.1, as it is an alternative for protecting only Boston).

We explored two cost scenarios. In Scenario 1, Boston adapts its shorelines to manage flooding to 14 feet NAVD88, building out the shoreline adaptations cited in Figure 11.2 through 2070 only, and then participates in building the OHB system in 2070, sharing costs with other municipalities. In Scenario 2, Boston also adapts its shorelines to manage flooding to 14 feet NAVD88 through 2070, but then increases the height of these systems and continues to add the additional shoreline solutions cited in Figure 11.2 in 2070. The costs of these scenarios are examined in Table 11.2. Here we use the cost of district-scale shoreline barriers to represent the cost of the broad range of biophysical and policy shoreline adaptation solutions that could be applied. Both cost

FIGURE 11.2

Shoreline Adaptation Solutions Necessary to Protect Boston over Time from 1% Coastal Flooding Event



Source: Woods Hole Group

scenarios in Table 11.2 are assumed to have the same level of coastal flood protection in Boston. As the results show, the total discounted cost of Scenario 1, $384 million, is greater than the total discounted cost of Scenario 2 of $255 million. The difference is misleading, however, because of the discounting. In 2070, the City of Boston, together with other communities, could decide to move forward with an Outer Harbor Barrier. Assuming shoreline protections can be built up, this would cost an estimated $508 million (2017 dollars based on $4,500 per linear foot for additional walls and $2,250 to expand existing walls). Even assuming that the City of Boston would not pay for the entire cost of building a barrier, the cost of shore based protections is dwarfed by the estimated $8-$12 billion OHB cost. When these costs are discounted back to 2018 at a rate of 7% (dividing by 1.07^52 or 34), the values are significantly diminished. The IHB option produces a similar result, especially since Boston would have to fund the entire cost of the IHB, approximately $7.6 billion, the average of the high and low estimates in Table 4.5.

Implications and Path Forward

Based upon the findings of this and the previous sections, it is clear that shore-based adaptation strategies, if effective, have clear advantages over harbor-wide strategies for Boston, at least to near the end of the current century. The same likely applies to other municipalities in Boston Harbor. The analysis has shown that while a harbor-wide barrier system would manage coastal flooding with perhaps minimal environmental impacts and moderate impacts on harbor users, its cost-effectiveness is low, and its operational period may extend only 50 to 60 years. Further, with limited potential to adapt or adjust its configuration once it is in place, the harbor-wide barrier offers limited opportunities to respond to the uncertainties of climate change over time. Even if such a barrier were planned, shore-based solutions would be needed until at least 2050, given the long lead-time to implement a harbor-wide barrier. Continuing to invest over time in a wide spectrum of shore-based actions that encompass green and gray infrastructure located around Boston's waterfront, rather than a harbor-wide barrier, has the potential to be highly cost-effective and offers several key advantages: multiple levels of protection, flexible and adaptive management of coastal flooding, high co-benefits that may address social justice concerns, long operational lifetimes, and minimal impacts to the harbor's aquatic environment and its users.

One option not explored is a hybrid solution where a barrier is only used to manage low frequency, intense events with a limited number of closures during a decade and shore-based alternatives manage all other events while providing complementary protection to the events managed by a barrier system. Given the results of the benefit:cost analyses which show the high cost-effectiveness of shore-based systems, such a hybrid system may only be acceptable if there is a limit on the functionality of shore-based solutions—which include both structural and non-structural approaches. Based upon the results of the Climate Ready Boston pilot projects in East Boston and Charlestown (CRB, 2017), any functionality limit on shore-based solutions are unlikely to occur until sea level rises 5 or more feet, unlikely until near the end of the century.

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TABLE 11.2

Scenarios for Protecting Boston from Coastal Flooding

Scenario	Discounted Cost of Shoreline Adaptation to 14 ft NAVD88 by 2070 ($Million)	Discounted Cost of HW Barrier Adaptation ($Million)	Discounted Cost of Rebuilding Shoreline Adaptation to 14 NAVD88 and Adding New Shoreline Adaptation in 2100	Total Discounted Cost ($Million)	Cost Assumptions
Scenario 1 Boston adapts shorelines to manage flooding to 14 NAVD88 (building out the shoreline adaptations in time through 2070 in Figure 11.2), then participates in building the outer harbor-wide barrier system in 2100.	240	144	NA	384	Boston's cost share of OHB is 50%, (Approximately 50% of the harbor-wide damages avoided are in Boston). Costs of rebuilding Charles River and Amelia Earhart dams from other sources. Cost of shoreline barriers is average of levee and seawall costs in Tables 4.2 and 4.5, $4500/ft. OHB cost is average of cost range in Table 4.2, $9.9B. Discount rate = 7%. O&M costs not included. Some very minor doubling accounting of shoreline barriers needed in Revere (Walls 07 and 08 in Figure 11.2) because needed in both OHB and the shoreline adaptation solution only.
Scenario 2 Boston adapts shorelines to manage flooding to 14 NAVD88 (building out the shoreline adaptations in time through 2070, then increases the height of these systems and adds the addition shoreline solutions in 2100 in Figure 11.2.	240	NA	15	255	Costs of rebuilding Charles River and Amelia Earhart dams from other sources. Cost of shoreline barriers is average of levee and seawall costs in Tables 4.2 and 4.5, $4500/ft. Cost of rebuilding systems at 14 ft NAVD88 in 2100 is 50% of original construction costs. Discount rate = 7%. O&M costs not included.

Source: UMass Boston

12 *Conclusions and Recommendations*

We recommend the City of Boston continue the strategy of shore-based flood protection strategies for the next few decades.

Summary

One of the recommendations of the recently completed Climate Ready Boston Initiative (City of Boston, 2016) is to “Launch a Harbor-Wide Flood Protection System Feasibility Study.” Options considered here include a Metro Harbor Dike lock system from Swampscott to Cohasset, and two storm barriers systems that would only be closed during storm flooding conditions. The Outer Harbor Barrier (OHB) would extend from Winthrop to Hull with additional shore-based protection in Hull, Winthrop, and Revere to prevent floods flanking the barrier from the ocean. The Inner Harbor Barrier (IHB) spans the passage between Logan Airport and the Seaport area of South Boston. It would also require shore-based protection systems north and south of it. This configuration assumes that the barrier and shore-based system could be compatible with Logan Airport operations. The preliminary assessment of the Metro Boston Dike Barrier identified significant navigational, hydrodynamic, physical, and environmental obstacles due to its location relatively far offshore in deep water with large waves during storms and its lock system. Compared to the OHB and IHB, it was exceedingly expensive, caused irreversible ecological changes, and deleteriously affected shipping activity. Therefore, it was not further considered.

The analysis assumes that a goal is not only to provide flood protection to Boston and, in the case of the OHB, Boston Harbor but also to maintain present and future commercial shipping and preserve as much as possible the ecological services of Boston Harbor in light of climate change. The implementation of any of the alternatives would represent a significant alteration to a complex socio-ecological system. Few estuarine alterations of this magnitude have ever been attempted.

Even though this has been only a preliminary analysis, it is clear that given the myriad of advantages of shore-based or district level solutions for Boston, building any harbor-wide barrier system within the next few decades, if ever, is an unreasonable strategy for the City of Boston and probably the other municipalities in Boston Harbor to consider.

Key Findings

1. It appears that the Inner and Outer Harbor Barrier systems investigated for this study could provide protection against present and future coastal storm flooding. Each would also require extensive construction of flood protection systems on the low elevation sections of neighboring and distant shorelines to prevent floods from flanking a barrier. The planned design life for infrastructure of this magnitude is likely on the order of 50 to 100 years. Given the extensive time to design and permit the project, the earliest either one could be functional is 2050.

It is clear that given the myriad of advantages of shore-based or district level solutions for Boston, building any harbor-wide barrier system within the next few decades, if ever, is an unreasonable strategy for the City of Boston and probably the other municipalities in Boston Harbor to consider.

2. The time period of their effectiveness depends upon the level of shoreline adaptation and the rate of SLR. After becoming operational, the gates would be open most of the time in order to enable commercial shipping to use the main navigation channels in and out of Boston Harbor and to minimize environmental impacts. After 50 to 60 years of operation (using the SLR and shore-based protection scenarios used in this report), however, the gates would close so frequently (> 50 times per year) because of higher tides and more frequent higher storms that they would no longer be functional as designed.

3. The size of the gate openings for the OHB is the minimum possible for maintaining commercial shipping. The openings of this size would not decrease the tidal range in Boston Harbor but would change circulation in parts of Boston Harbor resulting in some new areas of stagnation and sedimentation and significantly increased peak velocities in the shipping channels. There would also be an increase in the channel velocity with the IHB.

4. Total design, engineering, permitting, and construction costs for the IHM could range from $6.5 billion to $8.7 billion (2017 dollars) with operation and maintenance costs of approximately 1% of total construction costs. Approximately 60% of the cost is the floating sector gate. The IHB

might conflict with the air-space requirements at Logan Airport. Pumps would be needed at the IHB to adequately control upstream freshwater levels during times when the IHB would be closed because of a storm surge. It is possible these pumps could maintain the water at an elevation such that the Amelia Earhart Dam and the Charles River Dam might not need to close or pump or, if pumping is necessary, then less frequently.

It does not appear that the construction of an Outer Harbor Barrier would cause any irreversible negative transformations of the entire harbor environment based upon a careful qualitative assessment of water quality, habitat quality, or ecosystem services.

5. Total design, engineering, permitting, and construction costs of the OHB could range from $8.0 to $11.8 billion dollars (2017) with annual operation and maintenance costs estimated at approximately 1% of total construction costs. Over 60% of the costs are for the floating sector gates.

6. It does not appear that the construction of an Outer Harbor barrier would cause any irreversible negative transformations of the entire harbor environment based upon a careful qualitative assessment of water quality, habitat quality, or ecosystem services. While there would be some foreseeable impacts, most of these are modest and/or limited spatially or temporally. For a great part of the harbor system, 5 feet of sea level rise and the expected increase in water temperature due to climate change could have equal or greater environmental impacts than the construction of a harbor-wide barrier. This environmental assessment is based on an assumption of several (3-10) closures per year for major storms. Under future scenarios of biweekly or weekly closures for flood management, the environmental impacts would clearly be more severe.

7. Installation of an Inner Harbor Barrier would likely have very minor if not immeasurable impacts on environmental conditions except when the barrier would be closed. During a storm, the barrier could be closed for 46 to 84 hours with high freshwater discharge coming out of the Charles and Mystic Rivers over their respective dams. This freshwater containing combined sewer overflow effluent and street runoff would likely be contaminated. Since freshwater is less dense than salt water, it would sit on top of the Inner Harbor seawater until the barrier was re-opened. Even assuming pumps were installed to drain the water so it does not overflow the barrier, such pumps would require pump inlets set below this contaminated surface water and so would not remove the floating lens of contaminated freshwater.

8. A high level economic evaluation of ecosystem services assuming that salt marshes can migrate inland as SLR occurs found the overall effects of the OHB on ecosystem values are expected to be small (less than 3% decrease compared to no barrier).

9. The economic analysis of the damage reduction potential of the harbor-wide barriers is more approximate and aggregated than that of Climate Ready Boston (2016). As in the case of the closure analysis, these results show the value of a barrier depends upon the elevation of shore-based adaptation and its effectiveness. It is apparent, however, compared to the possible high cost effectiveness, co-benefits, management of tidal flooding, and adaptive nature of shore-based systems such as those currently being explored by the City of Boston in Charlestown, East Boston, and the Seaport and by private and public organizations, the advantages of the IHB and OHB systems are quite limited if shore-based systems are effective. Barrier preliminary benefit:cost ratios are quite low; they are significantly less than 1.0 in most cases considering a range of discount rates and complementary shore-based adaptation strategies.

10. The anticipated increased water velocity in the barrier openings could cause navigational and safety issues for both recreational and commercial vessels near the barrier openings at peak ebb and flood tides. Additionally, there may be greater vessel congestion near the openings in the OHB, especially near the northern barrier opening as its water velocity is expected to be more manageable than the southern barrier opening. The barrier could also impact the abundance, distribution, and/or behavior of fish populations, which would in turn impact both commercial and recreational fisheries.

11. There is a large increase in the magnitude of the population exposed to flooding in Boston

from the 1 % storm in 2100 under a moderate SLR scenario compared to the present number. There is not a large difference in the number that would be protected by the IHB and OHB in 2100. This is partly explained by limitations in the analysis as well as by the protection the inner barrier would provide to not only residents directly on the coast, but also those inland impacted by flood pathways originating on the coast; many of the same areas in Boston protected by the outer barrier. For both the inner and outer barriers, there are not significant percentage differences in the protected populations by category of social vulnerability compared to the Boston population as a whole without any flooding.

Recommendations

Based upon the findings of this project, it is clear that shore-based adaptation strategies, if effective, have clear advantages over harbor-wide strategies for Boston at least for several decades. The same likely applies to other municipalities in Boston Harbor. The analysis has shown that, while a harbor-wide barrier system would manage coastal flooding with perhaps minimal environmental impacts and moderate impacts on harbor users, its cost-effectiveness is low, and its operational period might extend only 50 to 60 years. Further, with limited potential to adapt or adjust its configuration once it is in place, the harbor-wide barrier would offer limited opportunities to respond to the uncertainties of climate change over time. Even if such a barrier were planned, shore-based solutions would be needed until at least 2050, given the long lead time to implement a harbor-wide barrier. Continuing to invest over time in a wide spectrum of shore-based actions that encompass green and gray infrastructure located around Boston's waterfront, rather than a harbor-wide barrier, has the potential to be highly cost-effective and offers several key advantages: multiple levels of protection, flexible and adaptive management of coastal flooding, high co-benefits that may address social justice concerns, long operational lifetimes, management of tidal flooding, and minimal impacts to the harbor's aquatic environment and its users.

This argues for maintaining the current focus on a shore-based layered approach that would include flexible, adaptive, shore-based or district level solutions along the Boston waterfront such as those currently being explored in Charlestown, East Boston and South Boston and soon to be examined for the downtown waterfront. These shore-based solutions would be needed in any case over the next few decades to manage coastal flooding during the design and construction period of any harbor-wide barrier if it is decided to build one in the future. The future extent and design of shoreline solutions can be decided over time as climate and other changes occur and the possible need for a harbor-wide barrier at the end of the century is more firmly resolved. Any future barrier built would probably best be used to complement shore-based systems by managing very large floods with the shore-based systems managing smaller events and helping to manage the very large events. This would limit the annual number of closures of a future barrier system. The decision regarding a barrier is very much dependent upon the future risk tolerance of the city and the performance of shore-based systems.

Therefore, it is also recommended that the City and region:

- Continue to monitor climate, environmental, economic, and social changes, risk-tolerances, the continuing evolution of the technology of harbor-wide barriers, and the global experience with existing harbor-wide barrier systems to determine if the feasibility of a harbor-wide barrier should be reexamined at some point in the future. It will be especially important to monitor the actual pace of sea level rise in Boston Harbor over the next several decades and

evolving climate science to determine whether shore-based solutions being implemented in Boston and adjacent cities will be adequate for the remainder of the century and/or beyond 2100.

- Since the consequences of 5, 7 or more feet of SLR by end of century are severe and must be considered, develop an adaptive adaptation planning process based upon monitoring of biophysical and socio-economic systems that periodically reconsiders the possible role of a harbor-wide barrier system; and
- Undertake strong greenhouse gas mitigation actions with many others to lessen the rate of climate change. Strong mitigation starting now could result in a SLR to 2 or 3 feet by 2100 instead of 5 to 7 feet or more. Limiting SLR to 3 feet or less would greatly reduce the need for future consideration of harbor-wide barrier systems in this century and early next century.

Research and Further Analysis Issues

This project also identified other analyses that need to be conducted if the feasibility of a harbor-wide barrier system is ever re-visited. These include:

- Analyses under several sea level rise scenarios. The benefits analysis was done assuming 5 feet of SLR by 2100, essentially emission scenario RCP4.5. Given recent historical emissions, the world is currently in the higher emission scenario of RCP8.5 (USGCRP, 2017). As shown in the closure analysis, the more rapid SLR of RCP8.5 actually lessens the effective life of a harbor-wide barrier to function as presently designed.
- As with any planning-level cost estimates, wide latitude for cost estimate refinement exists for the barrier systems. Loaded unit price and scaled cost features need to be refined if possible alignments are analyzed in more detail. Refinements in quantities and market research on local material availability would continue to refine unit price estimates.
- Refined closure analysis and evaluation of residual benefits over time of harbor-wide barrier systems after 50 to 60 years when closure frequency is high.
- The reliability of the gate systems of harbor-wide barriers.
- Impacts of a possible evolution from a flood and storm tide gate system to a locks system
- Some of the additional research needs on the environmental impacts are: 1) what will be the impacts of climate change on the ecosystems in the harbor; 2) what impact if any would a barrier have on migrating species; 3) how would a 3-day freshwater cap (a freshwater layer on top that cuts off air-sea exchange and vertical mixing is referred to as a cap), which could occur during freshwater flooding with the Inner Barrier, affect water column and benthic quality and habitat; 4) can salt marshes be nourished to keep up with sea-level rise; 5) how will local human adaptations affect the environment both locally and within the system as a whole; 6) what are differences between the expected first order impacts of a harbor-wide barrier and the potential impacts at the local level, e.g. at the 200m x 200m scale; 7) how would a barrier closing approximately 50 times per year impact the results of the environmental analysis; and 8) would the combined impacts of climate change and a harbor-wide barrier system interact in a presently unforeseeable manner that would increase the impacts described here.
- More granular analysis of the damages avoided by harbor-wide barriers to improve the estimates of their benefit:cost ratios. On the other hand, we have shown that for the same levels of protection, shore-based solutions, if effective, are less costly and are more advantageous for other reasons.
- More explicit analysis of values of co-benefits of harbor-wide barrier and shore-based adaptation systems and also potential for maladaptation due to either system. As shore-based systems are implemented, a valuable database of their performance and co-benefits needs to be developed. Social impacts need to be especially monitored.
- The nature, timing, effectiveness, and adaptive capacity of shore-based solutions will play

a large role in future investigations of cost-effectiveness of a Harbor Barrier alignment. The nature and presence of future shore-based solutions will vary across the study area landscape, as will the impacts of sea level rise and coastal flooding over time should the shore-based solutions be overcome. In the future, the region must evaluate the ability for different types of shore-based solutions to be adapted to higher design elevations, the impacts of policy changes in risk reduction (such as flood accommodation plans) and how a harbor barrier may fill in gaps in shore-based solutions to continue to reduce flood risk.

- The analysis of benefits (damages avoided) of harbor-wide barriers and shore-based systems assumes that building and socio-economic systems are rebuilt after damaging events as they were before the event. Some local adaptations will take place to lessen future impacts (e.g. more use of sandbags to better manage flooding though probably not as effective as planned adaptation). Therefore, generally storm damages for both harbor-wide barriers and alternative shoreline systems may be over-estimated. In addition, estimating the state of the future built and socio-economic land use and conditions at the end of this century is highly uncertain—presently we are assuming the same as the present. This may also lower future benefit estimates.
- More studies need to be conducted to determine more specifically how a harbor-wide barrier could impact the human uses occurring in Boston Harbor, e.g., velocity changes at the gate locations, perceptions of large, one-time projects vs. smaller short term projects, and trends in commercial shipping, water transportation, recreational boating, and other uses over time to determine whether and how changes in these uses might be more or less accommodating to barrier systems of various kinds.
- Our project has implicitly assumed a risk tolerance for the City and in addition has not carried out a detailed uncertainty analysis for all the components of flood management strategies. These should be carried out if the feasibility of a harbor-wide barrier system is ever considered.
- More analysis of funding and governance mechanisms. There is not currently a governance structure or governmental agency that would be able to manage the permitting, financing, design and construction of a harbor wide barrier in the Boston Harbor. Current local governmental structures are not set up for a multi-jurisdictional project of this scale. There are complex issues arising at the municipal, regional, state and federal level that would need to be addressed (Appendix F). It is unclear if it would make sense to establish a new agency or expand the charter of an existing one. In addition, since an agency would need bonding authority to pay for a project and ability to do regional planning there are many questions to be answered about how this could happen.
- More stakeholder input from the City and other organizations with interests in Boston Harbor.
- Research into the greenhouse gas emissions of different flood management solutions.

Shore-based solutions can provide the same level of protection as a barrier system at a lower cost, are adaptable, and can contribute to neighborhoods through co-benefits in a way that a harbor-wide barrier cannot.

Concluding Thoughts

Given its location and vulnerability to coastal flooding, the City of Boston must prepare for the impacts of climate change. A harbor-wide barrier would be difficult to design, costly to build and hard to adapt to new realities. Since is unlikely that a barrier system could be built before 2050, pursuing shore-based protection is essential regardless of whether a barrier were to be built or not. These shore-based solutions can provide the same level of protection at a lower cost, are adaptable and can contribute to neighborhoods through co-benefits in a way that a harbor-wide barrier cannot. For all these reasons, we recommend the City of Boston continue the strategy of shore-based flood protection strategies for the next few decades.

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APPENDIX A

COMPARISON OF COSTS OF GLOBAL BARRIERS

Since there is a limited number of large flood barriers presently constructed in the world, multiple studies have been performed to analyze the potential accuracy of planning-level cost estimation methods for such large features. In general, planning-level cost estimation can be broken down into a few components: one-time construction expenses, periodic operations and maintenance expenses, and ancillary features required.

1. **One-Time Construction Expenses** are defined by the funds required to build the primary barrier feature. They can be broken down into three subcomponents: Moveable Components, Immoveable Spans, and Percentages for Design, Construction Management, and Contingency.

    a. **Moveable Components:** these include all gates for navigation and ecological preservation. Moveable parts, in general, are the primary cost driver for the entire barrier system, with all other components comprising only fractions of the overall system cost. As noted in Aerts et al. (2013) and Jonkman et al. (2013), the moveable components of a barrier usually comprise a small portion of the overall length, but the largest portion of cost. The best example is the St. Petersburg barrier (cost of $6.9B in 2013 dollars), which spans over 25 km. Its moving parts comprise only 1700 m in total length (only 7% of the total length), yet comprise $6.0B of the total cost (roughly 87% of total cost in 2013 dollars). Another example is the Inner-Harbor Navigation (IHNC) Barrier in New Orleans where roughly 70% of the $1.2B cost of the IHNC Barrier (in 2013 dollars) was allocated for the moveable portions of the barrier (Aerts et al., 2013).

    b. **Immoveable Span:** these features can include earthen levee, rock dike, and concrete/steel wall sections which tie in or connect the moveable gate(s) to landward features. Wall systems, such as combi-wall or battered sheet-pile wall systems, like those employed in the IHNC Barrier, are generally more expensive than earthen or rock barrier systems. In general, earthen or rock barrier components are fractional cost components unless in deep water. The New Bedford, IHNC, and St. Petersburg barriers' immoveable components accounted respectively for 25%, 31%, and 13% of the overall construction cost while comprising 98%, 91%, and 93% of the overall barrier length. Within similar immoveable span lengths, variability in parametric costs can be attributed to the variability in design of the immoveable portions of these barriers: some are wide enough to support multi-lane road and rail traffic or public spaces, whereas others are only wide enough for at most, a small maintenance access roadway.

    c. **Engineering and Design (E&D), Construction Management (CM), and Contingency:** these features are generally reported as rolled into overall construction cost; however, in some studies, such as the U.S. Army Corps of Engineers' North Atlantic Coast Comprehensive Study (NACCS), Appendix C-Planning Analysis (2015), they are calculated based on percentages of the construction cost. It is typical to find estimates using approximately 12% for E&D, approximately 10% for CM. Contingency is also often computed as a percentage of the construction cost in large planning studies; however, the size of the percentage can range from over 100% in the early stages of planning down to 25% for latter stages of planning, before a project is moved into design.

2. **Periodic Operations and Maintenance (O&M):** the primary cost associated with the operation of large storm surge barriers relates to efforts to preserve the moveable gate(s) and the mechanical, hydraulic, and electrical systems which support the operation of the gate(s). Gate type plays a role in O&M costs; namely, if the gate is partially or fully submerged and/or constructed of structural steel, periodic efforts to inspect, remove, drydock, and sand blast/repaint gate leaves may be required. Traditional costs based on the interruption to navigation may also occur. According to Aerts et al (2013), O&M costs can generally be estimated as 5-10% of the construction cost or 0.5% to 2% of the construction cost annualized.

3. **Ancillary Measures:** often, when regional storm suppression systems such as levees and barriers are constructed, the behavior of storm surge outside of the barrier and the behavior of precipitation runoff inside the barrier are significantly affected. To ensure inducements of interior or exterior flooding are minimized, other features may be required including floodwalls, levees, land use and planning ordinances, residential and commercial structure floodproofing or buyouts, and forced drainage elements (pumps and conveyance). Additionally, the barrier feature may cause changes to local scour and longshore sediment transport patterns necessitating shoreline or seafloor armoring. Although the list of potential ancillary features is long, often the total price tag is small in comparison to the moveable portion of the barrier.

A summary of the geometric and monetary features of large existing floodgates can be found in Figure A.1).

Several attempts have been made to create a cost-estimating system for large flood barrier systems, to varying degrees of success. Mooyart et al. (2014) compared methods and found that in 2017 dollars, large flood barrier systems, on average, cost \$3.07M per meter span across all gate types and gate/barrier combinations, with a \$1.68M per meter standard deviation (i.e., roughly a 50% standard deviation). These costs are generally corroborated by Aerts' planning estimates for inner and outer harbor defense strategies for New York City. Other studies, such as NACCS, suggest a strong correlation between the volume of the moveable portion of the gate itself (based on height, width, and head), to cost. It found an international average of \$34,250 per cubic meter (2017 dollars) for moveable portions of large flood gates.

TABLE APPENDIX A1

Overview of Existing Storm Surge Barriers and their Characteristics and Costs (costs in US$, 2012 price levels)

Name Barrier	Gate Type	Country	Constr. Years	# Nav. Sector Gates	# Non Nav. (Tidal) Gates	# Lock	Span Movable Parts (m)	Total Width (m)	Gate Height (m)	Head (m)	Closure Time (min)	Construc-tion Costs ($mln)	Costs ($mln/m)	Movable parts ($min/m)	O&M Costs ($min/yr)
Hollandse Ijssel Barrier [5,12,14,23]	Vertical Lifting	NL	1954–1958	2		1	110	110	11.5	3.5	30	127	1.15	1.15	2
Fox Point Hurricane Barrier[15,16,21]	Vertical Rotating	USA	1961–1966	3	2		50	300	12	6	30	87.6	0.29	1.7	0.5
New Bedford Storm Surge Barrier[15,21]	Hor. Moving Sector	USA	1961–1966	2			50	2774	18	6	12	110.9	0.04	1.66	N/A
Stamford Hurricane Barrier[15,21]	Flap	USA	1965–1969	1	30			866	10.5	5	20	81.7	0.09	2.43	N/A
Thames Barrier[7,9,21]	Rotating Sector	UK	1974–1982	6	4		530	530	17	7.2	60	1883	3.55	3.55	13
Eastern Scheldt Barrier[5,7,10,12,21]	Vertical Lifting	NL	1974–1986		62	1	2400	2400	14	5	60	5227	2.18	2.18	20
Hartel Barrier[5,7,11,22]	Vertical Lifting	NL	1993–1996	2		1	170	170	9.3	5.5	50	185	1.09	1.09	2.4
Maeslant Barrier[5,7,12,21]	Floating Sector	NL	1989–1997	2			360	360	22	5	90	852	2.37	2.37	15
Cardiff Bay[26,27]	Sluice/ Lifting	UK	1994–2000	3	5	1	100	1100	7.5	3.5	30	340	0.31	3.0	15
Ramspol[5,7,13,21]	Inflatable Rubber Dam	NL	1996–2002				240	240	8.2	4.4	60	171	0.71	0.71	1.1
EMS[4,7,19,21]	Rotating Sector	Germany	1998–2002	2	5		476	476	10.5	3.8	30	376	0.79	0.79	6.3
St. Petersburg Barrier[3,8,24]	Floating Sector/ Vertical Lifting	Russia	1984–2011	3	64		1700	25400	23.5	5	45	6953	0.27	3.53	
Seabrook Barrier[7,18,21]	Vertical Lifting/ Sector	USA	2005–2011	2	2		130	130	8	4	15	165	1.26	1.26	2.1
IHNC Barrier[2,7,1718]	Sector/ Vert. Lifting	USA	2005–2011	3			250	2800	8	4	10	1,0	0.45	3.49	2.5
Venice MOSE[6,7,20,25]	Inflatable Flap	Italy	2003–today	78		3	3200	3200	15	3	45	6125	1.91	1.91	12.8

Note: Often flood barriers consist of multiple gate structures and types. The above figure lists the sum of all moveable gates as a single cumulative span. For example, the St. Petersburg barrier consists of over 60 environmental flow gates, a 110-meter vertical lift gate, and a 200-meter floating leaf sector gate for a cumulative moveable span of 1700m as reported in the figure above.

Sources: Cost Estimates for Flood Resilience and Protection Strategies in New York City, Aerts, J.C.J.H., Botzen, W.J.W., Moel, H. de, Bowman, M. Annals of the New York Academy of Sciences, 1294(1), 1–104

TABLE APPENDIX A1 FOOTNOTES — Footnotes reproduced from Aerts et al. (2013)

1 For barriers where the span of the movable parts is smaller than the total span, we subtract the cost of the dam. For the old US hurricane barriers we use a unit cost price of US$10 mln/km. For the newer barriers (constructed after 1990), we use the cost prices by Dijkman (2007) of US$40 mln/km. For the IHNC barrier, we use the unit cost price from Bos (2008) for a 50 ft wall of US$ 36 mln/km.

2 http://www.usace-isc.org/presentation/Construction%20Mgmt/Project%20Controls%20for%20New%20Orleans%20Surge%20Barrier_Stirm_Paul.pdf. Prices of only the movable parts (excluding floodwalls) is estimated at $673 mln.

3 Cost of whole project, including sea walls: http://www.halcrow.com/Our-projects/Project-details/St-Petersburg-Flood-Barrier-Russia

4 http://www.vncold.vn/Modules/CMS/Upload/13/Science/H4_EMS_Barrier(Germany)_23_02_09/H4_EMS_Barrier(Germany).pdf

5 http://www.deltawerken.com/Hollandse-IJssel-storm-barrier/322.html

6 Munaretto, S., Vellinga P., & Tobi, H. (2012) Flood Protection in Venice under Conditions of Sea-Level Rise: An Analysis of Institutional and Technical Measures.Coastal Management, 40, 355–380.

7 Hillen et al. (2010).

8 Cost of movable parts is estimated at 80% of the total price: ~$5,561 mln.

9 See Appendix D.

10 http://www.omroepzeeland.nl/nieuws/oosterscheldekering-blijft-huzarenstukje

11 Rijkwaterstaat (1992) Tracenota Europoortkering. http://www.scribd.com/doc/76807878/106/Bediening-en-onderhoud-kering

12 IenM (2011) Vaststelling van de begrotingsstaat van het Infrastructuurfonds voor het jaar 2012. Total operation and maintenance for 4 storm surge barriers is 43.9 mln Euro per year.

13 www.wgs.nl/publish/pages/6850/05-1_jaarverslaggeving.pdf

14 http://www.deltawerken.com/Hollandse-IJsselkering/56.html

15 http://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=1993

16 http://www.pbn.com/Providence-transfersbarrier-to-Army-Corps,48223

17 http://www.nola.com/politics/index.ssf/2011/03/southeast_louisiana_flood_prot.html

18 http://www.nafsma.org/pdf/2011-annual-meeting/NAFSMA_neworleanslocal_turner.pdf

19 http://home.teleos-web.de/hkoerber1/Meyer-Werft/Emssperrwerk.htm

20 http://www.telegraph.co.uk/news/worldnews/europe/italy/3629387/Moses-project-to-secure-future-of-Venice.html

21 Dircke et al. (2011).

22 RWS (2007)Waterloopkundige berekeningen TMR 2006 Benedenrivierengebied. RWS RIZA rapport 2007.017.

23 www.scribd.com/doc/83762881/17/Stormstuw-Hollandsche-IJssel

24 http://www.nce.co.uk/news/water/st-petersburg-flood-barrier-swing-through-the-sea/5210173.article.

25 http://en.wikipedia.org/wiki/MOSE_Project

26 Van der Meer (2006).

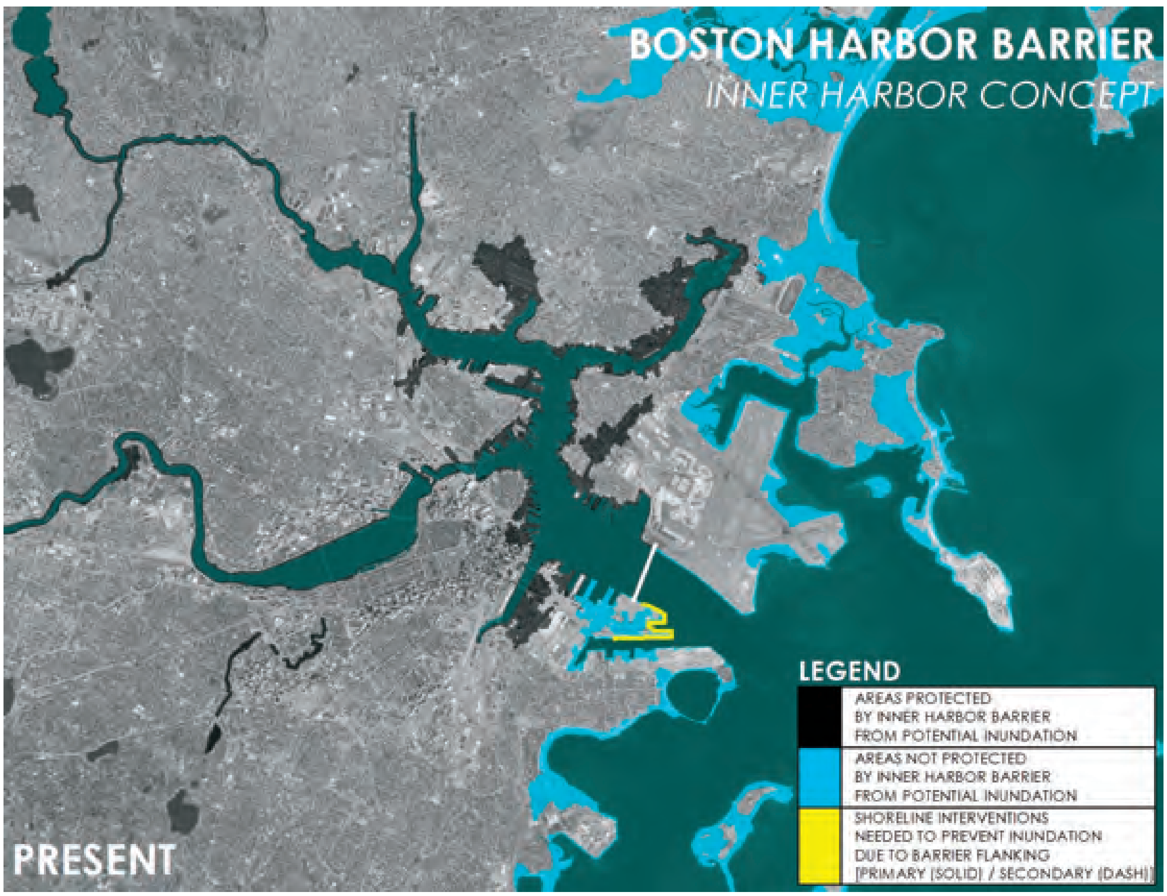
27 http://www.guardian.co.uk/society/2005/jan/05/environment.welshassembly

APPENDIX B

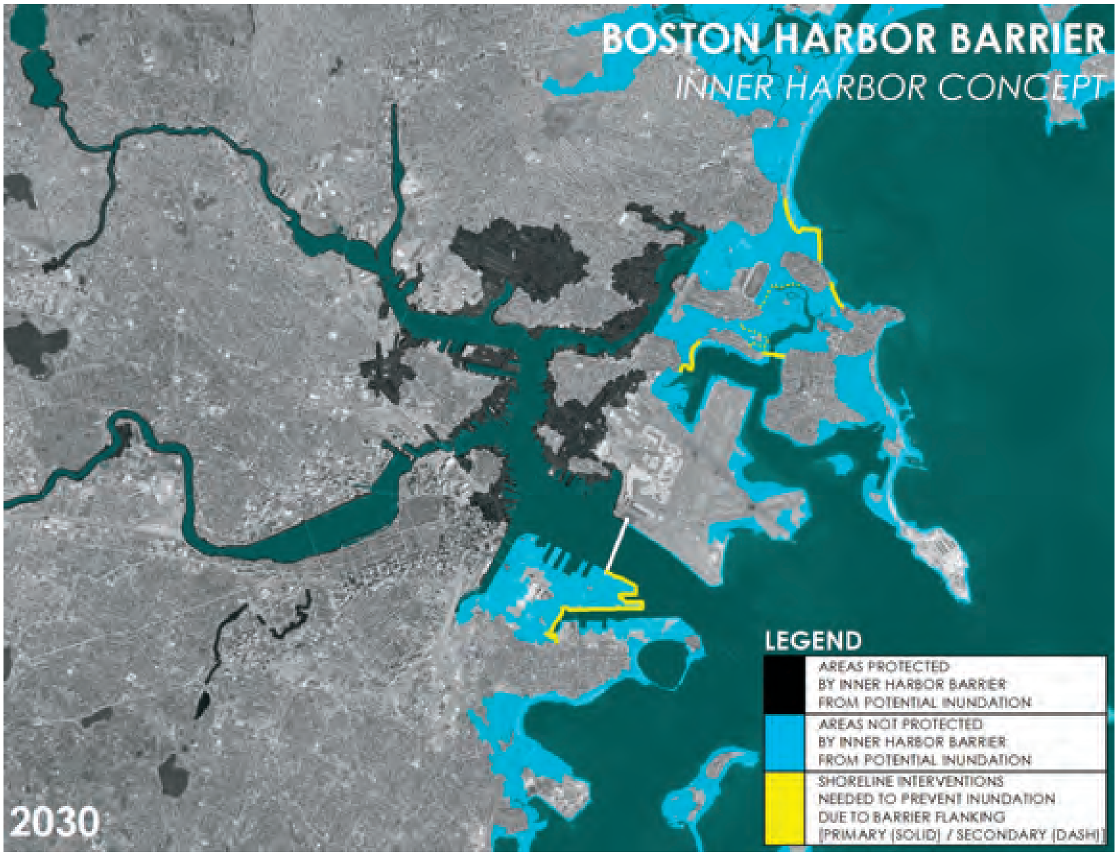
SHORE-BASED PROTECTION NEEDED FOR INNER HARBOR BARRIER

FIGURE APPENDIX B1

Shore-Based Protection Needed as Part of Inner Harbor for the Present



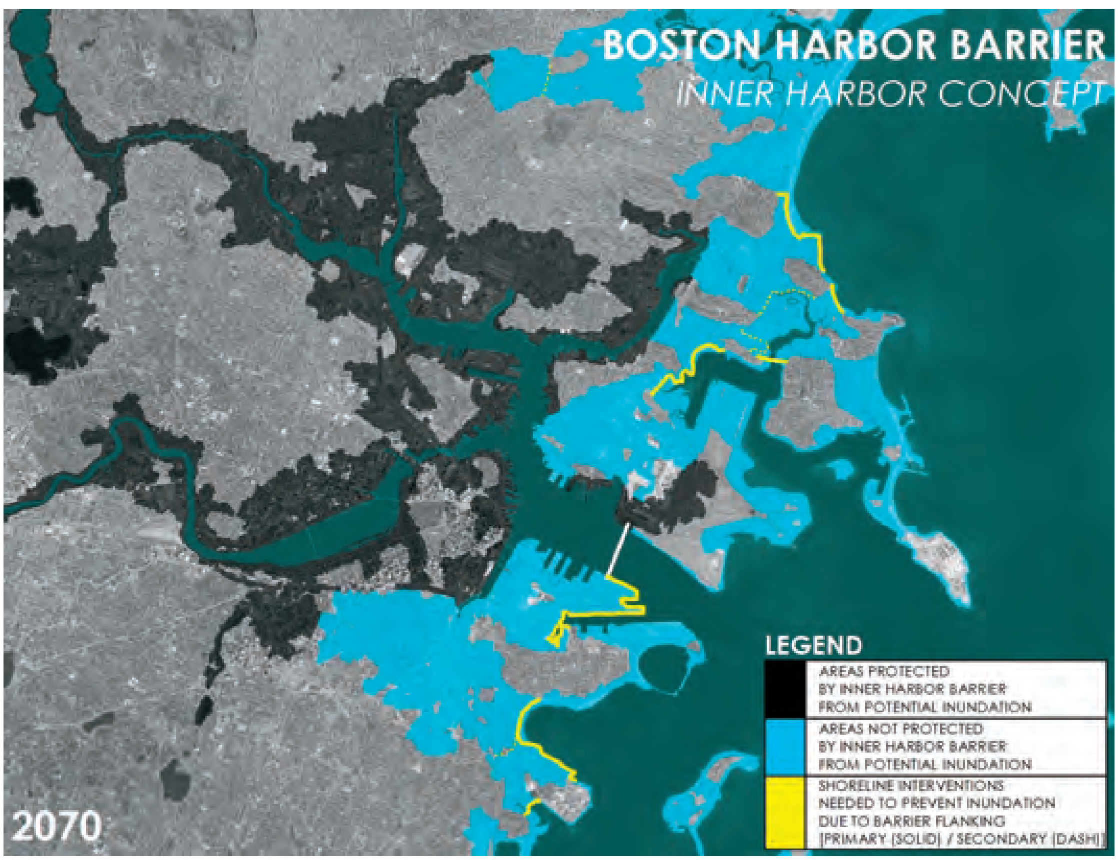
Source: Woods Hole Group



Source: Woods Hole Group

FIGURE APPENDIX B2

Shore-Based Protection Needed as Part of Inner Harbor for 2030



Source: Woods Hole Group

FIGURE APPENDIX B3

Shore-Based Protection Needed as Part of Inner Harbor for 2070

APPENDIX C

DETAILED RESULTS OF ECONOMIC AND VULNERABLE POPULATIONS ANALYSES

Provided in this appendix are tables to support the Boston Harbor Barrier preliminary benefit-cost review and vulnerable populations exposure analysis. When reviewing the tables, please consider the following assumptions and limitations of this data:

- Values are rounded to provide a general estimate of structure damage, contents losses, and displacement costs associated with each sea level rise scenario and associated frequencies. These values are not provided as precise values due to the high-level nature of this analysis.
- 2030 and 2013 estimates do not consider flooded areas landward of any of the three dams within the Boston Metropolitan Statistical Area. Therefore, results are considerably lower than the 2070 and 2100 scenarios.
- Vulnerable populations results are for the City of Boston only.

TABLE APPENDIX C1

Outer Barrier Single-Event Losses Avoided by Community

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Braintree	5-Foot	Outer Barrier	.1%	$47,000,000	$74,000,000	$5,000,000	$126,000,000
Brookline	5-Foot	Outer Barrier	.1%	$38,000,000	$33,000,000	$4,000,000	$75,000,000
Cambridge	5-Foot	Outer Barrier	.1%	$1,703,000,000	$2,099,000,000	$287,000,000	$4,089,000,000
Chelsea	5-Foot	Outer Barrier	.1%	$450,000,000	$712,000,000	$76,000,000	$1,238,000,000
Everett	5-Foot	Outer Barrier	.1%	$293,000,000	$567,000,000	$51,000,000	$911,000,000
Hingham	5-Foot	Outer Barrier	.1%	$123,000,000	$112,000,000	$18,000,000	$253,000,000
Hull	5-Foot	Outer Barrier	.1%	$424,000,000	$314,000,000	$105,000,000	$843,000,000
Malden	5-Foot	Outer Barrier	.1%	$496,000,000	$630,000,000	$96,000,000	$1,222,000,000
Medford	5-Foot	Outer Barrier	.1%	$1,018,000,000	$1,143,000,000	$228,000,000	$2,389,000,000
Milton	5-Foot	Outer Barrier	.1%	$32,000,000	$25,000,000	$6,000,000	$63,000,000
Newton	5-Foot	Outer Barrier	.1%	$1,000,000	$300,000	$100,000	$1,400,000
Quincy	5-Foot	Outer Barrier	.1%	$1,217,000,000	$1,040,000,000	$226,000,000	$2,483,000,000
Revere	5-Foot	Outer Barrier	.1%	$910,000,000	$1,030,000,000	$178,000,000	$2,118,000,000
Somerville	5-Foot	Outer Barrier	.1%	$598,000,000	$757,000,000	$90,000,000	$1,445,000,000
Weymouth	5-Foot	Outer Barrier	.1%	$97,000,000	$104,000,000	$15,000,000	$216,000,000
Winthrop	5-Foot	Outer Barrier	.1%	$479,000,000	$239,000,000	$109,000,000	$827,000,000
Braintree	5-Foot	Outer Barrier	1%	$37,000,000	$62,000,000	$4,000,000	$103,000,000
Brookline	5-Foot	Outer Barrier	1%	$23,000,000	$25,000,000	$2,000,000	$50,000,000
Cambridge	5-Foot	Outer Barrier	1%	$1,419,000,000	$1,747,000,000	$204,000,000	$3,370,000,000
Chelsea	5-Foot	Outer Barrier	1%	$381,000,000	$652,000,000	$59,000,000	$1,092,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Everett	5-Foot	Outer Barrier	1%	$256,000,000	$526,000,000	$41,000,000	$823,000,000
Hingham	5-Foot	Outer Barrier	1%	$114,000,000	$104,000,000	$16,000,000	$234,000,000
Hull	5-Foot	Outer Barrier	1%	$366,000,000	$287,000,000	$91,000,000	$744,000,000
Malden	5-Foot	Outer Barrier	1%	$400,000,000	$550,000,000	$67,000,000	$1,017,000,000
Medford	5-Foot	Outer Barrier	1%	$860,000,000	$992,000,000	$177,000,000	$2,029,000,000
Milton	5-Foot	Outer Barrier	1%	$28,000,000	$22,000,000	$5,000,000	$55,000,000
Newton	5-Foot	Outer Barrier	1%	$1,000,000	$300,000	$100,000	$1,400,000
Quincy	5-Foot	Outer Barrier	1%	$1,035,000,000	$907,000,000	$176,000,000	$2,118,000,000
Revere	5-Foot	Outer Barrier	1%	$764,000,000	$861,000,000	$141,000,000	$1,766,000,000
Somerville	5-Foot	Outer Barrier	1%	$405,000,000	$509,000,000	$48,000,000	$962,000,000
Weymouth	5-Foot	Outer Barrier	1%	$86,000,000	$99,000,000	$12,000,000	$197,000,000
Winthrop	5-Foot	Outer Barrier	1%	$410,000,000	$216,000,000	$90,000,000	$716,000,000
Braintree	5-Foot	Outer Barrier	2%	$34,000,000	$54,000,000	$3,000,000	$91,000,000
Brookline	5-Foot	Outer Barrier	2%	$19,000,000	$22,000,000	$2,000,000	$43,000,000
Cambridge	5-Foot	Outer Barrier	2%	$1,347,000,000	$1,671,000,000	$184,000,000	$3,202,000,000
Chelsea	5-Foot	Outer Barrier	2%	$372,000,000	$646,000,000	$58,000,000	$1,076,000,000
Everett	5-Foot	Outer Barrier	2%	$249,000,000	$510,000,000	$38,000,000	$797,000,000
Hingham	5-Foot	Outer Barrier	2%	$107,000,000	$97,000,000	$15,000,000	$219,000,000
Hull	5-Foot	Outer Barrier	2%	$329,000,000	$259,000,000	$82,000,000	$670,000,000
Malden	5-Foot	Outer Barrier	2%	$378,000,000	$528,000,000	$62,000,000	$968,000,000
Medford	5-Foot	Outer Barrier	2%	$806,000,000	$953,000,000	$161,000,000	$1,920,000,000
Milton	5-Foot	Outer Barrier	2%	$25,000,000	$19,000,000	$4,000,000	$48,000,000
Newton	5-Foot	Outer Barrier	2%	$1,000,000	$300,000	$100,000	$1,400,000
Quincy	5-Foot	Outer Barrier	2%	$984,000,000	$879,000,000	$166,000,000	$2,029,000,000
Revere	5-Foot	Outer Barrier	2%	$725,000,000	$835,000,000	$131,000,000	$1,691,000,000
Somerville	5-Foot	Outer Barrier	2%	$369,000,000	$475,000,000	$43,000,000	$887,000,000
Weymouth	5-Foot	Outer Barrier	2%	$77,000,000	$82,000,000	$10,000,000	$169,000,000
Winthrop	5-Foot	Outer Barrier	2%	$381,000,000	$208,000,000	$81,000,000	$670,000,000
Braintree	5-Foot	Outer Barrier	10%	$32,000,000	$52,000,000	$3,000,000	$87,000,000
Brookline	5-Foot	Outer Barrier	10%	$15,000,000	$17,000,000	$1,000,000	$33,000,000
Cambridge	5-Foot	Outer Barrier	10%	$1,083,000,000	$1,329,000,000	$133,000,000	$2,545,000,000
Chelsea	5-Foot	Outer Barrier	10%	$328,000,000	$575,000,000	$46,000,000	$949,000,000
Everett	5-Foot	Outer Barrier	10%	$225,000,000	$452,000,000	$31,000,000	$708,000,000
Hingham	5-Foot	Outer Barrier	10%	$102,000,000	$90,000,000	$14,000,000	$206,000,000
Hull	5-Foot	Outer Barrier	10%	$317,000,000	$251,000,000	$78,000,000	$646,000,000
Malden	5-Foot	Outer Barrier	10%	$328,000,000	$457,000,000	$48,000,000	$833,000,000
Medford	5-Foot	Outer Barrier	10%	$698,000,000	$814,000,000	$135,000,000	$1,647,000,000
Milton	5-Foot	Outer Barrier	10%	$24,000,000	$19,000,000	$4,000,000	$47,000,000
Newton	5-Foot	Outer Barrier	10%	$400,000	$200,000	$30,000	$630,000
Quincy	5-Foot	Outer Barrier	10%	$845,000,000	$763,000,000	$129,000,000	$1,737,000,000
Revere	5-Foot	Outer Barrier	10%	$622,000,000	$718,000,000	$105,000,000	$1,445,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Somerville	5-Foot	Outer Barrier	10%	$173,000,000	$213,000,000	$18,000,000	$404,000,000
Weymouth	5-Foot	Outer Barrier	10%	$87,000,000	$88,000,000	$10,000,000	$185,000,000
Winthrop	5-Foot	Outer Barrier	10%	$349,000,000	$188,000,000	$73,000,000	$610,000,000
Braintree	3-Foot	Outer Barrier	0%	$29,000,000	$51,000,000	$3,000,000	$83,000,000
Brookline	3-Foot	Outer Barrier	0%	$6,000,000	$7,000,000	$1,000,000	$14,000,000
Cambridge	3-Foot	Outer Barrier	0%	$578,000,000	$916,000,000	$64,000,000	$1,558,000,000
Chelsea	3-Foot	Outer Barrier	0%	$361,000,000	$629,000,000	$52,000,000	$1,042,000,000
Everett	3-Foot	Outer Barrier	0%	$241,000,000	$484,000,000	$34,000,000	$759,000,000
Hingham	3-Foot	Outer Barrier	0%	$94,000,000	$87,000,000	$12,000,000	$193,000,000
Hull	3-Foot	Outer Barrier	0%	$324,000,000	$257,000,000	$80,000,000	$661,000,000
Malden	3-Foot	Outer Barrier	0%	$355,000,000	$500,000,000	$57,000,000	$912,000,000
Medford	3-Foot	Outer Barrier	0%	$743,000,000	$897,000,000	$144,000,000	$1,784,000,000
Milton	3-Foot	Outer Barrier	0%	$24,000,000	$19,000,000	$4,000,000	$47,000,000
Newton	3-Foot	Outer Barrier	0%	$1,000,000	$300,000	$100,000	$1,400,000
Quincy	3-Foot	Outer Barrier	0%	$945,000,000	$856,000,000	$151,000,000	$1,952,000,000
Revere	3-Foot	Outer Barrier	0%	$685,000,000	$802,000,000	$124,000,000	$1,611,000,000
Somerville	3-Foot	Outer Barrier	0%	$206,000,000	$297,000,000	$25,000,000	$528,000,000
Weymouth	3-Foot	Outer Barrier	0%	$82,000,000	$84,000,000	$9,000,000	$175,000,000
Winthrop	3-Foot	Outer Barrier	0%	$364,000,000	$196,000,000	$76,000,000	$636,000,000
Braintree	3-Foot	Outer Barrier	1%	$28,000,000	$49,000,000	$2,000,000	$79,000,000
Brookline	3-Foot	Outer Barrier	1%	$100,000	$200,000	$0	$300,000
Cambridge	3-Foot	Outer Barrier	1%	$227,000,000	$389,000,000	$28,000,000	$644,000,000
Chelsea	3-Foot	Outer Barrier	1%	$326,000,000	$566,000,000	$44,000,000	$936,000,000
Everett	3-Foot	Outer Barrier	1%	$224,000,000	$450,000,000	$29,000,000	$703,000,000
Hingham	3-Foot	Outer Barrier	1%	$86,000,000	$81,000,000	$11,000,000	$178,000,000
Hull	3-Foot	Outer Barrier	1%	$290,000,000	$221,000,000	$65,000,000	$576,000,000
Malden	3-Foot	Outer Barrier	1%	$281,000,000	$398,000,000	$40,000,000	$719,000,000
Medford	3-Foot	Outer Barrier	1%	$645,000,000	$808,000,000	$113,000,000	$1,566,000,000
Milton	3-Foot	Outer Barrier	1%	$24,000,000	$19,000,000	$4,000,000	$47,000,000
Newton	3-Foot	Outer Barrier	1%	$300,000	$50,000	$0	$350,000
Quincy	3-Foot	Outer Barrier	1%	$789,000,000	$682,000,000	$112,000,000	$1,583,000,000
Revere	3-Foot	Outer Barrier	1%	$565,000,000	$609,000,000	$89,000,000	$1,263,000,000
Somerville	3-Foot	Outer Barrier	1%	$178,000,000	$251,000,000	$20,000,000	$449,000,000
Weymouth	3-Foot	Outer Barrier	1%	$82,000,000	$84,000,000	$9,000,000	$175,000,000
Winthrop	3-Foot	Outer Barrier	1%	$320,000,000	$173,000,000	$61,000,000	$554,000,000
Braintree	3-Foot	Outer Barrier	2%	$26,000,000	$43,000,000	$2,000,000	$71,000,000
Brookline	3-Foot	Outer Barrier	2%	$100,000	$200,000	$0	$300,000
Cambridge	3-Foot	Outer Barrier	2%	$194,000,000	$335,000,000	$23,000,000	$552,000,000
Chelsea	3-Foot	Outer Barrier	2%	$290,000,000	$484,000,000	$35,000,000	$809,000,000
Everett	3-Foot	Outer Barrier	2%	$194,000,000	$377,000,000	$22,000,000	$593,000,000
Hingham	3-Foot	Outer Barrier	2%	$69,000,000	$62,000,000	$8,000,000	$139,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Hull	3-Foot	Outer Barrier	2%	$267,000,000	$200,000,000	$54,000,000	$521,000,000
Malden	3-Foot	Outer Barrier	2%	$250,000,000	$354,000,000	$32,000,000	$636,000,000
Medford	3-Foot	Outer Barrier	2%	$572,000,000	$686,000,000	$91,000,000	$1,349,000,000
Milton	3-Foot	Outer Barrier	2%	$14,000,000	$13,000,000	$2,000,000	$29,000,000
Newton	3-Foot	Outer Barrier	2%	$200,000	$50,000	$0	$250,000
Quincy	3-Foot	Outer Barrier	2%	$708,000,000	$592,000,000	$96,000,000	$1,396,000,000
Revere	3-Foot	Outer Barrier	2%	$486,000,000	$517,000,000	$73,000,000	$1,076,000,000
Somerville	3-Foot	Outer Barrier	2%	$146,000,000	$189,000,000	$13,000,000	$348,000,000
Weymouth	3-Foot	Outer Barrier	2%	$68,000,000	$76,000,000	$7,000,000	$151,000,000
Winthrop	3-Foot	Outer Barrier	2%	$292,000,000	$155,000,000	$53,000,000	$500,000,000
Braintree	3-Foot	Outer Barrier	10%	$24,000,000	$40,000,000	$2,000,000	$66,000,000
Brookline	3-Foot	Outer Barrier	10%	$100,000	$200,000	$0	$300,000
Cambridge	3-Foot	Outer Barrier	10%	$184,000,000	$323,000,000	$22,000,000	$529,000,000
Chelsea	3-Foot	Outer Barrier	10%	$249,000,000	$389,000,000	$26,000,000	$664,000,000
Everett	3-Foot	Outer Barrier	10%	$163,000,000	$288,000,000	$18,000,000	$469,000,000
Hingham	3-Foot	Outer Barrier	10%	$61,000,000	$55,000,000	$7,000,000	$123,000,000
Hull	3-Foot	Outer Barrier	10%	$254,000,000	$182,000,000	$50,000,000	$486,000,000
Malden	3-Foot	Outer Barrier	10%	$187,000,000	$252,000,000	$25,000,000	$464,000,000
Medford	3-Foot	Outer Barrier	10%	$509,000,000	$631,000,000	$75,000,000	$1,215,000,000
Milton	3-Foot	Outer Barrier	10%	$13,000,000	$13,000,000	$2,000,000	$28,000,000
Newton	3-Foot	Outer Barrier	10%	$200,000	$50,000	$0	$250,000
Quincy	3-Foot	Outer Barrier	10%	$594,000,000	$503,000,000	$74,000,000	$1,171,000,000
Revere	3-Foot	Outer Barrier	10%	$419,000,000	$456,000,000	$57,000,000	$932,000,000
Somerville	3-Foot	Outer Barrier	10%	$122,000,000	$154,000,000	$11,000,000	$287,000,000
Weymouth	3-Foot	Outer Barrier	10%	$64,000,000	$71,000,000	$7,000,000	$142,000,000
Winthrop	3-Foot	Outer Barrier	10%	$254,000,000	$125,000,000	$42,000,000	$421,000,000
Braintree	1-Foot	Outer Barrier	.1%	$17,000,000	$23,000,000	$2,000,000	$42,000,000
Chelsea	1-Foot	Outer Barrier	.1%	$121,000,000	$193,000,000	$8,000,000	$322,000,000
Everett	1-Foot	Outer Barrier	.1%	$58,000,000	$110,000,000	$5,000,000	$173,000,000
Hingham	1-Foot	Outer Barrier	.1%	$49,000,000	$50,000,000	$4,000,000	$103,000,000
Hull	1-Foot	Outer Barrier	.1%	$164,000,000	$95,000,000	$22,000,000	$281,000,000
Malden	1-Foot	Outer Barrier	.1%	$29,000,000	$16,000,000	$5,000,000	$50,000,000
Milton	1-Foot	Outer Barrier	.1%	$23,000,000	$18,000,000	$4,000,000	$45,000,000
Quincy	1-Foot	Outer Barrier	.1%	$522,000,000	$473,000,000	$62,000,000	$1,057,000,000
Revere	1-Foot	Outer Barrier	.1%	$254,000,000	$249,000,000	$30,000,000	$533,000,000
Somerville	1-Foot	Outer Barrier	.1%	$17,000,000	$29,000,000	$0	$46,000,000
Weymouth	1-Foot	Outer Barrier	.1%	$53,000,000	$56,000,000	$5,000,000	$114,000,000
Winthrop	1-Foot	Outer Barrier	.1%	$171,000,000	$82,000,000	$19,000,000	$272,000,000
Braintree	1-Foot	Outer Barrier	1%	$13,000,000	$17,000,000	$1,000,000	$31,000,000
Chelsea	1-Foot	Outer Barrier	1%	$101,000,000	$149,000,000	$3,000,000	$253,000,000
Everett	1-Foot	Outer Barrier	1%	$54,000,000	$100,000,000	$1,000,000	$155,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Hingham	1-Foot	Outer Barrier	1%	$41,000,000	$43,000,000	$3,000,000	$87,000,000
Hull	1-Foot	Outer Barrier	1%	$139,000,000	$81,000,000	$19,000,000	$239,000,000
Malden	1-Foot	Outer Barrier	1%	$26,000,000	$14,000,000	$4,000,000	$44,000,000
Milton	1-Foot	Outer Barrier	1%	$17,000,000	$15,000,000	$2,000,000	$34,000,000
Quincy	1-Foot	Outer Barrier	1%	$302,000,000	$266,000,000	$26,000,000	$594,000,000
Revere	1-Foot	Outer Barrier	1%	$221,000,000	$219,000,000	$20,000,000	$460,000,000
Somerville	1-Foot	Outer Barrier	1%	$13,000,000	$14,000,000	$0	$27,000,000
Weymouth	1-Foot	Outer Barrier	1%	$37,000,000	$41,000,000	$2,000,000	$80,000,000
Winthrop	1-Foot	Outer Barrier	1%	$137,000,000	$69,000,000	$16,000,000	$222,000,000
Braintree	1-Foot	Outer Barrier	2%	$12,000,000	$15,000,000	$1,000,000	$28,000,000
Chelsea	1-Foot	Outer Barrier	2%	$92,000,000	$135,000,000	$2,000,000	$229,000,000
Everett	1-Foot	Outer Barrier	2%	$55,000,000	$100,000,000	$1,000,000	$156,000,000
Hingham	1-Foot	Outer Barrier	2%	$39,000,000	$41,000,000	$2,000,000	$82,000,000
Hull	1-Foot	Outer Barrier	2%	$86,000,000	$51,000,000	$9,000,000	$146,000,000
Malden	1-Foot	Outer Barrier	2%	$20,000,000	$8,000,000	$3,000,000	$31,000,000
Milton	1-Foot	Outer Barrier	2%	$17,000,000	$15,000,000	$2,000,000	$34,000,000
Quincy	1-Foot	Outer Barrier	2%	$285,000,000	$261,000,000	$21,000,000	$567,000,000
Revere	1-Foot	Outer Barrier	2%	$201,000,000	$208,000,000	$19,000,000	$428,000,000
Somerville	1-Foot	Outer Barrier	2%	$13,000,000	$14,000,000	$0	$27,000,000
Weymouth	1-Foot	Outer Barrier	2%	$33,000,000	$38,000,000	$2,000,000	$73,000,000
Winthrop	1-Foot	Outer Barrier	2%	$115,000,000	$60,000,000	$6,000,000	$181,000,000
Braintree	1-Foot	Outer Barrier	10%	$10,000,000	$11,000,000	$1,000,000	$22,000,000
Chelsea	1-Foot	Outer Barrier	10%	$35,000,000	$54,000,000	$1,000,000	$90,000,000
Everett	1-Foot	Outer Barrier	10%	$13,000,000	$23,000,000	$1,000,000	$37,000,000
Hingham	1-Foot	Outer Barrier	10%	$37,000,000	$35,000,000	$3,000,000	$75,000,000
Hull	1-Foot	Outer Barrier	10%	$57,000,000	$32,000,000	$3,000,000	$92,000,000
Malden	1-Foot	Outer Barrier	10%	$11,000,000	$5,000,000	$1,000,000	$17,000,000
Milton	1-Foot	Outer Barrier	10%	$16,000,000	$15,000,000	$2,000,000	$33,000,000
Quincy	1-Foot	Outer Barrier	10%	$244,000,000	$228,000,000	$18,000,000	$490,000,000
Revere	1-Foot	Outer Barrier	10%	$119,000,000	$136,000,000	$13,000,000	$268,000,000
Somerville	1-Foot	Outer Barrier	10%	$50,000	$10,000	$0	$60,000
Weymouth	1-Foot	Outer Barrier	10%	$30,000,000	$34,000,000	$2,000,000	$66,000,000
Winthrop	1-Foot	Outer Barrier	10%	$57,000,000	$30,000,000	$4,000,000	$91,000,000
Braintree	0-Feet	Outer Barrier	.1%	$15,000,000	$20,000,000	$1,000,000	$36,000,000
Chelsea	0-Feet	Outer Barrier	.1%	$42,000,000	$63,000,000	$2,000,000	$107,000,000
Everett	0-Feet	Outer Barrier	.1%	$31,000,000	$53,000,000	$1,000,000	$85,000,000
Hingham	0-Feet	Outer Barrier	.1%	$36,000,000	$34,000,000	$3,000,000	$73,000,000
Hull	0-Feet	Outer Barrier	.1%	$107,000,000	$67,000,000	$16,000,000	$190,000,000
Malden	0-Feet	Outer Barrier	.1%	$21,000,000	$9,000,000	$2,000,000	$32,000,000
Milton	0-Feet	Outer Barrier	.1%	$19,000,000	$16,000,000	$3,000,000	$38,000,000
Quincy	0-Feet	Outer Barrier	.1%	$371,000,000	$340,000,000	$43,000,000	$754,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Revere	0-Feet	Outer Barrier	.1%	$170,000,000	$163,000,000	$16,000,000	$349,000,000
Somerville	0-Feet	Outer Barrier	.1%	$50,000	$10,000	$0	$60,000
Weymouth	0-Feet	Outer Barrier	1%	$40,000,000	$45,000,000	$4,000,000	$89,000,000
Winthrop	0-Feet	Outer Barrier	.1%	$109,000,000	$57,000,000	$10,000,000	$176,000,000
Braintree	0-Feet	Outer Barrier	1%	$9,000,000	$9,000,000	$1,000,000	$19,000,000
Chelsea	0-Feet	Outer Barrier	1%	$35,000,000	$52,000,000	$1,000,000	$88,000,000
Everett	0-Feet	Outer Barrier	1%	$24,000,000	$36,000,000	$1,000,000	$61,000,000
Hingham	0-Feet	Outer Barrier	1%	$27,000,000	$26,000,000	$2,000,000	$55,000,000
Hull	0-Feet	Outer Barrier	1%	$97,000,000	$59,000,000	$9,000,000	$165,000,000
Malden	0-Feet	Outer Barrier	1%	$7,000,000	$3,000,000	$0	$10,000,000
Milton	0-Feet	Outer Barrier	1%	$16,000,000	$15,000,000	$2,000,000	$33,000,000
Quincy	0-Feet	Outer Barrier	1%	$235,000,000	$244,000,000	$15,000,000	$494,000,000
Revere	0-Feet	Outer Barrier	1%	$99,000,000	$116,000,000	$5,000,000	$220,000,000
Somerville	0-Feet	Outer Barrier	1%	$50,000	$10,000	$0	$60,000
Weymouth	0-Feet	Outer Barrier	1%	$32,000,000	$38,000,000	$2,000,000	$72,000,000
Winthrop	0-Feet	Outer Barrier	1%	$77,000,000	$44,000,000	$4,000,000	$125,000,000
Braintree	0-Feet	Outer Barrier	2%	$8,000,000	$9,000,000	$1,000,000	$18,000,000
Chelsea	0-Feet	Outer Barrier	2%	$14,000,000	$29,000,000	$1,000,000	$44,000,000
Everett	0-Feet	Outer Barrier	2%	$15,000,000	$32,000,000	$1,000,000	$48,000,000
Hingham	0-Feet	Outer Barrier	2%	$25,000,000	$22,000,000	$3,000,000	$50,000,000
Hull	0-Feet	Outer Barrier	2%	$55,000,000	$32,000,000	$3,000,000	$90,000,000
Malden	0-Feet	Outer Barrier	2%	$3,000,000	$2,000,000	$0	$5,000,000
Milton	0-Feet	Outer Barrier	2%	$15,000,000	$14,000,000	$2,000,000	$31,000,000
Quincy	0-Feet	Outer Barrier	2%	$179,000,000	$211,000,000	$12,000,000	$402,000,000
Revere	0-Feet	Outer Barrier	2%	$75,000,000	$101,000,000	$4,000,000	$180,000,000
Somerville	0-Feet	Outer Barrier	2%	$50,000	$10,000	$0	$60,000
Weymouth	0-Feet	Outer Barrier	2%	$30,000,000	$34,000,000	$1,000,000	$65,000,000
Winthrop	0-Feet	Outer Barrier	2%	$26,000,000	$13,000,000	$2,000,000	$41,000,000
Braintree	0-Feet	Outer Barrier	10%	$8,000,000	$8,000,000	$1,000,000	$17,000,000
Chelsea	0-Feet	Outer Barrier	10%	$8,000,000	$16,000,000	$1,000,000	$25,000,000
Everett	0-Feet	Outer Barrier	10%	$13,000,000	$28,000,000	$1,000,000	$42,000,000
Hingham	0-Feet	Outer Barrier	10%	$25,000,000	$21,000,000	$2,000,000	$48,000,000
Hull	0-Feet	Outer Barrier	10%	$35,000,000	$21,000,000	$2,000,000	$58,000,000
Malden	0-Feet	Outer Barrier	10%	$1,000,000	$1,000,000	$0	$2,000,000
Milton	0-Feet	Outer Barrier	10%	$13,000,000	$11,000,000	$2,000,000	$26,000,000
Quincy	0-Feet	Outer Barrier	10%	$163,000,000	$197,000,000	$12,000,000	$372,000,000
Revere	0-Feet	Outer Barrier	10%	$49,000,000	$87,000,000	$2,000,000	$138,000,000
Somerville	0-Feet	Outer Barrier	10%	$50,000	$10,000	$0	$60,000
Weymouth	0-Feet	Outer Barrier	10%	$27,000,000	$32,000,000	$1,000,000	$60,000,000
Winthrop	0-Foot	Outer Barrier	10%	$21,000,000	$11,000,000	$2,000,000	$34,000,000

TABLE APPENDIX C2

Outer Barrier Single-Event Losses Avoided by Neighborhood, City of Boston

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Allston	5-Foot	Outer Barrier	.1	$199,000,000	$284,000,000	$26,000,000	$509,000,000
Back Bay	5-Foot	Outer Barrier	.1	$628,000,000	$851,000,000	$90,000,000	$1,569,000,000
Charlestown	5-Foot	Outer Barrier	.1	$429,000,000	$481,000,000	$49,000,000	$959,000,000
Downtown	5-Foot	Outer Barrier	.1	$1,464,000,000	$1,975,000,000	$190,000,000	$3,629,000,000
East Boston	5-Foot	Outer Barrier	.1	$1,234,000,000	$1,236,000,000	$204,000,000	$2,674,000,000
Fenway	5-Foot	Outer Barrier	.1	$889,000,000	$1,010,000,000	$111,000,000	$2,010,000,000
Jamaica Plain	5-Foot	Outer Barrier	.1	$125,000,000	$101,000,000	$3,000,000	$229,000,000
North Dorchester	5-Foot	Outer Barrier	.1	$349,000,000	$426,000,000	$40,000,000	$815,000,000
Roxbury	5-Foot	Outer Barrier	.1	$460,000,000	$640,000,000	$44,000,000	$1,144,000,000
South Boston	5-Foot	Outer Barrier	.1	$997,000,000	$1,350,000,000	$173,000,000	$2,520,000,000
South Dorchester	5-Foot	Outer Barrier	.1	$401,000,000	$481,000,000	$53,000,000	$935,000,000
South End	5-Foot	Outer Barrier	.1	$881,000,000	$836,000,000	$111,000,000	$1,828,000,000
Allston	5-Foot	Outer Barrier	1%	$121,000,000	$180,000,000	$14,000,000	$315,000,000
Back Bay	5-Foot	Outer Barrier	1%	$544,000,000	$709,000,000	$61,000,000	$1,314,000,000
Charlestown	5-Foot	Outer Barrier	1%	$338,000,000	$375,000,000	$33,000,000	$746,000,000
Downtown	5-Foot	Outer Barrier	1%	$1,265,000,000	$1,705,000,000	$140,000,000	$3,110,000,000
East Boston	5-Foot	Outer Barrier	1%	$1,022,000,000	$1,015,000,000	$148,000,000	$2,185,000,000
Fenway	5-Foot	Outer Barrier	1%	$720,000,000	$825,000,000	$75,000,000	$1,620,000,000
Jamaica Plain	5-Foot	Outer Barrier	1%	$76,000,000	$60,000,000	$400,000	$136,400,000
North Dorchester	5-Foot	Outer Barrier	1%	$241,000,000	$315,000,000	$22,000,000	$578,000,000
Roxbury	5-Foot	Outer Barrier	1%	$260,000,000	$360,000,000	$22,000,000	$642,000,000
South Boston	5-Foot	Outer Barrier	1%	$812,000,000	$1,116,000,000	$125,000,000	$2,053,000,000
South Dorchester	5-Foot	Outer Barrier	1%	$303,000,000	$366,000,000	$35,000,000	$704,000,000
South End	5-Foot	Outer Barrier	1%	$702,000,000	$671,000,000	$67,000,000	$1,440,000,000
Allston	5-Foot	Outer Barrier	2%	$83,000,000	$106,000,000	$8,000,000	$197,000,000
Back Bay	5-Foot	Outer Barrier	2%	$488,000,000	$600,000,000	$50,000,000	$1,138,000,000
Charlestown	5-Foot	Outer Barrier	2%	$327,000,000	$363,000,000	$30,000,000	$720,000,000
Downtown	5-Foot	Outer Barrier	2%	$1,235,000,000	$1,669,000,000	$132,000,000	$3,036,000,000
East Boston	5-Foot	Outer Barrier	2%	$952,000,000	$925,000,000	$132,000,000	$2,009,000,000
Fenway	5-Foot	Outer Barrier	2%	$631,000,000	$730,000,000	$55,000,000	$1,416,000,000
Jamaica Plain	5-Foot	Outer Barrier	2%	$57,000,000	$36,000,000	$400,000	$93,400,000
North Dorchester	5-Foot	Outer Barrier	2%	$207,000,000	$269,000,000	$18,000,000	$494,000,000
Roxbury	5-Foot	Outer Barrier	2%	$201,000,000	$293,000,000	$16,000,000	$510,000,000
South Boston	5-Foot	Outer Barrier	2%	$724,000,000	$1,021,000,000	$108,000,000	$1,853,000,000
South Dorchester	5-Foot	Outer Barrier	2%	$260,000,000	$309,000,000	$30,000,000	$599,000,000
South End	5-Foot	Outer Barrier	2%	$657,000,000	$614,000,000	$62,000,000	$1,333,000,000
Allston	5-Foot	Outer Barrier	10%	$59,000,000	$70,000,000	$4,000,000	$133,000,000
Back Bay	5-Foot	Outer Barrier	10%	$379,000,000	$427,000,000	$29,000,000	$835,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Charlestown	5-Foot	Outer Barrier	10%	$212,000,000	$245,000,000	$17,000,000	$474,000,000
Downtown	5-Foot	Outer Barrier	10%	$1,016,000,000	$1,284,000,000	$88,000,000	$2,388,000,000
East Boston	5-Foot	Outer Barrier	10%	$813,000,000	$770,000,000	$104,000,000	$1,687,000,000
Fenway	5-Foot	Outer Barrier	10%	$382,000,000	$454,000,000	$27,000,000	$863,000,000
Jamaica Plain	5-Foot	Outer Barrier	10%	$16,000,000	$14,000,000	$0	$30,000,000
North Dorchester	5-Foot	Outer Barrier	10%	$114,000,000	$146,000,000	$10,000,000	$270,000,000
Roxbury	5-Foot	Outer Barrier	10%	$114,000,000	$177,000,000	$10,000,000	$301,000,000
South Boston	5-Foot	Outer Barrier	10%	$609,000,000	$856,000,000	$79,000,000	$1,544,000,000
South Dorchester	5-Foot	Outer Barrier	10%	$196,000,000	$230,000,000	$20,000,000	$446,000,000
South End	5-Foot	Outer Barrier	10%	$443,000,000	$481,000,000	$32,000,000	$956,000,000
Allston	3-Foot	Outer Barrier	.1	$86,000,000	$115,000,000	$6,000,000	$207,000,000
Back Bay	3-Foot	Outer Barrier	.1	$183,000,000	$200,000,000	$14,000,000	$397,000,000
Charlestown	3-Foot	Outer Barrier	.1	$328,000,000	$339,000,000	$29,000,000	$696,000,000
Downtown	3-Foot	Outer Barrier	.1	$1,064,000,000	$1,362,000,000	$98,000,000	$2,524,000,000
East Boston	3-Foot	Outer Barrier	.1	$984,000,000	$989,000,000	$131,000,000	$2,104,000,000
Fenway	3-Foot	Outer Barrier	.1	$312,000,000	$367,000,000	$21,000,000	$700,000,000
Jamaica Plain	3-Foot	Outer Barrier	.1	$13,000,000	$9,000,000	$0	$22,000,000
North Dorchester	3-Foot	Outer Barrier	.1	$174,000,000	$237,000,000	$16,000,000	$427,000,000
Roxbury	3-Foot	Outer Barrier	.1	$168,000,000	$261,000,000	$12,000,000	$441,000,000
South Boston	3-Foot	Outer Barrier	.1	$765,000,000	$1,068,000,000	$115,000,000	$1,948,000,000
South Dorchester	3-Foot	Outer Barrier	.1	$220,000,000	$266,000,000	$24,000,000	$510,000,000
South End	3-Foot	Outer Barrier	.1	$517,000,000	$569,000,000	$41,000,000	$1,127,000,000
Allston	3-Foot	Outer Barrier	1%	$7,000,000	$9,000,000	$120,000	$16,120,000
Back Bay	3-Foot	Outer Barrier	1%	$34,000,000	$32,000,000	$1,000,000	$67,000,000
Charlestown	3-Foot	Outer Barrier	1%	$279,000,000	$299,000,000	$22,000,000	$600,000,000
Downtown	3-Foot	Outer Barrier	1%	$889,000,000	$1,101,000,000	$71,000,000	$2,061,000,000
East Boston	3-Foot	Outer Barrier	1%	$876,000,000	$901,000,000	$107,000,000	$1,884,000,000
Fenway	3-Foot	Outer Barrier	1%	$13,000,000	$11,000,000	$70,000	$24,070,000
North Dorchester	3-Foot	Outer Barrier	1%	$130,000,000	$169,000,000	$11,000,000	$310,000,000
Roxbury	3-Foot	Outer Barrier	1%	$71,000,000	$111,000,000	$3,000,000	$185,000,000
South Boston	3-Foot	Outer Barrier	1%	$655,000,000	$927,000,000	$87,000,000	$1,669,000,000
South Dorchester	3-Foot	Outer Barrier	1%	$181,000,000	$215,000,000	$18,000,000	$414,000,000
South End	3-Foot	Outer Barrier	1%	$339,000,000	$378,000,000	$29,000,000	$746,000,000
Allston	3-Foot	Outer Barrier	2%	$4,000,000	$5,000,000	$20,000	$9,020,000
Back Bay	3-Foot	Outer Barrier	2%	$7,000,000	$6,000,000	$200,000	$13,200,000
Charlestown	3-Foot	Outer Barrier	2%	$250,000,000	$261,000,000	$17,000,000	$528,000,000
Downtown	3-Foot	Outer Barrier	2%	$709,000,000	$851,000,000	$48,000,000	$1,608,000,000
East Boston	3-Foot	Outer Barrier	2%	$797,000,000	$827,000,000	$85,000,000	$1,709,000,000
Fenway	3-Foot	Outer Barrier	2%	$3,000,000	$5,000,000	$30,000	$8,030,000
North Dorchester	3-Foot	Outer Barrier	2%	$78,000,000	$113,000,000	$7,000,000	$198,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Roxbury	3-Foot	Outer Barrier	2%	$23,000,000	$33,000,000	$1,000,000	$57,000,000
South Boston	3-Foot	Outer Barrier	2%	$561,000,000	$804,000,000	$66,000,000	$1,431,000,000
South Dorchester	3-Foot	Outer Barrier	2%	$153,000,000	$188,000,000	$14,000,000	$355,000,000
South End	3-Foot	Outer Barrier	2%	$211,000,000	$249,000,000	$11,000,000	$471,000,000
Allston	3-Foot	Outer Barrier	10%	$4,000,000	$5,000,000	$20,000	$9,020,000
Back Bay	3-Foot	Outer Barrier	10%	$7,000,000	$6,000,000	$200,000	$13,200,000
Charlestown	3-Foot	Outer Barrier	10%	$200,000,000	$222,000,000	$13,000,000	$435,000,000
Downtown	3-Foot	Outer Barrier	10%	$584,000,000	$664,000,000	$39,000,000	$1,287,000,000
East Boston	3-Foot	Outer Barrier	10%	$722,000,000	$739,000,000	$66,000,000	$1,527,000,000
Fenway	3-Foot	Outer Barrier	10%	$3,000,000	$4,000,000	$30,000	$7,030,000
North Dorchester	3-Foot	Outer Barrier	10%	$64,000,000	$94,000,000	$5,000,000	$163,000,000
Roxbury	3-Foot	Outer Barrier	10%	$13,000,000	$25,000,000	$1,000,000	$39,000,000
South Boston	3-Foot	Outer Barrier	10%	$523,000,000	$754,000,000	$57,000,000	$1,334,000,000
South Dorchester	3-Foot	Outer Barrier	10%	$124,000,000	$151,000,000	$10,000,000	$285,000,000
South End	3-Foot	Outer Barrier	10%	$95,000,000	$111,000,000	$260,000	$206,260,000
Charlestown	1-Foot	Outer Barrier	.1	$115,000,000	$134,000,000	$3,000,000	$252,000,000
Downtown	1-Foot	Outer Barrier	.1	$240,000,000	$287,000,000	$15,000,000	$542,000,000
East Boston	1-Foot	Outer Barrier	.1	$301,000,000	$374,000,000	$16,000,000	$691,000,000
Fenway	1-Foot	Outer Barrier	.1	$1,000,000	$2,000,000	$0	$3,000,000
North Dorchester	1-Foot	Outer Barrier	.1	$110,000,000	$174,000,000	$9,000,000	$293,000,000
South Boston	1-Foot	Outer Barrier	.1	$390,000,000	$546,000,000	$35,000,000	$971,000,000
South Dorchester	1-Foot	Outer Barrier	.1	$90,000,000	$131,000,000	$7,000,000	$228,000,000
Charlestown	1-Foot	Outer Barrier	1%	$70,000,000	$58,000,000	$1,000,000	$129,000,000
Downtown	1-Foot	Outer Barrier	1%	$147,000,000	$144,000,000	$2,000,000	$293,000,000
East Boston	1-Foot	Outer Barrier	1%	$231,000,000	$280,000,000	$8,000,000	$519,000,000
Fenway	1-Foot	Outer Barrier	1%	$1,000,000	$2,000,000	$0	$3,000,000
North Dorchester	1-Foot	Outer Barrier	1%	$51,000,000	$86,000,000	$3,000,000	$140,000,000
South Boston	1-Foot	Outer Barrier	1%	$256,000,000	$274,000,000	$15,000,000	$545,000,000
South Dorchester	1-Foot	Outer Barrier	1%	$37,000,000	$43,000,000	$2,000,000	$82,000,000
Charlestown	1-Foot	Outer Barrier	2%	$66,000,000	$55,000,000	$1,000,000	$122,000,000
Downtown	1-Foot	Outer Barrier	2%	$147,000,000	$144,000,000	$2,000,000	$293,000,000
East Boston	1-Foot	Outer Barrier	2%	$230,000,000	$279,000,000	$8,000,000	$517,000,000
Fenway	1-Foot	Outer Barrier	2%	$1,000,000	$2,000,000	$0	$3,000,000
North Dorchester	1-Foot	Outer Barrier	2%	$51,000,000	$85,000,000	$3,000,000	$139,000,000
South Boston	1-Foot	Outer Barrier	2%	$255,000,000	$273,000,000	$15,000,000	$543,000,000
South Dorchester	1-Foot	Outer Barrier	2%	$36,000,000	$42,000,000	$2,000,000	$80,000,000
Charlestown	1-Foot	Outer Barrier	10%	$15,000,000	$14,000,000	$120,000	$29,120,000
Downtown	1-Foot	Outer Barrier	10%	$59,000,000	$59,000,000	$2,000,000	$120,000,000
East Boston	1-Foot	Outer Barrier	10%	$31,000,000	$54,000,000	$2,000,000	$87,000,000
Fenway	1-Foot	Outer Barrier	10%	$1,000,000	$2,000,000	$0	$3,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
North Dorchester	1-Foot	Outer Barrier	10%	$3,000,000	$4,000,000	$10,000	$7,010,000
South Boston	1-Foot	Outer Barrier	10%	$100,000,000	$111,000,000	$10,000,000	$221,000,000
South Dorchester	1-Foot	Outer Barrier	10%	$27,000,000	$29,000,000	$1,000,000	$57,000,000
Charlestown	0-Feet	Outer Barrier	.1	$36,000,000	$46,000,000	$2,000,000	$84,000,000
Downtown	0-Feet	Outer Barrier	.1	$91,000,000	$106,000,000	$6,000,000	$203,000,000
East Boston	0-Feet	Outer Barrier	.1	$116,000,000	$163,000,000	$2,000,000	$281,000,000
Fenway	0-Feet	Outer Barrier	.1	$0	$0	$0	$0
North Dorchester	0-Feet	Outer Barrier	.1	$21,000,000	$25,000,000	$1,000,000	$47,000,000
South Boston	0-Feet	Outer Barrier	.1	$246,000,000	$340,000,000	$12,000,000	$598,000,000
South Dorchester	0-Feet	Outer Barrier	.1	$23,000,000	$41,000,000	$1,000,000	$65,000,000
Charlestown	0-Feet	Outer Barrier	1%	$17,000,000	$21,000,000	$1,000,000	$39,000,000
Downtown	0-Feet	Outer Barrier	1%	$16,000,000	$38,000,000	$1,000,000	$55,000,000
East Boston	0-Feet	Outer Barrier	1%	$85,000,000	$106,000,000	$2,000,000	$193,000,000
Fenway	0-Feet	Outer Barrier	1%	$0	$0	$0	$0
North Dorchester	0-Feet	Outer Barrier	1%	$3,000,000	$4,000,000	$10,000	$7,010,000
South Boston	0-Feet	Outer Barrier	1%	$155,000,000	$123,000,000	$4,000,000	$282,000,000
South Dorchester	0-Feet	Outer Barrier	1%	$6,000,000	$8,000,000	$120,000	$14,120,000
Charlestown	0-Feet	Outer Barrier	2%	$10,000,000	$13,000,000	$380,000	$23,380,000
Downtown	0-Feet	Outer Barrier	2%	$3,000,000	$4,000,000	$220,000	$7,220,000
East Boston	0-Feet	Outer Barrier	2%	$21,000,000	$40,000,000	$1,000,000	$62,000,000
Fenway	0-Feet	Outer Barrier	2%	$0	$0	$0	$0
North Dorchester	0-Feet	Outer Barrier	2%	$1,000,000	$1,000,000	$0	$2,000,000
South Boston	0-Feet	Outer Barrier	2%	$48,000,000	$50,000,000	$2,000,000	$100,000,000
South Dorchester	0-Feet	Outer Barrier	2%	$5,000,000	$7,000,000	$100,000	$12,100,000
Charlestown	0-Feet	Outer Barrier	10%	$5,000,000	$9,000,000	$300,000	$14,300,000
Downtown	0-Feet	Outer Barrier	10%	$3,000,000	$4,000,000	$220,000	$7,220,000
East Boston	0-Feet	Outer Barrier	10%	$13,000,000	$24,000,000	$370,000	$37,370,000
Fenway	0-Feet	Outer Barrier	10%	$0	$0	$0	$0
North Dorchester	0-Feet	Outer Barrier	10%	$1,000,000	$1,000,000	$0	$2,000,000
South Boston	0-Feet	Outer Barrier	10%	$47,000,000	$50,000,000	$2,000,000	$99,000,000
South Dorchester	0-Feet	Outer Barrier	10%	$4,000,000	$6,000,000	$100,000	$10,100,000

TABLE APPENDIX C3

Inner Barrier Single-Event Losses Avoided by Community

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Brookline	5-Foot	Inner Barrier	.1%	$38,000,000	$33,000,000	$4,000,000	$75,000,000
Cambridge	5-Foot	Inner Barrier	.1%	$1,703,000,000	$2,099,000,000	$287,000,000	$4,089,000,000
Chelsea	5-Foot	Inner Barrier	.1%	$450,000,000	$712,000,000	$76,000,000	$1,238,000,000
Everett	5-Foot	Inner Barrier	.1%	$290,000,000	$565,000,000	$51,000,000	$906,000,000
Malden	5-Foot	Inner Barrier	.1%	$412,000,000	$580,000,000	$74,000,000	$1,066,000,000
Medford	5-Foot	Inner Barrier	.1%	$1,018,000,000	$1,143,000,000	$228,000,000	$2,389,000,000
Revere	5-Foot	Inner Barrier	.1%	$295,000,000	$248,000,000	$59,000,000	$602,000,000
Somerville	5-Foot	Inner Barrier	.1%	$598,000,000	$757,000,000	$90,000,000	$1,445,000,000
Winthrop	5-Foot	Inner Barrier	.1%	$35,000,000	$24,000,000	$7,000,000	$66,000,000
Brookline	5-Foot	Inner Barrier	1%	$23,000,000	$25,000,000	$2,000,000	$50,000,000
Cambridge	5-Foot	Inner Barrier	1%	$1,419,000,000	$1,747,000,000	$204,000,000	$3,370,000,000
Chelsea	5-Foot	Inner Barrier	1%	$381,000,000	$652,000,000	$59,000,000	$1,092,000,000
Everett	5-Foot	Inner Barrier	1%	$254,000,000	$524,000,000	$41,000,000	$819,000,000
Malden	5-Foot	Inner Barrier	1%	$333,000,000	$512,000,000	$50,000,000	$895,000,000
Medford	5-Foot	Inner Barrier	1%	$860,000,000	$992,000,000	$177,000,000	$2,029,000,000
Revere	5-Foot	Inner Barrier	1%	$252,000,000	$208,000,000	$50,000,000	$510,000,000
Somerville	5-Foot	Inner Barrier	1%	$405,000,000	$509,000,000	$48,000,000	$962,000,000
Winthrop	5-Foot	Inner Barrier	1%	$31,000,000	$21,000,000	$6,000,000	$58,000,000
Brookline	5-Foot	Inner Barrier	2%	$19,000,000	$22,000,000	$2,000,000	$43,000,000
Cambridge	5-Foot	Inner Barrier	2%	$1,347,000,000	$1,671,000,000	$184,000,000	$3,202,000,000
Chelsea	5-Foot	Inner Barrier	2%	$372,000,000	$646,000,000	$58,000,000	$1,076,000,000
Everett	5-Foot	Inner Barrier	2%	$247,000,000	$509,000,000	$38,000,000	$794,000,000
Malden	5-Foot	Inner Barrier	2%	$313,000,000	$492,000,000	$47,000,000	$852,000,000
Medford	5-Foot	Inner Barrier	2%	$806,000,000	$953,000,000	$161,000,000	$1,920,000,000
Revere	5-Foot	Inner Barrier	2%	$233,000,000	$197,000,000	$45,000,000	$475,000,000
Somerville	5-Foot	Inner Barrier	2%	$369,000,000	$475,000,000	$43,000,000	$887,000,000
Winthrop	5-Foot	Inner Barrier	2%	$30,000,000	$20,000,000	$5,000,000	$55,000,000
Brookline	5-Foot	Inner Barrier	10%	$15,000,000	$17,000,000	$1,000,000	$33,000,000
Cambridge	5-Foot	Inner Barrier	10%	$1,083,000,000	$1,329,000,000	$133,000,000	$2,545,000,000
Chelsea	5-Foot	Inner Barrier	10%	$328,000,000	$575,000,000	$46,000,000	$949,000,000
Everett	5-Foot	Inner Barrier	10%	$223,000,000	$451,000,000	$31,000,000	$705,000,000
Malden	5-Foot	Inner Barrier	10%	$269,000,000	$428,000,000	$36,000,000	$733,000,000
Medford	5-Foot	Inner Barrier	10%	$698,000,000	$814,000,000	$135,000,000	$1,647,000,000
Revere	5-Foot	Inner Barrier	10%	$198,000,000	$170,000,000	$37,000,000	$405,000,000
Somerville	5-Foot	Inner Barrier	10%	$173,000,000	$213,000,000	$18,000,000	$404,000,000
Winthrop	5-Foot	Inner Barrier	10%	$25,000,000	$17,000,000	$4,000,000	$46,000,000
Brookline	3-Foot	Inner Barrier	.1%	$6,000,000	$7,000,000	$1,000,000	$14,000,000
Cambridge	3-Foot	Inner Barrier	.1%	$578,000,000	$916,000,000	$64,000,000	$1,558,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Chelsea	3-Foot	Inner Barrier	.1%	$361,000,000	$629,000,000	$52,000,000	$1,042,000,000
Everett	3-Foot	Inner Barrier	.1%	$239,000,000	$483,000,000	$33,000,000	$755,000,000
Malden	3-Foot	Inner Barrier	.1%	$292,000,000	$467,000,000	$42,000,000	$801,000,000
Medford	3-Foot	Inner Barrier	.1%	$743,000,000	$897,000,000	$144,000,000	$1,784,000,000
Revere	3-Foot	Inner Barrier	.1%	$217,000,000	$177,000,000	$42,000,000	$436,000,000
Somerville	3-Foot	Inner Barrier	.1%	$206,000,000	$297,000,000	$25,000,000	$528,000,000
Winthrop	3-Foot	Inner Barrier	.1%	$26,000,000	$19,000,000	$4,000,000	$49,000,000
Brookline	3-Foot	Inner Barrier	1%	$100,000	$200,000	$0	$300,000
Cambridge	3-Foot	Inner Barrier	1%	$227,000,000	$389,000,000	$28,000,000	$644,000,000
Chelsea	3-Foot	Inner Barrier	1%	$326,000,000	$566,000,000	$44,000,000	$936,000,000
Everett	3-Foot	Inner Barrier	1%	$223,000,000	$450,000,000	$29,000,000	$702,000,000
Malden	3-Foot	Inner Barrier	1%	$233,000,000	$377,000,000	$30,000,000	$640,000,000
Medford	3-Foot	Inner Barrier	1%	$645,000,000	$808,000,000	$113,000,000	$1,566,000,000
Revere	3-Foot	Inner Barrier	1%	$195,000,000	$157,000,000	$34,000,000	$386,000,000
Somerville	3-Foot	Inner Barrier	1%	$178,000,000	$251,000,000	$20,000,000	$449,000,000
Winthrop	3-Foot	Inner Barrier	1%	$23,000,000	$16,000,000	$3,000,000	$42,000,000
Brookline	3-Foot	Inner Barrier	2%	$100,000	$200,000	$0	$300,000
Cambridge	3-Foot	Inner Barrier	2%	$194,000,000	$335,000,000	$23,000,000	$552,000,000
Chelsea	3-Foot	Inner Barrier	2%	$290,000,000	$484,000,000	$35,000,000	$809,000,000
Everett	3-Foot	Inner Barrier	2%	$194,000,000	$377,000,000	$22,000,000	$593,000,000
Malden	3-Foot	Inner Barrier	2%	$205,000,000	$335,000,000	$24,000,000	$564,000,000
Medford	3-Foot	Inner Barrier	2%	$572,000,000	$686,000,000	$91,000,000	$1,349,000,000
Revere	3-Foot	Inner Barrier	2%	$176,000,000	$144,000,000	$29,000,000	$349,000,000
Somerville	3-Foot	Inner Barrier	2%	$146,000,000	$189,000,000	$13,000,000	$348,000,000
Winthrop	3-Foot	Inner Barrier	2%	$20,000,000	$14,000,000	$3,000,000	$37,000,000
Brookline	3-Foot	Inner Barrier	10%	$100,000	$200,000	$0	$300,000
Cambridge	3-Foot	Inner Barrier	10%	$184,000,000	$323,000,000	$22,000,000	$529,000,000
Chelsea	3-Foot	Inner Barrier	10%	$249,000,000	$389,000,000	$26,000,000	$664,000,000
Everett	3-Foot	Inner Barrier	10%	$162,000,000	$288,000,000	$18,000,000	$468,000,000
Malden	3-Foot	Inner Barrier	10%	$155,000,000	$238,000,000	$19,000,000	$412,000,000
Medford	3-Foot	Inner Barrier	10%	$509,000,000	$631,000,000	$75,000,000	$1,215,000,000
Revere	3-Foot	Inner Barrier	10%	$166,000,000	$133,000,000	$26,000,000	$325,000,000
Somerville	3-Foot	Inner Barrier	10%	$122,000,000	$154,000,000	$11,000,000	$287,000,000
Winthrop	3-Foot	Inner Barrier	10%	$19,000,000	$12,000,000	$3,000,000	$34,000,000
Chelsea	1-Foot	Inner Barrier	.1%	$121,000,000	$193,000,000	$8,000,000	$322,000,000
Everett	1-Foot	Inner Barrier	.1%	$57,000,000	$110,000,000	$5,000,000	$172,000,000
Revere	1-Foot	Inner Barrier	.1%	$96,000,000	$74,000,000	$12,000,000	$182,000,000
Somerville	1-Foot	Inner Barrier	.1%	$17,000,000	$29,000,000	$0	$46,000,000
Winthrop	1-Foot	Inner Barrier	.1%	$9,000,000	$6,000,000	$1,000,000	$16,000,000
Chelsea	1-Foot	Inner Barrier	1%	$101,000,000	$149,000,000	$3,000,000	$253,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total
Everett	1-Foot	Inner Barrier	1%	$54,000,000	$100,000,000	$1,000,000	$155,000,000
Revere	1-Foot	Inner Barrier	1%	$75,000,000	$60,000,000	$5,000,000	$140,000,000
Somerville	1-Foot	Inner Barrier	1%	$13,000,000	$14,000,000	$0	$27,000,000
Winthrop	1-Foot	Inner Barrier	1%	$8,000,000	$5,000,000	$280,000	$13,280,000
Chelsea	1-Foot	Inner Barrier	2%	$92,000,000	$135,000,000	$2,000,000	$229,000,000
Everett	1-Foot	Inner Barrier	2%	$54,000,000	$100,000,000	$1,000,000	$155,000,000
Revere	1-Foot	Inner Barrier	2%	$62,000,000	$55,000,000	$5,000,000	$122,000,000
Somerville	1-Foot	Inner Barrier	2%	$13,000,000	$14,000,000	$0	$27,000,000
Winthrop	1-Foot	Inner Barrier	2%	$8,000,000	$5,000,000	$130,000	$13,130,000
Chelsea	1-Foot	Inner Barrier	10%	$35,000,000	$54,000,000	$1,000,000	$90,000,000
Everett	1-Foot	Inner Barrier	10%	$13,000,000	$23,000,000	$1,000,000	$37,000,000
Revere	1-Foot	Inner Barrier	10%	$33,000,000	$24,000,000	$4,000,000	$61,000,000
Somerville	1-Foot	Inner Barrier	10%	$0	$0	$0	$0
Winthrop	1-Foot	Inner Barrier	10%	$7,000,000	$3,000,000	$1,000,000	$11,000,000
Chelsea	0-Feet	Inner Barrier	.1%	$42,000,000	$63,000,000	$2,000,000	$107,000,000
Everett	0-Feet	Inner Barrier	.1%	$31,000,000	$52,000,000	$1,000,000	$84,000,000
Revere	0-Feet	Inner Barrier	.1%	$61,000,000	$36,000,000	$5,000,000	$102,000,000
Somerville	0-Feet	Inner Barrier	.1%	$50,000	$10,000	$0	$60,000
Winthrop	0-Feet	Inner Barrier	.1%	$7,000,000	$5,000,000	$1,000,000	$13,000,000
Chelsea	0-Feet	Inner Barrier	1%	$35,000,000	$52,000,000	$1,000,000	$88,000,000
Everett	0-Feet	Inner Barrier	1%	$23,000,000	$35,000,000	$1,000,000	$59,000,000
Revere	0-Feet	Inner Barrier	1%	$30,000,000	$19,000,000	$1,000,000	$50,000,000
Somerville	0-Feet	Inner Barrier	1%	$50,000	$10,000	$0	$60,000
Winthrop	0-Feet	Inner Barrier	1%	$5,000,000	$4,000,000	$0	$9,000,000
Chelsea	0-Feet	Inner Barrier	2%	$14,000,000	$29,000,000	$1,000,000	$44,000,000
Everett	0-Feet	Inner Barrier	2%	$15,000,000	$32,000,000	$1,000,000	$48,000,000
Revere	0-Feet	Inner Barrier	2%	$10,000,000	$7,000,000	$0	$17,000,000
Somerville	0-Feet	Inner Barrier	2%	$50,000	$10,000	$0	$60,000
Winthrop	0-Feet	Inner Barrier	2%	$4,000,000	$3,000,000	$0	$7,000,000
Chelsea	0-Feet	Inner Barrier	10%	$8,000,000	$16,000,000	$1,000,000	$25,000,000
Everett	0-Feet	Inner Barrier	10%	$13,000,000	$28,000,000	$1,000,000	$42,000,000
Revere	0-Feet	Inner Barrier	10%	$9,000,000	$6,000,000	$0	$15,000,000
Somerville	0-Feet	Inner Barrier	10%	$50,000	$10,000	$0	$60,000
Winthrop	0-Feet	Inner Barrier	10%	$3,000,000	$3,000,000	$0	$6,000,000

TABLE APPENDIX C4

Inner Barrier Single-Event Losses Avoided by Neighborhood, City of Boston

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total Damages
Allston	5-Foot	Inner Barrier	.1%	$199,000,000	$284,000,000	$26,000,000	$509,000,000
Back Bay	5-Foot	Inner Barrier	.1%	$628,000,000	$851,000,000	$90,000,000	$1,569,000,000
Charlestown	5-Foot	Inner Barrier	.1%	$425,000,000	$476,000,000	$48,000,000	$949,000,000
Downtown	5-Foot	Inner Barrier	.1%	$1,464,000,000	$1,975,000,000	$190,000,000	$3,629,000,000
East Boston	5-Foot	Inner Barrier	.1%	$1,219,000,000	$1,226,000,000	$202,000,000	$2,647,000,000
Fenway	5-Foot	Inner Barrier	.1%	$889,000,000	$1,010,000,000	$111,000,000	$2,010,000,000
Jamaica Plain	5-Foot	Inner Barrier	.1%	$125,000,000	$101,000,000	$3,000,000	$229,000,000
North Dorchester	5-Foot	Inner Barrier	.1%	$240,000,000	$273,000,000	$28,000,000	$541,000,000
Roxbury	5-Foot	Inner Barrier	.1%	$460,000,000	$640,000,000	$44,000,000	$1,144,000,000
South Boston	5-Foot	Inner Barrier	.1%	$935,000,000	$1,296,000,000	$165,000,000	$2,396,000,000
South End	5-Foot	Inner Barrier	.1%	$881,000,000	$836,000,000	$111,000,000	$1,828,000,000
Allston	5-Foot	Inner Barrier	1%	$108,000,000	$175,000,000	$8,000,000	$291,000,000
Back Bay	5-Foot	Inner Barrier	1%	$426,000,000	$619,000,000	$31,000,000	$1,076,000,000
Charlestown	5-Foot	Inner Barrier	1%	$230,000,000	$320,000,000	$14,000,000	$564,000,000
Downtown	5-Foot	Inner Barrier	1%	$961,000,000	$1,330,000,000	$59,000,000	$2,350,000,000
East Boston	5-Foot	Inner Barrier	1%	$636,000,000	$728,000,000	$47,000,000	$1,411,000,000
Fenway	5-Foot	Inner Barrier	1%	$595,000,000	$758,000,000	$37,000,000	$1,390,000,000
Jamaica Plain	5-Foot	Inner Barrier	1%	$193,000,000	$218,000,000	$8,000,000	$419,000,000
North Dorchester	5-Foot	Inner Barrier	1%	$128,000,000	$165,000,000	$10,000,000	$303,000,000
Roxbury	5-Foot	Inner Barrier	1%	$215,000,000	$334,000,000	$15,000,000	$564,000,000
South Boston	5-Foot	Inner Barrier	1%	$516,000,000	$722,000,000	$37,000,000	$1,275,000,000
South End	5-Foot	Inner Barrier	1%	$518,000,000	$580,000,000	$38,000,000	$1,136,000,000
Allston	5-Foot	Inner Barrier	2%	$83,000,000	$106,000,000	$8,000,000	$197,000,000
Back Bay	5-Foot	Inner Barrier	2%	$488,000,000	$600,000,000	$50,000,000	$1,138,000,000
Charlestown	5-Foot	Inner Barrier	2%	$323,000,000	$359,000,000	$30,000,000	$712,000,000
Downtown	5-Foot	Inner Barrier	2%	$1,235,000,000	$1,669,000,000	$132,000,000	$3,036,000,000
East Boston	5-Foot	Inner Barrier	2%	$945,000,000	$920,000,000	$131,000,000	$1,996,000,000
Fenway	5-Foot	Inner Barrier	2%	$631,000,000	$730,000,000	$55,000,000	$1,416,000,000
Jamaica Plain	5-Foot	Inner Barrier	2%	$57,000,000	$36,000,000	$400,000	$93,400,000
North Dorchester	5-Foot	Inner Barrier	2%	$148,000,000	$180,000,000	$14,000,000	$342,000,000
Roxbury	5-Foot	Inner Barrier	2%	$201,000,000	$293,000,000	$16,000,000	$510,000,000
South Boston	5-Foot	Inner Barrier	2%	$700,000,000	$999,000,000	$105,000,000	$1,804,000,000
South End	5-Foot	Inner Barrier	2%	$657,000,000	$614,000,000	$62,000,000	$1,333,000,000
Allston	5-Foot	Inner Barrier	10%	$59,000,000	$70,000,000	$4,000,000	$133,000,000
Back Bay	5-Foot	Inner Barrier	10%	$379,000,000	$427,000,000	$29,000,000	$835,000,000
Charlestown	5-Foot	Inner Barrier	10%	$208,000,000	$241,000,000	$17,000,000	$466,000,000
Downtown	5-Foot	Inner Barrier	10%	$1,016,000,000	$1,284,000,000	$88,000,000	$2,388,000,000
East Boston	5-Foot	Inner Barrier	10%	$810,000,000	$767,000,000	$104,000,000	$1,681,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total Damages
Fenway	5-Foot	Inner Barrier	10%	$382,000,000	$454,000,000	$27,000,000	$863,000,000
Jamaica Plain	5-Foot	Inner Barrier	10%	$16,000,000	$14,000,000	$0	$30,000,000
North Dorchester	5-Foot	Inner Barrier	10%	$107,000,000	$140,000,000	$9,000,000	$256,000,000
Roxbury	5-Foot	Inner Barrier	10%	$114,000,000	$177,000,000	$10,000,000	$301,000,000
South Boston	5-Foot	Inner Barrier	10%	$594,000,000	$840,000,000	$77,000,000	$1,511,000,000
South End	5-Foot	Inner Barrier	10%	$443,000,000	$481,000,000	$32,000,000	$956,000,000
Allston	3-Foot	Inner Barrier	.1%	$86,000,000	$115,000,000	$6,000,000	$207,000,000
Back Bay	3-Foot	Inner Barrier	.1%	$183,000,000	$200,000,000	$14,000,000	$397,000,000
Charlestown	3-Foot	Inner Barrier	.1%	$324,000,000	$336,000,000	$28,000,000	$688,000,000
Downtown	3-Foot	Inner Barrier	.1%	$1,064,000,000	$1,362,000,000	$98,000,000	$2,524,000,000
East Boston	3-Foot	Inner Barrier	.1%	$978,000,000	$983,000,000	$131,000,000	$2,092,000,000
Fenway	3-Foot	Inner Barrier	.1%	$312,000,000	$367,000,000	$21,000,000	$700,000,000
Jamaica Plain	3-Foot	Inner Barrier	.1%	$13,000,000	$9,000,000	$0	$22,000,000
North Dorchester	3-Foot	Inner Barrier	.1%	$128,000,000	$159,000,000	$11,000,000	$298,000,000
Roxbury	3-Foot	Inner Barrier	.1%	$168,000,000	$261,000,000	$12,000,000	$441,000,000
South Boston	3-Foot	Inner Barrier	.1%	$730,000,000	$1,035,000,000	$110,000,000	$1,875,000,000
South End	3-Foot	Inner Barrier	.1%	$517,000,000	$569,000,000	$41,000,000	$1,127,000,000
Allston	3-Foot	Inner Barrier	1%	$7,000,000	$9,000,000	$120,000	$16,120,000
Back Bay	3-Foot	Inner Barrier	1%	$34,000,000	$32,000,000	$1,000,000	$67,000,000
Charlestown	3-Foot	Inner Barrier	1%	$277,000,000	$297,000,000	$21,000,000	$595,000,000
Downtown	3-Foot	Inner Barrier	1%	$889,000,000	$1,101,000,000	$71,000,000	$2,061,000,000
East Boston	3-Foot	Inner Barrier	1%	$873,000,000	$898,000,000	$107,000,000	$1,878,000,000
Fenway	3-Foot	Inner Barrier	1%	$13,000,000	$11,000,000	$70,000	$24,070,000
North Dorchester	3-Foot	Inner Barrier	1%	$109,000,000	$137,000,000	$9,000,000	$255,000,000
Roxbury	3-Foot	Inner Barrier	1%	$71,000,000	$111,000,000	$3,000,000	$185,000,000
South Boston	3-Foot	Inner Barrier	1%	$629,000,000	$900,000,000	$84,000,000	$1,613,000,000
South End	3-Foot	Inner Barrier	1%	$339,000,000	$378,000,000	$29,000,000	$746,000,000
Allston	3-Foot	Inner Barrier	2%	$4,000,000	$5,000,000	$20,000	$9,020,000
Back Bay	3-Foot	Inner Barrier	2%	$7,000,000	$6,000,000	$200,000	$13,200,000
Charlestown	3-Foot	Inner Barrier	2%	$248,000,000	$258,000,000	$17,000,000	$523,000,000
Downtown	3-Foot	Inner Barrier	2%	$709,000,000	$851,000,000	$48,000,000	$1,608,000,000
East Boston	3-Foot	Inner Barrier	2%	$795,000,000	$825,000,000	$85,000,000	$1,705,000,000
Fenway	3-Foot	Inner Barrier	2%	$3,000,000	$5,000,000	$30,000	$8,030,000
North Dorchester	3-Foot	Inner Barrier	2%	$60,000,000	$85,000,000	$5,000,000	$150,000,000
Roxbury	3-Foot	Inner Barrier	2%	$23,000,000	$33,000,000	$1,000,000	$57,000,000
South Boston	3-Foot	Inner Barrier	2%	$538,000,000	$778,000,000	$64,000,000	$1,380,000,000
South End	3-Foot	Inner Barrier	2%	$211,000,000	$249,000,000	$11,000,000	$471,000,000
Allston	3-Foot	Inner Barrier	10%	$4,000,000	$5,000,000	$20,000	$9,020,000
Back Bay	3-Foot	Inner Barrier	10%	$7,000,000	$6,000,000	$200,000	$13,200,000
Charlestown	3-Foot	Inner Barrier	10%	$198,000,000	$220,000,000	$13,000,000	$431,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total Damages
Downtown	3-Foot	Inner Barrier	10%	$584,000,000	$664,000,000	$39,000,000	$1,287,000,000
East Boston	3-Foot	Inner Barrier	10%	$720,000,000	$737,000,000	$66,000,000	$1,523,000,000
Fenway	3-Foot	Inner Barrier	10%	$3,000,000	$4,000,000	$30,000	$7,030,000
North Dorchester	3-Foot	Inner Barrier	10%	$47,000,000	$66,000,000	$3,000,000	$116,000,000
Roxbury	3-Foot	Inner Barrier	10%	$13,000,000	$25,000,000	$1,000,000	$39,000,000
South Boston	3-Foot	Inner Barrier	10%	$503,000,000	$730,000,000	$56,000,000	$1,289,000,000
South End	3-Foot	Inner Barrier	10%	$95,000,000	$111,000,000	$260,000	$206,260,000
Charlestown	1-Foot	Inner Barrier	.1%	$113,000,000	$132,000,000	$3,000,000	$248,000,000
Downtown	1-Foot	Inner Barrier	.1%	$240,000,000	$287,000,000	$15,000,000	$542,000,000
East Boston	1-Foot	Inner Barrier	.1%	$299,000,000	$373,000,000	$16,000,000	$688,000,000
Fenway	1-Foot	Inner Barrier	.1%	$1,000,000	$2,000,000	$0	$3,000,000
North Dorchester	1-Foot	Inner Barrier	.1%	$91,000,000	$142,000,000	$7,000,000	$240,000,000
South Boston	1-Foot	Inner Barrier	.1%	$376,000,000	$530,000,000	$33,000,000	$939,000,000
Charlestown	1-Foot	Inner Barrier	1%	$79,000,000	$66,000,000	$1,000,000	$146,000,000
Downtown	1-Foot	Inner Barrier	1%	$157,000,000	$152,000,000	$3,000,000	$312,000,000
East Boston	1-Foot	Inner Barrier	1%	$242,000,000	$303,000,000	$9,000,000	$554,000,000
Fenway	1-Foot	Inner Barrier	1%	$1,000,000	$2,000,000	$0	$3,000,000
North Dorchester	1-Foot	Inner Barrier	1%	$55,000,000	$90,000,000	$3,000,000	$148,000,000
South Boston	1-Foot	Inner Barrier	1%	$263,000,000	$292,000,000	$15,000,000	$570,000,000
South Dorchester	1-Foot	Inner Barrier	1%	$0	$0	$0	$0
Charlestown	1-Foot	Inner Barrier	2%	$64,000,000	$53,000,000	$1,000,000	$118,000,000
Downtown	1-Foot	Inner Barrier	2%	$147,000,000	$144,000,000	$2,000,000	$293,000,000
East Boston	1-Foot	Inner Barrier	2%	$228,000,000	$278,000,000	$8,000,000	$514,000,000
Fenway	1-Foot	Inner Barrier	2%	$1,000,000	$2,000,000	$0	$3,000,000
North Dorchester	1-Foot	Inner Barrier	2%	$48,000,000	$83,000,000	$3,000,000	$134,000,000
South Boston	1-Foot	Inner Barrier	2%	$246,000,000	$261,000,000	$14,000,000	$521,000,000
Charlestown	1-Foot	Inner Barrier	10%	$15,000,000	$13,000,000	$110,000	$28,110,000
Downtown	1-Foot	Inner Barrier	10%	$59,000,000	$59,000,000	$2,000,000	$120,000,000
East Boston	1-Foot	Inner Barrier	10%	$26,000,000	$49,000,000	$1,000,000	$76,000,000
Fenway	1-Foot	Inner Barrier	10%	$1,000,000	$2,000,000	$0	$3,000,000
North Dorchester	1-Foot	Inner Barrier	10%	$1,000,000	$1,000,000	$10,000	$2,010,000
South Boston	1-Foot	Inner Barrier	10%	$91,000,000	$99,000,000	$9,000,000	$199,000,000
Charlestown	0-Feet	Inner Barrier	.1%	$34,000,000	$43,000,000	$2,000,000	$79,000,000
Downtown	0-Feet	Inner Barrier	.1%	$91,000,000	$106,000,000	$6,000,000	$203,000,000
East Boston	0-Feet	Inner Barrier	.1%	$112,000,000	$158,000,000	$2,000,000	$272,000,000
Fenway	0-Feet	Inner Barrier	.1%	$0	$0	$0	$0
North Dorchester	0-Feet	Inner Barrier	.1%	$17,000,000	$22,000,000	$0	$39,000,000
South Boston	0-Feet	Inner Barrier	.1%	$239,000,000	$330,000,000	$11,000,000	$580,000,000
Charlestown	0-Feet	Inner Barrier	1%	$16,000,000	$18,000,000	$0	$34,000,000
Downtown	0-Feet	Inner Barrier	1%	$16,000,000	$38,000,000	$1,000,000	$55,000,000

Community	Sea Level Rise Scenario	Barrier System	Frequency	Building Damage	Contents Losses	Displacement	Total Damages
East Boston	0-Feet	Inner Barrier	1%	$81,000,000	$102,000,000	$1,000,000	$184,000,000
Fenway	0-Feet	Inner Barrier	1%	$0	$0	$0	$0
North Dorchester	0-Feet	Inner Barrier	1%	$500,000	$700,000	$10,000	$1,210,000
South Boston	0-Feet	Inner Barrier	1%	$149,000,000	$115,000,000	$3,000,000	$267,000,000
Charlestown	0-Feet	Inner Barrier	2%	$9,000,000	$10,000,000	$0	$19,000,000
Downtown	0-Feet	Inner Barrier	2%	$3,000,000	$4,000,000	$0	$7,000,000
East Boston	0-Feet	Inner Barrier	2%	$20,000,000	$39,000,000	$1,000,000	$60,000,000
Fenway	0-Feet	Inner Barrier	2%	$0	$0	$0	$0
North Dorchester	0-Feet	Inner Barrier	2%	$0	$0	$0	$0
South Boston	0-Feet	Inner Barrier	2%	$43,000,000	$44,000,000	$2,000,000	$89,000,000
Charlestown	0-Feet	Inner Barrier	10%	$4,000,000	$6,000,000	$200,000	$10,200,000
Downtown	0-Feet	Inner Barrier	10%	$3,000,000	$4,000,000	$200,000	$7,200,000
East Boston	0-Feet	Inner Barrier	10%	$12,000,000	$23,000,000	$400,000	$35,400,000
Fenway	0-Feet	Inner Barrier	10%	$0	$0	$0	$0
North Dorchester	0-Feet	Inner Barrier	10%	$0	$0	$0	$0
South Boston	0-Feet	Inner Barrier	10%	$43,000,000	$44,000,000	$2,000,000	$89,000,000

TABLE APPENDIX C5

Outer Harbor Barrier Exposed Vulnerable Populations Results, 5-Foot SLR 1% Event Scenario, City of Boston Neighborhoods

Census Tract	Community	Barrier System	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
25025000100	Allston	Outer	270	100	30	30	30	60	110	90
25025000802	Allston	Outer	760	280	40	20	60	330	360	350
25025000803	Allston	Outer	6580	2380	220	120	370	2740	2650	900
25025010600	Back Bay	Outer	2860	1250	150	690	290	350	700	1080
25025010701	Back Bay	Outer	2420	980	150	100	80	420	460	500
25025010702	Back Bay	Outer	2360	1000	90	310	50	220	310	520
25025010801	Back Bay	Outer	2780	1210	250	350	80	70	450	420
25025010802	Back Bay	Outer	2830	1150	220	410	100	310	480	720
25025020101	Back Bay	Outer	1460	620	210	190	60	100	140	290
25025020200	Back Bay	Outer	990	400	60	40	30	190	170	250
25025040200	Charlestown	Outer	210	80	70	20	20	80	100	110
25025040300	Charlestown	Outer	120	50	20	10	10	20	20	30
25025040401	Charlestown	Outer	910	370	170	130	130	160	160	310
25025040600	Charlestown	Outer	640	270	80	80	40	100	50	180
25025040801	Charlestown	Outer	3900	1480	750	410	430	1770	1760	2350
25025020301	Downtown	Outer	2020	830	60	440	210	460	620	910
25025020303	Downtown	Outer	2600	1060	240	230	160	460	1030	630
25025030100	Downtown	Outer	520	230	20	50	30	150	40	210
25025030200	Downtown	Outer	1590	670	10	180	90	370	140	560
25025030300	Downtown	Outer	2930	1310	180	570	380	500	530	1070
25025030400	Downtown	Outer	450	190	30	40	30	100	40	140
25025030500	Downtown	Outer	1200	510	90	90	40	150	120	250
25025070101	Downtown	Outer	3050	1240	260	450	250	820	1230	1220
25025070200	Downtown	Outer	1270	470	110	170	140	650	840	640
25025050101	East Boston	Outer	320	110	80	30	50	120	230	170
25025050200	East Boston	Outer	2360	810	540	150	230	800	1750	1050
25025050300	East Boston	Outer	2250	830	670	470	540	1470	1600	2100
25025050400	East Boston	Outer	2100	810	290	210	200	610	1270	890
25025050500	East Boston	Outer	1840	680	330	330	140	570	1140	970
25025050600	East Boston	Outer	2060	750	360	130	200	730	1540	910
25025050700	East Boston	Outer	4500	1580	880	190	370	1230	3280	1490
25025050901	East Boston	Outer	910	320	170	50	90	320	640	390
25025051000	East Boston	Outer	1950	770	390	340	370	410	890	790
25025051101	East Boston	Outer	2880	1100	640	310	300	920	1370	1290
25025051200	East Boston	Outer	1390	540	260	150	190	360	600	550
25025981300	East Boston	Outer	390	150	50	0	0	10	130	20
25025010103	Fenway	Outer	3720	1330	30	10	110	2140	1620	360

Census Tract	Community	Barrier System	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
25025010104	Fenway	Outer	4470	1740	80	370	230	1790	1550	1360
25025010203	Fenway	Outer	3570	1380	100	190	300	1520	1260	1680
25025010204	Fenway	Outer	3040	1130	10	30	120	1430	1000	870
25025010403	Fenway	Outer	3000	1210	70	440	440	1650	1320	2130
25025010404	Fenway	Outer	5820	2200	70	50	280	4300	1750	2300
25025010408	Fenway	Outer	460	170	10	10	0	150	130	170
25025010500	Fenway	Outer	3040	1250	30	470	400	1250	1070	1470
25025080801	Jamaica Plain	Outer	1270	440	220	80	170	930	860	750
25025081001	Jamaica Plain	Outer	410	160	60	50	80	250	230	310
25025081100	Jamaica Plain	Outer	100	40	10	10	10	40	50	50
25025090700	North Dorchester	Outer	1770	690	300	170	230	550	690	770
25025091001	North Dorchester	Outer	1620	640	280	160	240	520	680	730
25025091100	North Dorchester	Outer	490	180	130	40	60	150	260	210
25025091300	North Dorchester	Outer	250	90	70	30	30	120	230	160
25025080100	Roxbury	Outer	1060	410	140	50	90	480	900	310
25025080300	Roxbury	Outer	60	20	10	0	10	30	60	40
25025080401	Roxbury	Outer	340	130	110	40	80	210	310	270
25025080601	Roxbury	Outer	840	300	120	20	60	530	420	400
25025090600	Roxbury	Outer	470	170	160	40	50	190	450	250
25025060101	South Boston	Outer	470	200	50	50	50	60	10	120
25025060200	South Boston	Outer	390	160	60	30	20	40	10	70
25025060301	South Boston	Outer	280	120	20	40	30	40	10	90
25025060400	South Boston	Outer	1160	510	90	160	60	150	70	320
25025060501	South Boston	Outer	180	70	20	10	10	20	10	40
25025060600	South Boston	Outer	1970	820	60	180	120	160	270	350
25025060700	South Boston	Outer	1890	580	630	170	290	1080	1540	1360
25025060800	South Boston	Outer	1930	790	200	150	70	260	190	430
25025061000	South Boston	Outer	160	60	50	10	30	90	90	110
25025061101	South Boston	Outer	1260	420	450	120	200	890	1010	1100
25025061200	South Boston	Outer	2400	980	160	120	90	390	370	530
25025091600	South Dorchester	Outer	220	70	70	20	40	110	190	150
25025092101	South Dorchester	Outer	1980	690	400	170	330	710	1390	930
25025100603	South Dorchester	Outer	1520	600	170	280	140	100	470	390
25025100700	South Dorchester	Outer	1260	510	250	200	120	140	140	370
25025100800	South Dorchester	Outer	570	220	140	70	90	70	270	150
25025070300	South End	Outer	3870	1680	440	480	180	820	920	1380
25025070500	South End	Outer	5460	2130	870	570	530	1380	2500	2090
25025070600	South End	Outer	2240	930	320	110	10	230	400	360
25025070700	South End	Outer	2360	930	280	200	260	460	1070	700

Census Tract	Community	Barrier System	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
25025070800	South End	Outer	3710	1470	280	240	340	1150	1400	1420
25025070900	South End	Outer	3330	1260	320	250	530	970	1850	1260
25025071101	South End	Outer	3750	1500	490	350	550	1620	1910	2060
25025071201	South End	Outer	3130	1190	760	280	910	1760	1910	2230
25025080500	South End	Outer	2500	860	670	230	630	1820	2310	2310

TABLE APPENDIX C6

Inner Harbor Barrier Exposed Vulnerable Populations Results, 5-Foot SLR 1% Event Scenario, City of Boston Neighborhoods

Census Tract	Community	Barrier System	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
25025000100	Allston	Inner	270	100	30	30	30	60	110	90
25025000802	Allston	Inner	760	280	40	20	60	330	360	350
25025000803	Allston	Inner	6580	2380	220	120	370	2740	2650	900
25025010600	Back Bay	Inner	2860	1250	150	690	290	350	700	1080
25025010701	Back Bay	Inner	2420	980	150	100	80	420	460	500
25025010702	Back Bay	Inner	2360	1000	90	310	50	220	310	520
25025010801	Back Bay	Inner	2780	1210	250	350	80	70	450	420
25025010802	Back Bay	Inner	2830	1150	220	410	100	310	480	720
25025020101	Back Bay	Inner	1460	620	210	190	60	100	140	290
25025020200	Back Bay	Inner	990	400	60	40	30	190	170	250
25025040200	Charlestown	Inner	210	80	70	20	20	80	100	110
25025040300	Charlestown	Inner	120	50	20	10	10	20	20	30
25025040401	Charlestown	Inner	910	370	170	130	130	160	160	310
25025040600	Charlestown	Inner	640	270	80	80	40	100	50	180
25025040801	Charlestown	Inner	3900	1480	750	410	430	1770	1760	2350
25025020301	Downtown	Inner	2020	830	60	440	210	460	620	910
25025020303	Downtown	Inner	2600	1060	240	230	160	460	1030	630
25025030100	Downtown	Inner	520	230	20	50	30	150	40	210
25025030200	Downtown	Inner	1590	670	10	180	90	370	140	560
25025030300	Downtown	Inner	2930	1310	180	570	380	500	530	1070
25025030400	Downtown	Inner	450	190	30	40	30	100	40	140
25025030500	Downtown	Inner	1200	510	90	90	40	150	120	250
25025070101	Downtown	Inner	3050	1240	260	450	250	820	1230	1220
25025070200	Downtown	Inner	1270	470	110	170	140	650	840	640
25025050101	East Boston	Inner	320	110	80	30	50	120	230	170
25025050200	East Boston	Inner	2360	810	540	150	230	800	1750	1050
25025050300	East Boston	Inner	2250	830	670	470	540	1470	1600	2100
25025050400	East Boston	Inner	2100	810	290	210	200	610	1270	890
25025050500	East Boston	Inner	1840	680	330	330	140	570	1140	970
25025050600	East Boston	Inner	2060	750	360	130	200	730	1540	910
25025050700	East Boston	Inner	4500	1580	880	190	370	1230	3280	1490
25025050901	East Boston	Inner	910	320	170	50	90	320	640	390
25025051000	East Boston	Inner	1950	770	390	340	370	410	890	790
25025051101	East Boston	Inner	2700	1030	600	290	280	870	1290	1210
25025051200	East Boston	Inner	1390	540	260	150	190	360	600	550
25025981300	East Boston	Inner	390	150	50	0	0	10	130	20

Census Tract	Community	Barrier System	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
25025010103	Fenway	Inner	3720	1330	30	10	110	2140	1620	360
25025010104	Fenway	Inner	4470	1740	80	370	230	1790	1550	1360
25025010203	Fenway	Inner	3570	1380	100	190	300	1520	1260	1680
25025010204	Fenway	Inner	3040	1130	10	30	120	1430	1000	870
25025010403	Fenway	Inner	3000	1210	70	440	440	1650	1320	2130
25025010404	Fenway	Inner	5820	2200	70	50	280	4300	1750	2300
25025010408	Fenway	Inner	460	170	10	10	0	150	130	170
25025010500	Fenway	Inner	3040	1250	30	470	400	1250	1070	1470
25025080801	Jamaica Plain	Inner	1270	440	220	80	170	930	860	750
25025081001	Jamaica Plain	Inner	410	160	60	50	80	250	230	310
25025081100	Jamaica Plain	Inner	100	40	10	10	10	40	50	50
25025090700	North Dorchester	Inner	1770	690	300	170	230	550	690	770
25025091001	North Dorchester	Inner	200	80	30	20	30	60	80	90
25025091100	North Dorchester	Inner	460	170	120	40	50	140	250	200
25025091300	North Dorchester	Inner	250	90	70	30	30	120	230	160
25025080100	Roxbury	Inner	1060	410	140	50	90	480	900	310
25025080300	Roxbury	Inner	60	20	10	0	10	30	60	40
25025080401	Roxbury	Inner	340	130	110	40	80	210	310	270
25025080601	Roxbury	Inner	840	300	120	20	60	530	420	400
25025090600	Roxbury	Inner	470	170	160	40	50	190	450	250
25025060400	South Boston	Inner	210	90	20	30	10	30	10	60
25025060501	South Boston	Inner	180	70	20	10	10	20	10	40
25025060600	South Boston	Inner	1970	820	60	180	120	160	270	350
25025060700	South Boston	Inner	1890	580	630	170	290	1080	1540	1360
25025060800	South Boston	Inner	1930	790	200	150	70	260	190	430
25025061000	South Boston	Inner	160	60	50	10	30	90	90	110
25025061101	South Boston	Inner	1260	420	450	120	200	890	1010	1100
25025061200	South Boston	Inner	2400	980	160	120	90	390	370	530
25025070300	South End	Inner	3870	1680	440	480	180	820	920	1380
25025070500	South End	Inner	5460	2130	870	570	530	1380	2500	2090
25025070600	South End	Inner	2240	930	320	110	10	230	400	360
25025070700	South End	Inner	2360	930	280	200	260	460	1070	700
25025070800	South End	Inner	3710	1470	280	240	340	1150	1400	1420
25025070900	South End	Inner	3330	1260	320	250	530	970	1850	1260
25025071101	South End	Inner	3750	1500	490	350	550	1620	1910	2060
25025071201	South End	Inner	3130	1190	760	280	910	1760	1910	2230
25025080500	South End	Inner	2500	860	670	230	630	1820	2310	2310

TABLE APPENDIX C7

Outer Harbor Barrier Exposed Vulnerable Populations Results, 0-Feet SLR 1% Event Scenario, City of Boston Neighborhoods

Census Tract	Community	Barrier System	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
25025040801	Charlestown	Outer	3900	1120	420	220	120	120	510	510
25025050300	East Boston	Outer	2251	200	70	60	40	50	130	140
25025050400	East Boston	Outer	2372	510	200	70	50	50	150	310
25025050500	East Boston	Outer	1857	200	70	40	40	20	60	120
25025050600	East Boston	Outer	2063	1810	660	320	110	180	640	1350
25025050700	East Boston	Outer	4504	1110	390	220	50	90	300	810
25025050901	East Boston	Outer	4165	20	10	0	0	0	10	10
25025051000	East Boston	Outer	4089	70	30	10	10	10	10	30
25025051101	East Boston	Outer	6093	50	20	10	10	10	20	20
25025091001	North Dorchester	Outer	2742	200	80	30	20	30	60	80
25025060600	South Boston	Outer	2357	930	390	30	80	60	70	130
25025061200	South Boston	Outer	3240	60	20	0	0	0	10	10
25025100603	South Dorchester	Outer	1904	140	60	20	30	10	10	40
25025100800	South Dorchester	Outer	5546	30	10	10	0	0	0	10

TABLE APPENDIX C8

Inner Harbor Barrier Exposed Vulnerable Populations Results, 0-Feet SLR 1% Event Scenario, City of Boston Neighborhoods

Census Tract	Community	Barrier System	Total Persons Exposed	Medical Illness	Children	Older Adults	Disabilities	Low to No Income	People of Color	Limited English
25025040801	Charlestown	Inner	1120	420	220	120	120	510	510	680
25025050300	East Boston	Inner	200	70	60	40	50	130	140	190
25025050400	East Boston	Inner	510	200	70	50	50	150	310	220
25025050500	East Boston	Inner	200	70	40	40	20	60	120	110
25025050600	East Boston	Inner	1810	660	320	110	180	640	1350	800
25025050700	East Boston	Inner	1110	390	220	50	90	300	810	370
25025050901	East Boston	Inner	20	10	0	0	0	10	10	10
25025051000	East Boston	Inner	70	30	10	10	10	10	30	30
25025051101	East Boston	Inner	20	10	0	0	0	10	10	10
25025060600	South Boston	Inner	930	390	30	80	60	70	130	160
25025061200	South Boston	Inner	60	20	0	0	0	10	10	10

APPENDIX D

METHODOLOGY FOR ECONOMIC AND VULNERABLE POPULATIONS ANALYSES

ARCADIS Design & Consultancy for natural and built assets

Memo from Carly Foster, AICP, CFM and Kelli Thurson, CFM to Paul Kirshen, PhD, dated Monday, April 23, 2018

UMass Boston is working to evaluate the feasibility of constructing a barrier in the Boston Harbor to reduce risk from flooding and sea level rise. In support of this effort, Arcadis calculated potential losses avoided in the form of reduced direct physical damage to structures and their contents and inventory, as well as benefitting populations, including numbers of people in general and members of vulnerable populations for which flood exposure could be reduced across the study area.[1] Arcadis used the losses avoided to conduct a preliminary benefit-cost analysis for two possible configurations of the Harbor Barrier. To understand potential losses avoided and benefitting populations, Arcadis modeled potential impacts associated with 16 flood scenarios corresponding to the 10 percent, 2 percent, 1 percent, and 0.1 percent annual exceedance probability flood events for four sea level rise estimates—zero feet (present-day conditions), one-foot, three-feet, and five-feet. The information provided herein is intended to support the feasibility study and should be considered a data point in a broader decision-making process regarding a harbor barrier, rather than providing a definitive verdict on the viability of a harbor barrier or any harbor barrier configuration.

The analysis described in this memorandum made use of the following data (more detailed provided in the Methodology section):

- Flood hazard data produced by Woods Hole Group
- Tax assessor data from each municipality within the project's study area
- Climate Ready Boston (CRB) methodologies and sources:
  - USACE depth-damage functions used in the Climate Ready Boston (CRB) exposure and consequence analysis, gathered from the North Atlantic Coast Comprehensive Study (NACCS) Physical Depth Damage Function Summary Report and the West Shore Lake Pontchartrain Hurricane and Storm Damage Risk Reduction Study
  - Building replacement costs calculation methodology
  - Displacement and relocation costs methodology
  - 2010 U.S. Census population estimates
  - Vulnerable Populations data compiled by Dr. Atyia Martin for the City of Boston, determined using Census and American Community Survey (ACS) data

The analysis reports potential losses avoided and benefitting populations as a result of two possible barrier alignments: the Outer Harbor Barrier, which stretches from Winthrop to Hull, and the Inner Harbor Barrier, from Logan Airport to the South Boston Waterfront (Figure D1). This memorandum presents a summary of single-event and annualized losses avoided, followed by the analysis approach and limitations for use by UMass Boston in the final project deliverable. While the results reflect similar outputs to those produced for Climate Ready Boston (CRB), this analysis differs in both approach and some of the data used. The analysis methodology, described in the Methodology Section

1 The study area included communities in Boston, Braintree, Brookline, Cambridge, Chelsea, Everett, Hingham, Hull, Malden, Medford, Milton, Newton, Quincy, Revere, Somerville, Weymouth, and Winthrop, which represent the extent of communities expected to benefit from the Outer Harbor Barrier configuration, subsequently described in this memorandum.

below, was presented to and deemed acceptable by the UMB project team and the Steering Committee based on the level of detail needed for this feasibility assessment, the scale of the project area, budget and schedule allocated to model losses avoided, and to ensure consistency of process across the entirety of the study area.

Analysis Summary

This summary of the analysis approach presents three components of the preliminary benefit-cost review for the Harbor Barrier Feasibility Study:

- Loss and exposure categories considered
- Expected losses avoided attributable to a Harbor Barrier. Analysts evaluated the potential losses avoided, and the expected benefits of a Harbor Barrier, from sixteen different flood event scenarios correlating to specific flood event exceedance probabilities (calculated at varying sea level intervals associated with the 4.5 RCP emissions scenario from the Boston Research Advisory Group report used in Climate Ready Boston (2016))[2]
- A preliminary comparison of expected Harbor Barrier benefits (losses avoided) over time when compared to costs over time under multiple barrier configurations, cost scenarios, and shoreline flood risk reduction scenarios

FIGURE APPENDIX D1

Inner and Outer Harbor Barrier Configurations

Sources: Arcadis, Esri World Imagery

LOSS AND EXPOSURE CATEGORIES

Analysts estimated impacts across the study area as a result of flooding under 16 flood events that correlated to the 10-percent, 2-percent, 1-percent, and 0.1-percent annual exceedance probabilities in each of four sea level rise intervals based on the 4.5 RCP rate. Analysts used regression analysis in order to understand the annual exceedance probability that each of these 16 events correlated to at each sea level rise interval. Refer to Table 1 for detailed descriptions of each impact category explored in this analysis.[3]

Building Direct Physical Damage and Displacement Analysis Approach

As noted in the Introduction, the building direct physical damage and displacement analysis conducted for the project identifies expected structure damage, contents losses, and displacement costs associated with four sea level rise scenarios, with four flood frequencies each for a total of 16 results variations. Analysts used ArcGIS to select impacted parcels and applied USACE depth-damage functions to generate expected impacts. The economic analysis for the project is executed at a less granular level that CRB, as it aggregates impacted properties by use for a census tract for damage function application, rather than conducting the analysis on a per-structure basis. Data sources and a detailed methodology not described above is provided herein.

DATA SOURCES

- *Flood Depth Grids:* Woods Hole Group developed flood depth grids for the Boston Harbor considering four sea level rise scenarios

2 Flood hazard data from Woods Hole Group were used to estimate potential flood impacts across the study area.

3 Direct physical damages to infrastructure and business, transportation, and service interruption losses not contemplated in this analysis.

TABLE APPENDIX D1

Expected Loss and Exposure Category Descriptions

Loss Category	Description
Direct Physical Damage to Buildings	Structure damage expected due to flooding based on 2016 RS Means Replacement Costs associated with specific building types and characteristics. Damages to buildings calculated using USACE depth-damage curves gathered from the North Atlantic Coast Comprehensive Study (NACCS) Physical Depth Damage Function Summary Report (USACE, 2015); depth damage curves define the relationship between the depth of flooding in a structure and the percent of damage that occurs. The percent damage is applied to the replacement value of the building for an estimate of direct physical damage.
Direct Physical Damage to Contents and Inventory	The 2016-dollar value of structure contents and inventory damaged due to flooding. Contents and inventory damage are also estimated through depth-damage curves from the USACE West Shore Lake Pontchartrain Hurricane and Storm Damage Risk Reduction Study (USACE, 2014). Contents and inventory estimated as a share above the structure replacement cost based on building type, characteristics, and use.
Displacement (also known as Relocation) Costs to Businesses and Occupants	Displacement is a function of direct physical damage and flood depth, and includes relocation and rental costs associated with displacement, method sourced from Climate Ready Boston (2016).
Exposure Category	**Description**
People Exposed	Considers the number of people that live in residential or mixed-use structures exposed to flood impacts. Exposed persons are estimated through the amount of residential square footage within the inundation area of each flood frequency
Vulnerable Populations	Arcadis examined the presence of seven categories of vulnerable populations that may be exposed to flooding, including medical illness, children, older adults, disabilities, low-to-no income, people of color, and those who speak limited English. Dr. Atyia Martin previously explored these seven categories for the City of Boston, the results of which Arcadis used for this study. Vulnerable populations are not mutually exclusive, and one person can and often does meet multiple categories of social vulnerability.

(0 feet, 1-foot, 3-foot, and 5-foot estimates) with four flood frequencies each (10 percent, 2 percent, 1 percent, and 0.1 percent annual chance events). The flood depth grids do not consider any existing or planned resiliency improvements or mitigation projects; all assumptions made for the flood depth grids by Woods Hole Group will carry through the economic and vulnerable populations analyses.

- *MassGIS Level 4 Assessor's Parcel Data:* The MassGIS parcel data contains property boundaries and database information from each community's assessor, and standardizes parcel data across all communities in Massachusetts, with the exception of Boston. The parcel data provided building use, size, and height information used in this analysis.
- *City of Boston Property Tax Assessing Data (2017):* Boston conducts its own assessor's information map exercise, but still provides building use and size information.
- USACE Depth Damage Functions used in CRB:
  - *USACE North Atlantic Coast Comprehensive Study (NACCS) Physical Depth Damage Function Summary Report (2015):* Following Hurricane Sandy, the USACE collected empirical data to estimate the damages that would occur from future events. This report produced coastal damage functions for residential, non-residential, and public property. DDFs were obtained from this study to estimate direct physical damages related to modeled storm surge scenarios.
  - *USACE West Shore Lake Pontchartrain Hurricane and Storm Damage Risk Reduction Study (2014):* This study conducted by

4 Flood hazard data from Woods Hole Group were used to estimate potential flood impacts across the study area.

5 Displacement is a function of direct physical damage and flood depth, and includes relocation costs associated with displacement. Displacement costs are those borne by occupants during the time when a building becomes uninhabitable due to expected flood damage, and are applicable to both residential and non-residential property owners.

the USACE produced contents-to-structure ratio values (CSRVs) for residential and non-residential structures. CSRVs were used as a percentage of the total building replacement values to determine total contents replacement values for structures in the project area. While produced for a separate region, analysts determined this study to be the best and most recent data available for use with the DDFs.

- *FEMA BCA Toolkit 5.1:* USACE NACCS damage functions do not provide depth displacement. As such, analysts extracted displacement tables from the FEMA BCA Toolkit to estimate displacement time[4] for structures based on flood depth.
- *RS Means Building Construction Cost Data (2016):* Analysts calculated building replacement square foot costs for various structure types in Boston. The same building replacement values were used in the CRB analysis.
- Displacement costs from the Climate Ready Boston report, developed using 2016 local rental rates gathered from Zillow, Trulia, and Loopnet.
- *Hazus Occupancy Classes:* a building classification system developed by FEMA Hazus-MH Flood Technical Manual to categorize similar buildings so that standard values can be applied to similar structure types.
- U.S. 2010 Census Data provided by census tract.
- *Socially Vulnerable Populations Data:* as acquired from Dr. Atyia Martin,[5] developed for *A framework to understand the relationship between social factors that reduce resilience in cities: Application to the City of Boston.* Published 2015 in the *International Journal of Disaster Risk Reduction.*

TABLE APPENDIX D2

Parcel Inventory Details

Municipality	Parcel Data Year (Fiscal Year)
Braintree	2013
Boston	2017
Brookline	2011
Cambridge	2013
Chelsea	2011
Everett	2017
Hingham	2011
Hull	2011
Malden	2017
Medford	2011
Milton	2018
Quincy	2015
Revere	2017
Somerville	2012
Weymouth	2011
Winthrop	2016

Source: Arcadis

METHODOLOGY

1. Develop Parcel Inventory

The parcel inventory compiles structure use, square footage, and building height of each municipality included in the analysis, and maps those parcels to occupancy codes to standardize expected damage impacts across buildings of similar uses. As shown in Table 2, the sources of the parcel data available through MassGIS are not available at consistent time periods. This likely underestimates the results of the analysis, as recent growth in some communities are not represented.

1.1 Occupancy Mapping

Structures may be classified according to both construction features (type) and use (occupancy). Analysts used structure use information to assign a Hazus occupancy code to each use present in the parcel inventory; refer to Table D3 for a list of occupancy codes and descriptions. Mapping to Hazus occupancy classes allows analysts to accomplish the following:

- Aggregate parcels with similar uses across census tracts;
- Apply consistent depth damage functions and displacement and restoration time multipliers across uses; and
- Estimate consistent replacement values for similar structures.

1.2 Square Footage Analysis

Damages to buildings using the NACCS depth damage functions requires assessment based on the square footage within a certain number of stories. The number of stories analyzed by the damage function is related to the structure use, type, and the expected location and value of mechanical, electrical, and plumbing (MEP) assets in buildings. A significant portion of a building's value is captured in MEP assets; damage costs to these assets can therefore be disproportionate to those of other contents. Urban high rise damage functions, for example, analyze damages as a percent of the square footage of the first ten floors given the NACCS assumption that MEP assets are located within the basement or first floor of the structure. To conduct this square footage analysis, analysts multiplied the square footage per floor by the number of stories identified in the USACE NACCS or the total number of stories, whichever is less, for each structure. For structures identified as mixed use, an analysis of square footage is developed for both residential and commercial square footage.

1.3 Building and Contents Replacement Values

Building replacement values (BRVs) and Contents Replacement Values (CRVs) are required to determine expected damage to buildings. Replacement values are different from assessed market value because it is an estimate of the cost to construct an identical structure of the same type and occupancy using today's market values for materials, labor costs, and considering new technologies and regulations that may affect the construction process. Analysts used the same BRV and CRVs used in the CRB exposure and consequence analysis, which were obtained from 2016 RSMeans square footage costs for each occupancy class. For mixed use structures analysts assumed that commercial areas are contained to the first two floors of a structure (if a building is over two stories tall), and multiplied the commercial replacement values and residential replacement values by the area of commercial and residential space within a building, respectively. The two values are then added together to obtain an estimate of the total replacement value of the building.

2. Identify Exposed Parcels and Expected Flood Depths

Once the parcel inventory was complete with square footage analysis and replacement values, analysts used GIS to overlay flood depth grids provided by Woods Hole Group over the parcel inventory. Since the hazard data provided are in depth, rather than elevations, grade elevations to estimate first floor was not necessary for this analysis. Analysts extracted the average flood depth present within an exposed parcel to account for changes in grade and first floor elevation that may impact depth. In a quality control review of exposed parcels and the average flood depth, analysts removed many parcels located on the edge of the flood extent, assuming structures themselves may not be flooded within a parcel. Furthermore, this review resulted in removing many parcels that were gathering inaccurate flood depths due to edge issues present in the hazard data. This process was executed for each of the 16 flood scenarios included in the analysis.

3. Aggregate Parcels

Due to the schedule and budget of the economic analysis and the size of the study area, analysts elected to aggregate parcel information across census tracts rather than evaluate each individual parcel. Because the parcel inventory was taken at face value, aggregating parcels also mitigates some inaccuracies or outdated information that are likely present in the parcel inventory. Analysts aggregated exposed structures within a census tract based on Hazus occupancy codes, and extracted the median building size, median flood depth, and median height of all parcels in that tract corresponding to a single occupancy code. The remainder of the analysis focuses on the aggregation of exposed parcels across census tracts; this level of analysis is considered appropriate for the project, as it is meant to conceptually evaluate the expected economic benefits of implementing some variation of a barrier in the Boston Harbor. To reduce variation in building sizes across sea level rise scenarios and flood frequencies as the extents change and different parcels are impacted, analysts used the median building size generated for the 0.1% annual chance flood extents for each of the sea level rise scenarios. Median flood depths were generated for each flood frequency and sea level rise scenario.

4. Execute Calculations

The analysis for the Inner and Outer Harbor Barrier systems executes three calculations: expected building damage, contents losses, and displacement costs. Each calculation uses the same data, methodology, and assumptions used for the CRB exposure and consequence analysis, save for the aggregated nature of the data. Because the parcel information and exposure is generated at the census tract level, analysts multiplied the aggregated results by the number of expected flooded parcels per occupancy type within the tract to account for multiple flooded parcels.

4.1 Building Damage and Contents Losses

Following Hurricane Sandy, the USACE developed DDFs specific to the Northeast for coastal flooding in a report titled the North Atlantic Coast Comprehensive Study (NACCS). As this information contains the most current and best available data, analysts used these functions to evaluate direct physical damages for each class of building in Table D3. Depth damage functions are a relationship between the depth of floodwater in a structure and the percent of damage that can be attributed to the flooding. Once expected flood depths were defined for each flood scenario, analysts applied the damage functions to estimate the percent of structure and contents damage costs.

TABLE APPENDIX D3

Replacement Values from CRB (2016 dollars/sq foot)

Hazus Code	Occupancy Description	BRV	CRV
RES1	Single Family Dwelling	$143.14	$98.77
RES2	Mobile Home	$137.47	$156.71
RES3A	Multi Family Dwelling—Duplex	$117.76	$81.25
RES3B	Multi-Family Dwelling 3—Units	$227.31	$156.85
RES3C	Multi-Family Dwelling 5—9 Units	$227.31	$156.85
RES3D	Multi-Family Dwelling 10—19 Units	$216.42	$149.33
RES3E	Multi-Family Dwelling 20—49 Units	$209.84	$144.79
RES3F	Multi-Family Dwelling 50+ Units	$202.67	$139.84
RES4	Temporary Lodging	$211.01	$145.59
RES5	Institutional Dormitory	$242.70	$167.46
RES6	Nursing Home	$246.88	$170.35
COM1	Retail Trade	$137.67	$163.82
COM2	Wholesale Trade	$133.41	$276.16
COM3	Personal and Repair Services	$160.45	$378.66
COM4	Business/Professional/Technical Services	$198.63	$107.26
COM5	Depository Institutions	$299.43	$161.69
COM6	Hospital	$426.82	$230.48
COM7	Medical Office/Clinic	$241.96	$130.66
COM8	Entertainment & Recreation	$252.25	$428.83
COM9	Theaters	$211.95	$114.45
COM10	Parking	$89.34	$48.24
IND1	Heavy Industrial	$151.75	$314.12
IND2	Light Industrial	$133.41	$276.16
IND3	Food/Drugs/Chemicals	$205.59	$425.56
IND4	Metals/Minerals Processing	$205.59	$425.56
IND5	High Technology	$205.59	$425.56
IND6	Construction	$133.41	$276.16
AGR1	Agriculture	$133.41	$0.00
REL1	Church/Membership Organizations	$213.29	$117.31
GOV1	General Services	$169.99	$93.49
GOV2	Emergency Response	$283.68	$425.52
EDU1	Schools/Libraries	$228.41	$228.41
EDU2	Colleges/Universities	$200.58	$200.58

Source: Arcadis

The percent of structure and contents damage is related to 1-foot depth increments, and are multiplied by a structure or contents total replacement value to produce a physical loss value in dollars.

4.2 Displacement Costs

Displacement costs are those borne by occupants during the time when a building becomes uninhabitable due to expected flood damage, and are applicable to both residential and non-residential property owners. While the CRB analysis includes both relocation costs and business interruption costs, this economic analysis considers only relocation costs due to the size of the study area and the project budget. Relocation costs are associated with moving a household or a business to a new location and resuming life or business in that new location, and are derived from displacement time. Calculating displacement costs is an intersection of owner occupancy rates, rental rates, and displacement time. These values were gathered from the CRB analysis as appropriate, and thus assumes that rental rates in the City apply to the Metro area. To process relocation costs, analysts used the below equation.

COMPARISON TO CLIMATE READY BOSTON

This analysis differs from Climate Ready Boston (2016) in both the approach and data used due to the size of the study area and project constraints. Principally, the Harbor Barrier Analysis aggregated parcel information to the census tract level to assess expected losses, while Climate Ready Boston evaluated site-specific expected losses.

The economic analysis executed for CRB was based on a Boston-specific asset inventory, which included an updated building stock (2015), site-specific asset analysis, and City-specific replacement costs and rental values. Arcadis executed the economic analysis for the Inner and Outer Harbor Barriers at a much higher level and does not consider site-specific evaluations of flood hazard data or the built environment context. The aggregated analysis approach to estimating potential losses avoided resulted in outcomes with trends that differ from Climate Ready Boston (2016). For example, Climate Ready Boston concluded with higher building damage and greater flood risk present in South Boston than other City neighborhoods. Climate Ready Boston notes that these results are likely due to large, high-value development located on the waterfront in South Boston.

Additional analysis variations that would result in different economic losses avoided for the City of Boston include:

- The aggregated analysis uses median structure square footage and height information across a census tract. In the case where there is a large census tract with a mix of structure types and sizes, the potential losses avoided are tempered by the aggregated structure information. Large developments on the waterfront at risk of frequent flooding from high-probability events are not captured to the same degree that a site-specific analysis would accomplish. This yielded conservatively low results in areas dominated by waterfront high rises.
- The Inner and Outer Harbor Barrier analyses do not evaluate business interruption costs.
- Hazard data for the CRB study included sea level rise assumptions for coastal and riverine flooding for 9 inches, 21 inches, and 36 inches. Hazard data for this analysis considers flooding

TABLE APPENDIX D4

Relocation Cost Equation

RELi = ∑ if percentDAM – BLi,j > 10 percent: Fai,j * [(1 – percentOOi) * (DC1) + percentOOi * (DCi + RENTi * DTi,j)]

Where:

RELi	Relocation costs for occupancy class I (in dollars)
Fai,j	Floor area of occupancy group i and depth j (in square feet)
PercentDA M – BLi,j	Percent building damage for occupancy i and water depth j, (from depth-damage function), if greater than 10 percent
DCi	Disruption costs for occupancy i (in dollars)
DTi,j	Displacement time (in days) for occupancy i and water depth j (in days)
percentOOi	Percent owner occupied for occupancy I
RENTi	Rental cost for occupancy I (in $/ft^2/day)

Source: Hazus Flood Technical Manual 2.1

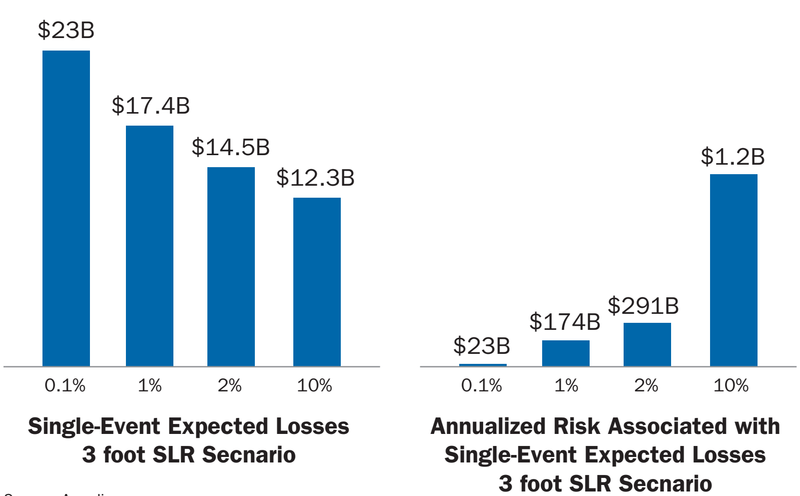
for 0, 1-foot, 3-foot, and 5-foot sea level rise estimates, and thus represents different flood hazard extents.

ASSUMPTIONS AND LIMITATIONS OF THE BUILDING DIRECT PHYSICAL DAMAGE AND DISPLACEMENT ANALYSIS

- NACCS damage functions are applicable to the project study area, and account for underground networks by applying a percent damage for negative flood depths. The underground networks of the study area could not be analyzed due to budget and time constraints, and the level of analysis completed.
- For uses which contain a mixture of residential and commercial uses, commercial occupancies are assumed to be located on the bottom two floors, with residential above (for structures over two stories tall).
- The asset inventory was constructed from assessor's databases from varying years. Damage estimates for some communities are based on dated property information.
- The analysis does not account for population growth, and as such, estimates of future exposed populations are likely underestimated.
- As the flood depth grids do not account for existing or planned adaptation measures to reduce flood risk, results may overestimate damages in some cases. Nevertheless, these overestimates are likely balanced as recent development and population growth are not fully accounted for throughout the study area.
- Analysts did not consider flood areas inland of the metro area's three dams for the 0 and 1-foot sea level rise scenarios, as these are likely caused by rainfall and riverine flooding and will not be reduced by the Inner or the Outer Harbor Barrier. This results in a conservative estimation of flood risk in these areas.

FIGURE APPENDIX D2

Consequence and Probability Example using Four Flood Event Scenarios



Source: Arcadis

Methods to Annualize Losses

Estimating potential benefits of a Harbor Barrier configuration requires calculations of annualized losses avoided. Annualized values represent monetary loss that can be expected due to risk (consequence times probability) over any given one year-period. As evidenced in Figure D2, risk associated with lower impact, higher probability events is often higher than risk associated with larger, more intense storms with lower probability. This is because the expected frequency of impact for higher probability events is likely to lead to increased costs over time.[6]

This evaluation includes information for 16 flood event scenarios that correlate to the 10%, 2%, 1%, and 0.1% annual chance exceedance probabilities in each of four sea level rise scenarios. As sea level rise occurs over time, it is reasonable to expect that flood events become more frequent and the annual probability of occurrence changes. For example, a storm with a 10-foot flood elevation may equate to the 1% annual chance event in 2030 but may be the equivalent to the 10% annual chance event in 2070 given an additional two feet of sea level rise. The increased probability of flooding has a significant effect on expected flood risk over time.

The evolution of probability of event occurrence over time is accounted for through a regression analysis; analysts gathered water surface elevations for each of the sixteen This evaluation includes information for 16 flood events flood scenarios from the Boston Harbor Tide Gauge (Figure D3) and created a curve for each sea level rise scenario that calculates event probability over time. The curves assumes that exceedance probability correlations at the tide gauge are applicable to the study area,[7] and allow analysts to consider additional flood events within a sea level rise scenario, to generate expected losses avoided. Table D5

6 Unmitigated frequent flood events can also lead to disinvestment in an area over time. The economic and quality of life implications of chronic loss of use is not contemplated in this study.

7 A recommended future refinement is to calculatae both losses avoided and exceedance probabilities on the site-specific basis across the study area.

demonstrates the results of the regression analysis, and displays how the redistribution of exceedance probabilities based on each sea level rise scenario impacts annual chance event expectations and generates additional flood events to consider.

An important assumption of the evaluation is that regression analysis that applies to the Boston Harbor tide gauge can be applied throughout both the Inner and Outer Harbor Barrier configurations the study areas. A refinement of this study would be to calculate both losses avoided and exceedance probabilities on the site specific basis across the study area.

Exceedance probabilities shown in Table D5 not only allow analysts to consider 16 flood scenarios per sea level rise scenario, but also allows for those values to be annualized and included in the sensitivity analysis presented in the final report. The annualization method uses damage frequency curves and an algebraic approach to approximate the expected annualized losses avoided between two single-event loss avoidance. Losses avoided are annualized by plotting losses avoided and correlating frequencies for one sea level rise scenario, and estimating the area underneath the damage frequency curve as shown in Figure D4. This area represents an approximate annual damage amount for a sea level

FIGURE APPENDIX D3

NOAA Boston Harbor Tide Gauge Location

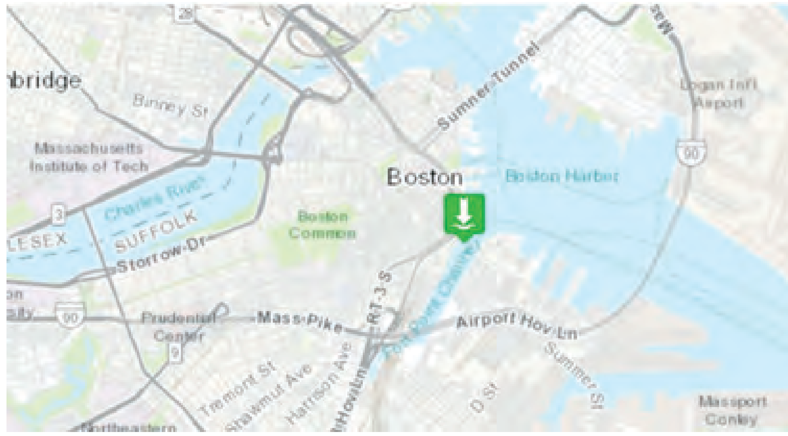


TABLE APPENDIX D5

Water Surface Elevations at the Boston Tide Gauge and Correlated Exceedance Probabilities

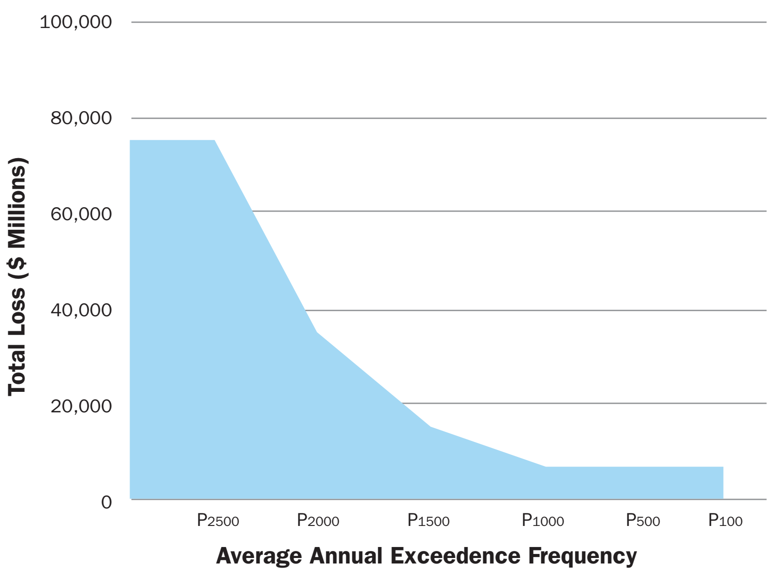
Sea Level Rise Scenario	Exceedance Probability within sea level rise interval	Water Surface Elevation (ft-NAVD88)	Correlating Exceedance Probability: 0-foot SLR Scenario	Correlating Exceedance Probability: 1-foot SLR Scenario	Correlating Exceedance Probability: 3-foot SLR Scenario	Correlating Exceedance Probability: 5-foot SLR Scenario
0 feet (2013)	10%	8.1	14.56603%	96.03901%	***14666.7142%***	***351707.4%***
	2%	8.9	1.86290%	15.13757%	3027.3006%	***75515.5%***
	1%	9.4	0.51519%	4.77047%	1129.1646%	***28869.9%***
	0.1%	9.9	0.14248%	1.50337%	421.1715%	***11037.1%***
1-foot (2030)	10%	9	1.44061%	12.01592%	2485.3976%	***62304.3%***
	2%	9.8	0.18425%	1.89394%	513.0014%	13377.4%
	1%	10.2	0.06589%	0.75192%	233.0665%	6198.7%
	0.1%	11	0.00843%	0.11852%	48.1064%	1330.9%
3-foot (2070)	10%	11.8	0.00108%	0.01868%	9.9295%	285.8%
	2%	12.5	0.00018%	0.00371%	2.4964%	74.4%
	1%	13.1	0.00004%	0.00093%	0.7645%	23.5%
	0.1%	14.1	0.00000%	0.00009%	0.1064%	3.4%
5-foot (2100)	10%	13.5	0.00001%	0.00037%	0.3473%	10.9%
	2%	14.4	0.00000%	0.00005%	0.0589%	1.9%
	1%	14.8	0.00000%	0.00002%	0.0267%	0.9%
	0.1%	15.9	0.00000%	0.00000%	0.0031%	0.1%

Note: Events identified in ***bold italics*** were removed from the analysis for that particular sea level rise scenario. The analysis assumed that any flood events expected to occur more frequently than twice a month would lead to chronic loss of use, and the damages were removed from the evaluation. This would lead to conservatively low loss estimates at higher sea levels as the implications of chronic loss of use are not contemplated in the study. A refinement of the study would be to evaluate the economic and quality of life risk associated with flooding so frequent that uses would need to be significantly modified or eliminated.

Source: Arcadis

FIGURE APPENDIX D4

Example Damage Frequency Curve



Source: Federal Emergency Management Agency Hazus—MH 2.1 Technical Manual, Earthquake Model

rise scenario. This algebraic equation is provided below; analysts executed this equation for each flood scenario, and in the case of the least frequent flood scenario multiplied the expected losses by the annual chance of occurrence for an annualized value estimate.

Equation

Annualized Value = Average losses avoided between two loss events of consecutive magnitude multiplied by the difference in percent annual chance

Equation Example

- Loss Event 1: $991,975,441 at the 14666.7142% annual chance event with 3 feet of sea level rise
- Loss Event 2: $1,181,809,298.09 at the 3027.3006% annual chance event with 3 feet of sea level rise

Calculation

(($991,975,441 + $1,181,809,298.09)/2)*(3027.3006%–14666.7142%) = $126,507,898,960.40 annualized value for the 14666.7142% annual chance event with 3 feet of sea level rise.

The sensitivity analysis assumes that the Harbor Barrier provides an outer, second layer of defense to the study area, and it is assumed to only mitigate losses that exceed the level of protection expected at the shore (equivalent events exceeding a flood elevation of 12 ft NAVD88[8] or 14 ft NAVD88[9] at the Boston Harbor tide gauge, depending on the scenario below evaluated). Furthermore, two scenarios for shore-based solution effectiveness exist: total effectiveness (the shoreline solutions will perform perfectly and provide protection up to the design elevation, with the Harbor Barrier configuration capturing incremental loss above the design elevation as benefits provided by a barrier alignment), and total failure (shoreline solutions would not perform in the occurrence of a flood event greater than the design elevation). These assumptions include the upper and lower bound of potential benefits gained through a Harbor Barrier configuration, although neither are likely occurrences. The range is necessary because the effectiveness of the shore-based solutions is highly dependent on the nature of the solution, and these will vary across the study area landscape. The nature of loss is dependent on the behavior of the shore-based solution and the amount of time overtopping occurs. It's important to note that the scenario assumes that shore level solutions would not be adapted to higher levels of protection beyond the equivalent of 14 feet NAVD88 at the Boston Harbor tide gauge through 2130 or 12 feet NAVD88 at the Boston Harbor tide gauge through 2100 (depending on the selected Shore-Based Solutions and Construction Timeline Scenario). This also assumes total flood mitigation of the shoreline across the study area by the time the Harbor Barrier is in place. Current planning at the shore in South Boston, for example, is focused on designs that could be adapted in the future to the 1% annual chance exceedance probability event at 5 feet of sea level rise, which is the equivalent of 14 feet NAVD88 at the Boston Harbor tide gauge. Adaptation of shore-based solutions to higher levels of protection over time is not considered in the analysis. The annualized project benefits per sea level rise scenario for each of the shore-based solutions sensitivity scenarios are provided in Table D6 through Table D9 on the pages that follow.

8 Correlates to roughly the 3 to 10 percent annual chance exceedance probability at the Boston Harbor tide gauge with three feet of sea level rise. Deemed a reasonable lower bound for feasible shoreline adaptation.

9 Correlates to roughly the 0.1 percent annual chance exceedance probability with three feet of sea level rise. Selected as upper bound due to the fact that recent shoreline adaptation concepts in East Boston and Charlestown identified a goal for shoreline protections to be adaptable to this level of protection in the long term.

Once annualized benefits are determined, analysts discount the annualized values over time to calculate the present value of losses avoided (benefits) to compare to project costs. To do this, analysts apply a discount rate to annualized benefits expected over the life of a Harbor Barrier configuration to account for the fact that project costs and benefits in several decades time should be valued at a lower rate than costs and benefits expected today. This is covered in more detail in the main body of the final report; each design elevation scenario (12 feet NAVD88 and 14 feet NAVD88) has its own expectation of Barrier functionality timelines that are integrated into the present value calculations. In short, a shoreline solutions scenario constructed to 12 feet NAVD88 assumes a Harbor Barrier would be useful in 2050 and functional to 2100. Annualized losses avoided for the year 2050 through 2070 are interpolated between 1 foot and 3 feet sea level rise annualized losses avoided, and annualized losses from 2070 to 2100 are interpolated between the 3 feet and 5 feet sea level rise losses avoided. Alternatively, a scenario with shoreline solutions built to 14 feet NAVD88 assumes that losses avoided will increase between the years 2070 and 2100 (using the 3-foot and 5-foot sea level rise annualized losses avoided to interpolate), and remain static between the years 2100 and 2130 due to the fact that losses were not calculated for any intervals above 5 feet of sea level rise for the purposes of this study.

Vulnerable Populations Analysis Approach

The Vulnerable Populations Analysis uses parcels exposed to flooding identified in the economic analysis to determine the location and concentration of seven social vulnerability factors in the City of Boston, including those with medical illness, young children, older adults, the disabled, low-to-no income, people of color, and those with limited English capabilities. A similar populations analysis for the remainder of the project's study area was conducted by UMass Boston.

TABLE APPENDIX D6

Annualized Losses Avoided (project benefits), Outer and Inner Harbor Barrier Configurations, Assuming 14-Foot Design Elevation of Shore-based Protections and Total Failure of Shore Solutions in Occurrence of Event over 14 feet NAVD88

Sea Level Rise Scenario	Water Surface Elevation (ft-NAVD88)	Redistributed Exceedance Probability: 0-foot SLR Scenario	Single-Event Losses (Outer Barrier)	Single-Event Losses (Inner Barrier)	Annualized Losses (Outer Barrier)	Annualized Losses (Inner Barrier)
1-foot (2030)	14.1	0.00009%	$23,070,106,785	$17,343,222,042	$11,736	$9,035
	14.4	0.00005%	$27,888,454,294	$21,887,495,683	$8,062	$6,323
	14.8	0.00002%	$30,125,253,141	$23,618,140,687	$5,667	$4,462
	15.9	0.00000%	$37,116,538,281	$29,327,894,461	$535	$423
TOTAL ANNUALIZED BENEFITS, 1-FOOT SLR SCENARIO, 14-foot SHORE-BASED PROTECTION, TOTAL FAILURE ASSUMPTION					**$26,001**	**$20,244**
3-feet (2070)	14.1	0.1064%	$23,070,106,785	$17,343,222,042	$12,102,679	$9,317,311
	14.4	0.0589%	$27,888,454,294	$21,887,495,683	$9,315,652	$7,307,147
	14.8	0.0267%	$30,125,253,141	$23,618,140,687	$7,962,886	$6,269,958
	15.9	0.0031%	$37,116,538,281	$29,327,894,461	$1,133,566	$895,695
TOTAL ANNUALIZED BENEFITS, 3-FOOT SLR SCENARIO, 14-foot SHORE-BASED PROTECTION, TOTAL FAILURE ASSUMPTION					**$30,514,783**	**$23,790,111**
5-feet (2100)	14.1	*3.4%*	$23,070,106,785	$17,343,222,042	$382,935,341	$294,804,798
	14.4	*1.9%*	$27,888,454,294	$21,887,495,683	$299,718,037	$235,097,197
	14.8	*0.9%*	$30,125,253,141	$23,618,140,687	$263,794,859	$207,711,478
	15.9	*0.1%*	$37,116,538,281	$29,327,894,461	$39,932,980	$31,553,325
TOTAL ANNUALIZED BENEFITS, 5-FOOT SLR SCENARIO, 14-foot SHORE-BASED PROTECTION, TOTAL FAILURE ASSUMPTION					**$986,381,217**	**$769,166,798**

Source: Arcadis

DATA SOURCES

- US 2010 Census population estimates per census tract
- Parcel inventory
- Statistics on vulnerable populations as determined using Census and American Community Survey (ACS) data compiled by Dr. Atyia Martin.

METHODOLOGY

The Vulnerable Populations analysis estimates the number of residents exposed to flooding at the 0 and 5-foot 1% annual chance event flood scenarios and calculates the expected distribution of socially vulnerable populations among exposed residents.

1. Exposed Residents

The first step to identifying exposed residents begins by estimating the number of residents per parcel throughout the study area, using the parcel inventory and U.S. 2010 Census data provided by census tract. Residential population per parcel

TABLE APPENDIX D7

Annualized Losses Avoided (project benefits), Outer and Inner Harbor Barrier Configurations, Assuming 12-Foot Design Elevation of Shore-based Protections and Total Failure of Shore Solutions in Occurrence of Event over 12 Feet NAVD88

Sea Level Rise Scenario	Water Surface Elevation (ft-NAVD88)	Redistributed Exceedance Probability: 0-foot SLR Scenario	Single-Event Losses (Outer Barrier)	Single-Event Losses (Inner Barrier)	Annualized Losses (Outer Barrier)	Annualized Losses (Inner Barrier)
1-foot (2030)	12.5	0.00371%	$14,556,083,165	$10,528,091,953	$445,058	$324,516
	13.1	0.00093%	$17,446,191,029	$12,806,507,234	$110,292	$83,070
	13.5	0.00037%	$21,978,259,095	$16,887,277,675	$62,219	$47,278
	14.1	0.00009%	$23,070,106,785	$17,343,222,042	$11,736	$9,035
	14.4	0.00005%	$27,888,454,294	$21,887,495,683	$8,062	$6,323
	14.8	0.00002%	$30,125,253,141	23,618,140,687	$5,667	$4,462
	15.9	0.00000%	$37,116,538,281	29,327,894,461	$535	$423
TOTAL ANNUALIZED BENEFITS, 1-FOOT SLR SCENARIO, 12-foot SHORE-BASED PROTECTION, TOTAL FAILURE ASSUMPTION					**$643,570**	**$475,108**
3-feet (2070)	12.5	*2.4964%*	$14,556,083,165	$10,528,091,953	$277,125,583	$202,067,339
	13.1	*0.7645%*	$17,446,191,029	$12,806,507,234	$82,228,785	$61,933,238
	13.5	*0.3473%*	$21,978,259,095	$16,887,277,675	$54,272,298	$41,239,406
	14.1	0.1064%	$23,070,106,785	$17,343,222,042	$12,102,679	$9,317,311
	14.4	0.0589%	$27,888,454,294	$21,887,495,683	$9,315,652	$7,307,147
	14.8	0.0267%	$30,125,253,141	$23,618,140,687	$7,962,886	$6,269,958
	15.9	0.0031%	$37,116,538,281	$29,327,894,461	$1,133,566	$895,695
TOTAL ANNUALIZED BENEFITS, 3-FOOT SLR SCENARIO, 12-foot SHORE-BASED PROTECTION, TOTAL FAILURE ASSUMPTION					**$444,141,448**	**$329,030,095**
5-feet (2100)	12.5	74.4%	$14,556,083,165	10,528,091,953	$8,146,222,417	$5,939,853,957
	13.1	23.5%	$17,446,191,029	$12,806,507,234	$2,481,327,614	$1,868,891,214
	13.5	10.9%	$21,978,259,095	$16,887,277,675	$1,675,995,188	$1,273,523,505
	14.1	*3.4%*	$23,070,106,785	$17,343,222,042	$382,935,341	$294,804,798
	14.4	*1.9%*	$27,888,454,294	$21,887,495,683	$299,718,037	$235,097,197
	14.8	*0.9%*	$30,125,253,141	$23,618,140,687	$263,794,859	$207,711,478
	15.9	*0.1%*	$37,116,538,281	$29,327,894,461	$39,932,980	$31,553,325
TOTAL ANNUALIZED BENEFITS, 5-FOOT SLR SCENARIO, 12-foot SHORE-BASED PROTECTION, TOTAL FAILURE ASSUMPTION					**$13,289,926,437**	**$9,851,435,474**

Source: Arcadis

TABLE APPENDIX D8

Annualized Losses Avoided (project benefits), Outer and Inner Harbor Barrier Configurations, Assuming 14-foot Design Elevation of Shore-based Protections and Total Effectiveness of Shore Solutions in Occurrence of Event over 14 Feet NAVD88

Sea Level Rise Scenario	Water Surface Elevation (ft-NAVD88)	Redistributed Exceedance Probability: 0-foot SLR Scenario	Single-Event Losses (Outer Barrier)	Single-Event Losses (Inner Barrier)	Annualized Losses (Outer Barrier)	Annualized Losses (Inner Barrier)
1-foot (2030)	14.1	0.00009%	$1,091,847,690	$455,944,368	$1,613	$1,257
	14.4	0.00005%	$5,910,195,199	$5,000,218,008	$1,953	$1,630
	14.8	0.00002%	$8,146,994,045	$6,730,863,012	$1,962	$1,616
	15.9	0.00000%	$15,138,279,186	$12,440,616,787	$218	$179
TOTAL ANNUALIZED BENEFITS, 1-FOOT SLR SCENARIO, 14-foot SHORE-BASED PROTECTION, TOTAL EFFECTIVENESS ASSUMPTION					**$5,747**	**$4,682**
3-feet (2070)	14.1	0.1064%	$1,091,847,690	$455,944,368	$1,662,988	$1,295,841
	14.4	0.0589%	$5,910,195,199	$5,000,218,008	$2,257,258	$1,883,739
	14.8	0.0267%	$8,146,994,045	$6,730,863,012	$2,757,481	$2,270,319
	15.9	0.0031%	$15,138,279,186	$12,440,616,787	$462,334	$379,945
TOTAL ANNUALIZED BENEFITS, 3-FOOT SLR SCENARIO, 14-foot SHORE-BASED PROTECTION, TOTAL EFFECTIVENESS ASSUMPTION					**$7,140,061**	**$5,829,844**
5-feet (2100)	14.1	*3.4%*	$1,091,847,690	$455,944,368	$52,617,845	$41,001,107
	14.4	*1.9%*	$5,910,195,199	$5,000,218,008	$72,624,098	$60,606,652
	14.8	*0.9%*	$8,146,994,045	$6,730,863,012	$91,349,966	$75,211,230
	15.9	*0.1%*	$15,138,279,186	$12,440,616,787	$16,286,988	$13,384,624
TOTAL ANNUALIZED BENEFITS, 5-FOOT SLR SCENARIO, 14-foot SHORE-BASED PROTECTION, TOTAL EFFECTIVENESS ASSUMPTION					**$232,878,897**	**$190,203,612**

Source: Arcadis

was estimated per the steps below. Note that this analysis did not use aggregated parcel information similar to the economic analysis, but rather used parcel-level information for building size and use.

- Assign census tract to parcels.
- Identify the total amount of residential space existing within a census tract. Analysts identified residential and mixed-use parcels using structure use codes provided in the Assessing Data. For mixed-use parcels 3 stories tall or higher, analysts assumed that the first two floors are commercial space and did not include that assumed commercial square footage in the population analysis.
- Identify the total amount of residential space exposed within a census tract for the 1% annual chance event for 0 and 5-foot sea level rise scenarios, using parcels identified in the economic analysis. Analysts followed the same approach to identify residential and mixed-use parcels, and the square footage, within the entire census tract to maintain consistency.
- Divide the exposed residential square footage within a census tract by the total residential square footage in the census tract. This provides you with the percentage of residential square footage exposed to flooding.
- Multiply the percentage of residential area exposed by the total population within a building's census tract. This provides an estimate of the number of people exposed within a census tract.

2. Vulnerable Populations

Dr. Martin's vulnerable populations data reports the percentage of seven vulnerable populations which are expected to reside in a given census tract for the City of Boston. Therefore, the Vulnerable Populations Analysis is executed with census-tract granularity. Analysts applied the tract-specific percent population factor for each of the seven vulnerable populations to the total number of people identified as exposed in the

TABLE APPENDIX D9

Annualized Losses Avoided (project benefits), Outer and Inner Harbor Barrier Configurations, Assuming 12-foot Design Elevation of Shore-based Protections and Total Failure of Shore Solutions in Occurrence of Event over 12 Feet NAVD88

Sea Level Rise Scenario	Water Surface Elevation (ft-NAVD88)	Redistributed Exceedance Probability: 0-foot SLR Scenario	Single-Event Losses (Outer Barrier)	Single-Event Losses (Inner Barrier)	Annualized Losses (Outer Barrier)	Annualized Losses (Inner Barrier)
1-foot (2030)	12.5	0.00371%	$2,249,519,710	$1,673,595,052	$102,761	$78,236
	13.1	0.00093%	$5,139,627,575	$3,952,010,333	$41,435	$33,528
	13.5	0.00037%	$9,671,695,641	$8,032,780,774	$28,225	$22,819
	14.1	0.00009%	$10,763,543,331	$8,488,725,142	$6,068	$4,957
	14.4	0.00005%	$15,581,890,840	13,032,998,782	$4,641	$3,863
	14.8	0.00002%	$17,818,689,686	$14,763,643,786	$3,593	$2,970
	15.9	0.00000%	$24,809,974,827	$20,473,397,561	$358	$295
TOTAL ANNUALIZED BENEFITS, 1-FOOT SLR SCENARIO, 12-foot SHORE-BASED PROTECTION, TOTAL EFFECTIVNESS ASSUMPTION					**$187,081**	**$146,667**
3-feet (2070)	12.5	*2.4964%*	$2,249,519,710	$1,673,595,052	$63,986,757	$48,715,262
	13.1	*0.7645%*	$5,139,627,575	$3,952,010,333	$30,892,431	$24,997,047
	13.5	*0.3473%*	$9,671,695,641	$8,032,780,774	$24,619,481	$19,904,387
	14.1	0.1064%	$10,763,543,331	$8,488,725,142	$6,257,051	$5,111,418
	14.4	0.0589%	$15,581,890,840	13,032,998,782	$5,363,356	$4,463,494
	14.8	0.0267%	$17,818,689,686	$14,763,643,786	$5,048,158	$4,172,830
	15.9	0.0031%	$24,809,974,827	$20,473,397,561	$757,714	$625,272
TOTAL ANNUALIZED BENEFITS, 3-FOOT SLR SCENARIO, 12-foot SHORE-BASED PROTECTION, TOTAL EFFECTIVENESS ASSUMPTION					**$136,924,949**	**$107,989,709**
5-feet (2100)	12.5	74.4%	$2,249,519,710	$1,673,595,052	$1,880,917,490	$1,432,005,501
	13.1	23.5%	$5,139,627,575	$3,952,010,333	$932,206,922	$754,308,381
	13.5	10.9%	$9,671,695,641	$8,032,780,774	$760,279,791	$614,671,895
	14.1	*3.4%*	$10,763,543,331	$8,488,725,142	$197,976,505	$161,728,050
	14.4	*1.9%*	$15,581,890,840	13,032,998,782	$172,558,467	$143,606,667
	14.8	*0.9%*	$17,818,689,686	$14,763,643,786	$167,235,618	$138,237,697
	15.9	*0.1%*	$24,809,974,827	$20,473,397,561	$26,692,581	$22,026,940
TOTAL ANNUALIZED BENEFITS, 5-FOOT SLR SCENARIO, 12-foot SHORE-BASED PROTECTION, TOTAL EFFECTIVENESS ASSUMPTION					**$4,137,867,375**	**$3,266,585,130**

census tract to the 1% annual chance event for the 0 and 5-foot sea level rise scenarios. This estimates the presence, distribution, and concentration of vulnerable populations exposed to coastal flooding throughout the City of Boston. UMass Boston conducted a similar analysis throughout the remaining study area.

ASSUMPTIONS AND LIMITATIONS

The number of people exposed in this analysis only considers residents of structures exposed to flooding and does not include a review of people who work or visit areas exposed to flooding. While it is reasonable to assume that residents of structures exposed to flood risk will also be exposed

to system outages such as public transportation and essential services including energy, water, and wastewater, this analysis does not consider impacts to people who live outside of flood inundation zones but are affected by interruption of the aforementioned services. Therefore, the analysis does not consider all persons that could be adversely affected by a flood event. The analysis considers a static population and does not account for future development and population growth.

The Vulnerable Populations Analysis is completely dependent upon the exposed population generated in the economic analysis and data provided by Dr. Atyia Martin. All assumptions which apply to those studies also apply to this analysis.

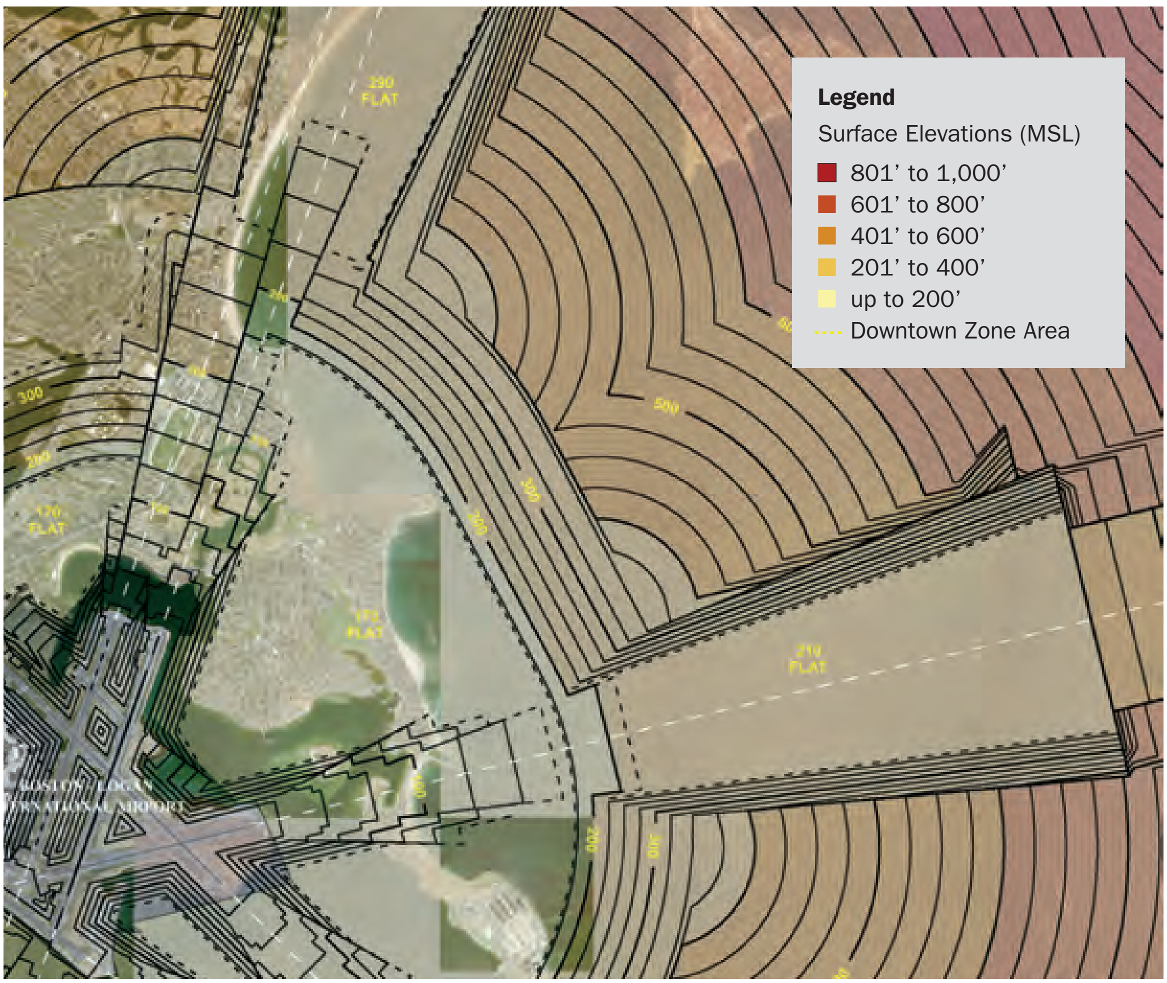
Each social vulnerability category is not mutually exclusive, and one person can be represented in multiple categories. The vulnerable populations analysis is not meant for use in determining the total number of socially vulnerable people exposed to coastal flooding, but instead to identify the locations and concentrations of such populations in the context of risk areas.

APPENDIX E

LOGAN AIRPORT AIRSPACE MAP

FIGURE APPENDIX E1A

Logan International Airport Composite of Critical Air Space Surfaces



Notes: Dashed lines identify transition from “Flat” to “Sloping” surface. Contour Interval = 25 ft.

Source: Massport

Composite Map Parameters

This Composite Map is intended for informational and conceptual planning purposes only and does not represent actual survey data nor should it be used in the development of a FAA Form 7460. Massport does not certify the accuracy, information or title to the properties contained in this plan nor make any warranties of any kind, express or implied, in fact or by law, with respect to boundaries, easements, restrictions, claims, overlaps, or other encumbrances affecting such properties.

This Composite Map does not replace the FAA's 7460 review process. Consistency with the surfaces shown on this map does not ensure that the proposal will be acceptable to the FAA and air carriers. Massport reserves the right to re-assess, review and see modifications to projects that may be consistent with this Composite Map but that through the FAA 7460 process are found to have unexpected impacts to Boston Logan's safety or efficiency.

Surface elevations are referenced in feet Above Mean Sea Level (AMSL–NAVD88).

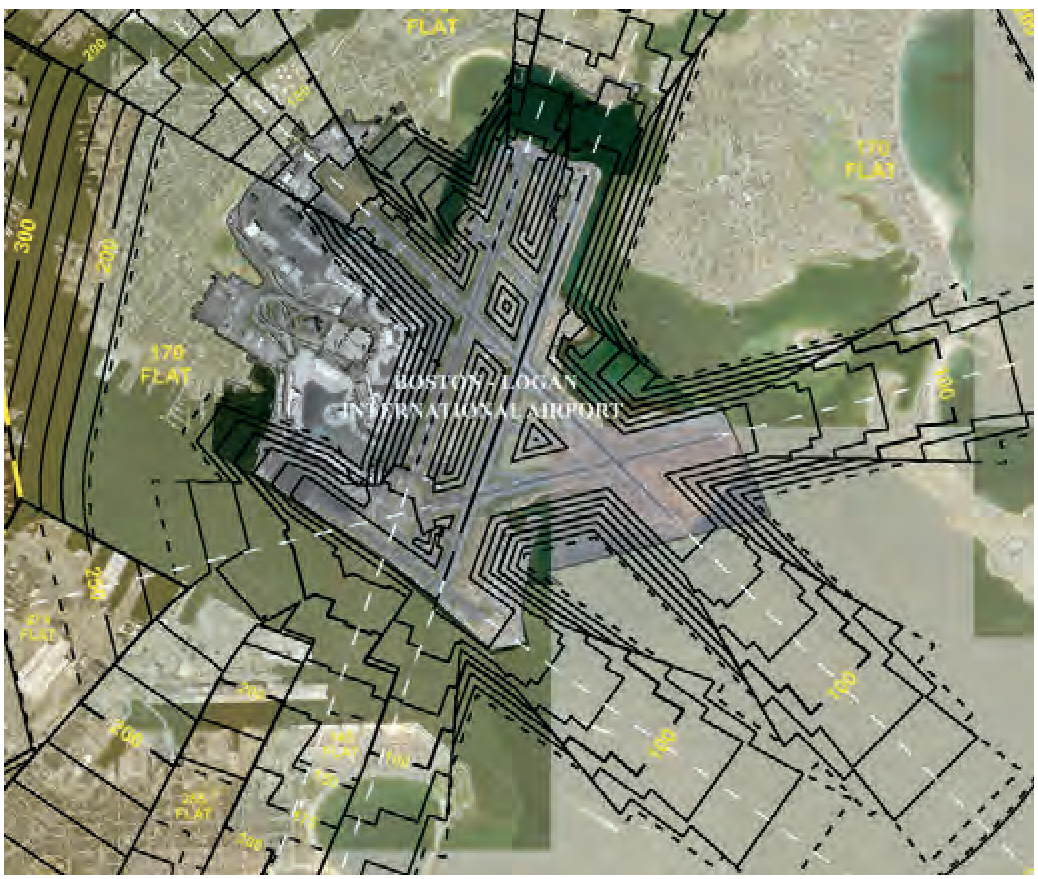
Composite Map Parameters

Surface Types	Runways
CIRCLE-TO-LAND	ALL RUNWAYS (EXCEPT 14)
ICAO/AC ONE ENGINE INOP.	4R, 4L, 9, 14, 15R, 22L, 22R, 27, 33L
IFR STND DEPARTURE	4R, 9, 14, 15R, 22L^, 22R^, 27^, 33L
IFR NON-STND DEPARTURE	4L
ILS APPROACH	4R, 15R, 22L, 27, 33L
ILS MISSED APPROACH	4R*, 15R, 22L, 27, 33L*^^
LOCALIZER APPROACH**	4R, 15R, 22L, 27, 33L
LNAV APPROACH**	4R, 15R, 22L, 27, 32, 33L
LNAV MISSED APPROACH	4R, 15R, 22L, 27, 32, 33L
PART 77–STANDARD	EAST OF 4R/22L
PART 77–VFR ONLY	WEST OF 4R/22L (N. OF DOWNTOWN)
VISABILITY (CIRCLING)	ALL RUNWAYS (EXCEPT 14)
VISABILITY (STRAIGHT-IN)	4R, 15R, 22L, 27, 32, 33L
VNAV APPROACH	4R, 15R, 27, 33L
VNAV MISSED APPROACH	4R, 15R, 27, 33L

^ INCLUDES TRANSITION FROM PREVIOUS CRITERIA
* CAT 1 AND CAT 3
^^ CAT 3 SHIFTED 200° NW
** ACCOUNTS FOR 7:1 DRIFT DOWN

FIGURE APPENDIX E1B

Logan International Airport Composite of Critical Air Space Surfaces



Legend

Surface Elevations (MSL)

- 801' to 1,000'
- 601' to 800'
- 401' to 600'
- 201' to 400'
- up to 200'
- Downtown Zone Area

Notes: Dashed lines identify transition from "Flat" to "Sloping" surface. Contour Interval = 25 ft.

Source: Massport

APPENDIX F

REGULATORY REQUIREMENTS FOR HARBOR-WIDE BARRIERS

The following tables provide an overview of federal, state, and local reviews that may be required as part of the implementation of these protection strategies. The tables include the entity/entities that oversee the regulatory programs, and descriptions of the programs themselves, including important activities and jurisdictions as well as whether the program applies to upland, intertidal, and/or subtidal areas. As displayed by the tables, the large number of agencies likely involved, and reviews needed, highlight the highly complex and lengthy regulatory process that would be needed to construct and install protection systems such as these.

The federal, state, and local regulatory reviews described in this section recognize the importance of balancing the need(s) for and advantage(s) of the project with the public's rights and interests in natural, cultural, and historic resource protection; environmental quality; safety; and public access. In other words, a project's social and economic benefits are evaluated against the adverse impacts to the natural and human environments.

These tables are not comprehensive, but contain major regulatory programs and subsequent reviews that might be needed for the different protection options (e.g., a barrier and/or shore-based berms, levees, and flood walls).

TABLE APPENDIX F1

Anticipated Areas Affected by the Three Protection System Options

	Inner and Outer Harbor Barriers	Shore-based Berms, Levees, and Flood Walls
Anticipated Affected Areas	• Land under tidal waters (submerged land: High Low Water (HLW) to 3 nm offshore) owned by state; • Intertidal area (High High Water (HHW) to HLW) may be privately-owned with reserved public trust rights held by the Commonwealth. • Public and private property upland of Mean High Water (MHW) in several municipalities	• Public and private property upland of MHW line in several municipalities. • Likely some intertidal areas (HHW to HLW): public or privately owned, the latter with reserved public trust rights held by the Commonwealth. • Potential impacts to land under tidal waters

TABLE APPENDIX F2

Review of Federal Regulations Pertinent to the Construction of a Harbor Barrier

The construction and installation of the flood protection options noted above would require a complex federal review process, likely consisting of the following regulatory programs.

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
U.S. Army Corps of Engineers	Rivers and Harbors Act of 1899, Section 10, 33 U.S.C. § 403	Requires that regulated activities (e.g., placement/removal of structures, work involving dredging) conducted below the Ordinary High Water (OHW) elevation of navigable waters of the United States be approved/permitted by the USACOE.	Building any wharf, pier, dolphin, boom, weir, breakwater, bulkhead, jetty, or other structures; or excavating or filling, or in any manner to alter or modify the course, location, condition, or capacity of, any port, roadstead, haven, harbor, canal, lake, harbor of refuge, or enclosure within the limits of any breakwater, or of the channel of any navigable water of the United States.	Navigable waters of the U.S.
U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers	Clean Water Act, Section 404, 33 U.S.C. § 1344	Establishes a program to regulate the discharge of dredged or fill materials into waters of the U.S. (including wetlands) without a permit from the USACOE.	The discharge of dredge or fill material (1) from normal farming, silviculture, and ranching activities such as plowing, seeding, cultivating, minor drainage, harvesting for the production of food, fiber, and forest products, or upland soil and water conservation practices; (2) for the purpose of maintenance, including emergency reconstruction of recently damaged parts, of currently serviceable structures such as dikes, dams, levees, groins, riprap, breakwaters, causeways, and bridge abutments or approaches, and transportation structures; (3 for the purpose of construction or maintenance of farm or stock ponds or irrigation ditches, or the maintenance of drainage ditches; (4) for the purpose of construction of temporary sedimentation basins on a construction site which does not include placement of fill material into the navigable waters; (5) for the purpose of construction or maintenance or farm roads or forest roads, or temporary roads for moving mining equipment, where such roads are constructed and maintained, in accordance with best management practices, to assure that flow and circulation patterns and chemical and biological characteristics of the navigable waters are not impaired, that the reach of the navigable waters is not reduced, and that any adverse effect on the aquatic environment will be otherwise minimized; (6) resulting from any activity with respect to which a State has an approved program under section 1288(b)(4) of this title which meets the requirements of subparagraphs (B) and (C) of such section, is not prohibited by or otherwise subject to regulation under this section or section 1311(a) or 1342 of this title (except for effluent standards or prohibitions under section 1317 of this title). Any discharge of dredged or fill material into the navigable waters incidental to any activity having as its purpose bringing an area of the navigable waters into a use to which it was not previously subject, where the flow or circulation of navigable waters may be impaired or the reach of such waters be reduced, shall be required to have a permit under this section.	Waters of the United States (navigable waters, their tributaries, and adjacent wetlands)
U.S. Environmental Protection Agency and Massachusetts Department of Environmental Protection	Clean Water Act, Section 402, National Pollutant Discharge Elimination System (NPDES) Permit Program, 33 U.S.C. § 1342	EPA's National Pollutant Discharge Elimination System Permit program controls discharges from point sources to waters of the United States.	Point sources are discrete conveyances such as pipes or man-made ditches. Individual homes that are connected to a municipal system, use a septic system, or do not have a surface discharge do not need an NPDES permit; however, industrial, municipal, and other facilities must obtain permits if their discharges go directly to surface waters.	All waters with a "significant nexus" to "navigable waters"

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
U.S. Environmental Protection Agency	National Environmental Policy Act of 1969, 42 U.S.C. §§ 4321 et seq.	The National Environmental Policy Act (NEPA) is our basic national charter for protection of the environment. It establishes policy, sets goals (section 101), and provides means (section 102) for carrying out the policy. The NEPA process is intended to help public officials make decisions that are based on understanding of environmental consequences, and take actions that protect, restore, and enhance the environment.	NEPA requires Federal agencies to integrate environmental values into their decision-making processes by considering the environmental impacts (positive and negative) of their major proposed actions and reasonable alternatives to those actions. Major Federal actions include the following: • New/continuing activities financed, assisted, conducted, or approved by Federal agencies, • New/revised rules, regulations, plans, policies, or procedures, and • Legislative proposals.	NEPA applies whenever a proposed activity or action is proposed on federal lands, or requires passage across federal lands, or will be funded in part or in whole by federal money, or will affect the air or water quality that is regulated by federal law.
U.S. Environmental Protection Agency	Clean Air Act, 42 U.S.C. §§ 7401 et seq.	Law that defines EPA's responsibilities for protecting and improving the nation's air quality and the stratospheric ozone layer. The purpose of the act is to combat a variety of air pollution problems and to tackle emerging pollution threats.	The Clean Air Act controls air pollution from 1) major stationary sources (e.g., factories, boilers, power plants), and 2) mobile sources (e.g., diesel boats and ships, gasoline boats and personal watercraft).	United States, including the Outer Continental Shelf
U.S. Environmental Protection Agency	Oil Pollution Act, 33 U.S.C. §§ 2701 et seq.	Sets forth requirements for prevention of, preparedness for, and response to oil discharges at specific non-transportation-related facilities. The OPA greatly increased federal oversight of maritime oil transportation.	Provides that the responsible party for a vessel or facility from which oil is discharged, or which poses a substantial threat of a discharge, is liable for: (1) certain specified damages resulting from the discharged oil; and (2) removal costs incurred in a manner consistent with the National Contingency Plan (NCP). Exceptions to the Clean Water Act (CWA) liability provisions include: (1) discharges of oil authorized by a permit under Federal, State, or local law; (2) discharges of oil from a public vessel; or (3) discharges of oil from onshore facilities covered by the liability provisions of the Trans-Alaska Pipeline Authorization Act.	Navigable waters, exclusive economic zones, or the shorelines of such covered waters
Federal Aviation Administration	Structures Interfering with Air Commerce or National Security, 49 U.S.C. § 44718	The Federal Aviation Administration (FAA) of the US Department of Transportation, is responsible for review of any proposed construction that would intrude into navigable airspace. Federal regulations at 14 CFR Part 77 (pursuant to 49 U.S.C. Section 44718) require the filing of a notice for the proposed construction or alteration of certain objects that may affect the navigable airspace.	The construction, alteration, establishment, or expansion, or the proposed construction, alteration, establishment, or expansion, of a structure or sanitary landfill.	Vertical structures greater than 200 feet must have FAA approval [may not apply to a barrier project, as the barrier would be less than 200 feet]
U.S. Coast Guard (Department of Homeland Security)	Coast Guard Vessel Operating Requirements, 33 U.S.C. §§ 1223-1224	The Secretary of the Department of Homeland Security may construct, operate, maintain, improve, or expand vessel traffic services, consisting of measures for controlling or supervising vessel traffic or for protecting navigation and the marine environment and may include, but need not be limited to one or more of the following: reporting and operating requirements, surveillance and communications systems, routing systems, and fairways.	Impacts to navigation.	Navigable waters of the U.S. (tidal waters to mean high water)

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
National Oceanic and Atmospheric Administration and Massachusetts Office of Coastal Zone Management	Coastal Zone Management Act, 16 U.S.C. §§ 1451 et seq.	Federal Consistency Review requires that federal actions within and outside of the coastal zone, which may have effects on coastal use or natural resources of the coastal zone, be consistent with the state's federally approved coastal management program.	Federal actions, within and outside the coastal zone, which have reasonably foreseeable effects on any coastal use (land or water) or natural resource of the coastal zone be consistent with the enforceable policies of a state's federally approved coastal management program. Federal actions include federal agency activities, federal license or permit activities, and federal financial assistance activities.	State and federal U.S. waters
U.S. Fish and Wildlife Service (Department of the Interior) and the National Marine Fisheries Service (National Oceanic and Atmospheric Administration)	Endangered Species Act, 16 U.S.C. §1531	The purposes of this Act are to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved, to provide a program for the conservation of such endangered species and threatened species. All federal departments and agencies shall seek to conserve endangered species and threatened species.	Any agency action which is likely to jeopardize the continued existence of any species proposed to be listed under section 4 or result in the destruction or adverse modification of critical habitat proposed to be designated for such species. Additionally, any individual action that involves the importation, take, sale, transport, etc. of endangered species.	Applies to individuals, organizations, and agencies subject to United States jurisdiction
National Marine Fisheries Service (National Oceanic and Atmospheric Administration)	Marine Mammal Protection Act, 16 U.S.C. §§ 1361 et seq.	Prohibits with, with certain exceptions, the "take" of marine mammals in U.S. waters and by U.S. citizens on the high seas.[1] "Take" is defined under the MMPA as "to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal" (16 U.S.C. 1362).[2]	Any activity that includes the taking and importation of marine mammals and/or marine mammal products without a permit.	U.S. Waters and U.S. citizens on the high seas, and importation of marine mammals and marine mammal products to the U.S.
National Marine Fisheries Service (National Oceanic and Atmospheric Administration)	Magnuson-Stevens Fishery Conservation and Management Act, 16 U.S.C. §§ 1801 et seq.	The primary law governing marine fisheries management in U.S. federal waters.[3] Conservation and management measures shall: 1. Prevent overfishing while achieving optimum yield. 2. Be based upon the best scientific information available. 3. Manage individual stocks as a unit throughout their range, to the extent practicable; inter-related stocks shall be managed as a unit or in close coordination. 4. Not discriminate between residents of different states; any allocation of privileges must be fair and equitable. 5. Where practicable, promote efficiency, except that no such measure shall have economic allocation as its sole purpose. 6. Take into account and allow for variations among and contingencies in fisheries, fishery resources, and catches. 7. Minimize costs and avoid duplications, where practicable. 8. Take into account the importance of fishery resources to fishing communities to provide for the sustained participation of, and minimize adverse impacts to, such communities (consistent with conservation requirements). 9. Minimize bycatch or mortality from bycatch. 10. Promote safety of human life at sea.	The Act authorizes no impediment to, or interference with, recognized legitimate uses of the high seas, except as necessary for the conservation and management of fishery resources. Any activity that may interfere with conservation and management of Fishery resources would come into question.	U.S. Federal Waters (out to 200 miles)

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
U.S. Fish and Wildlife Service (Department of the Interior)	Migratory Bird Treaty Act, 16 U.S.C. §§ 703 et seq. and Exec. Order No. 13186, Responsibilities of Federal Agencies to Protect Migratory Birds, 3 CFR 13186 (2001)	Unless and except as permitted by regulations made as hereinafter provided in this subchapter, it shall be unlawful at any time, by any means or in any manner, to pursue, hunt, take, capture, kill, attempt to take, capture, or kill, possess, offer for sale, sell, offer to barter, barter, offer to purchase, purchase, deliver for shipment, ship, export, import, cause to be shipped, exported, or imported, deliver for transportation, transport or cause to be transported, carry or cause to be carried, or receive for shipment, transportation, carriage, or export, any migratory bird, any part, nest, or egg of any such bird, or any product, whether or not manufactured, which consists, or is composed in whole or part, of any such bird or any part, nest, or egg thereof.	The Treaty Act applies to any person who does not have a waiver or permit. The Executive Order directs federal agencies that take actions that either directly or indirectly affect migratory birds to develop a Memorandum of Understanding.	Migratory birds between the United States and Great Britain.
Secretary of the Interior, all Federal agencies	National Historic Preservation Act, 54 U.S.C. §§ 300101 et seq.	The intent of this act is to preserve historical and archaeological sites in the U.S., and requires federal agencies to evaluate the impact of all federally funded or permitted projects on historic properties.	Any action (e.g., license, project, construction) that could impact have an effect on historic properties (prehistoric or historic district, site, building, structure, or object).	Jurisdiction of U.S. federal agencies
Secretary of the Interior, all Federal agencies	Preservation of Historical and Archeological Data, 54 U.S.C. §§ 312501-312508	Provides for the preservation of scientific, prehistorical, historical, and archeological data (including relics and specimens) which might be irrevocably lost or destroyed by any Federal or federally assisted or licensed project, activity, or program.	Any Federal or federally assisted or licensed construction project, activity, or program that could result in the irrevocable loss or destruction of scientific, prehistorical, historical, and archeological data.	Jurisdiction of U.S. federal agencies
All Federal agencies	Exec. Order No. 12898, Federal Actions to Address Environmental Justice in Minority and Low-Income Populations, 3 CFR 12898 (1994)	Directs federal agencies to make achieving environmental justice part of its mission.	Federal actions that may affect human health or have environmental effects on minority and low income populations.	Applies to Federal agency activities in the United States and its territories and possessions, the District of Columbia, the Commonwealth of Puerto Rico, and the Commonwealth of the Mariana Islands.

1 National Oceanic and Atmospheric Administration. Marine Mammal Protection Act. Online at: *http://www.nmfs.noaa.gov/pr/laws/mmpa*.

2 National Oceanic and Atmospheric Administration. Glossary. Online at: *http://www.nmfs.noaa.gov/pr/glossary.htm#take*.

3 National Oceanic and Atmospheric Administration Fisheries. Magnuson-Stevens Act. Online at: *http://www.nmfs.noaa.gov/pr/glossary.htm#take*.

TABLE APPENDIX F3

Review of State Regulations Pertinent to the Construction of a Harbor Barrier

The table below summarizes the primary state laws and regulations that would govern barrier project activities. Due to the integrated nature of the Massachusetts coastal ecosystem and the large scale of some of the barrier options, such a project may have wide-ranging impacts beyond the geographic area enclosed by the barriers.

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
Massachusetts Environmental Policy Act Office	Massachusetts Environmental Policy Act, M.G.L ch. 301, §61-62, 301 CMR 11.00	Review of environmental impacts of development projects and other activities that require one or more state agency actions.	Any activity requiring a state permit, including structures and work.	Any project requiring state agency action, including granting state permits or licenses, providing state financial assistance, or transferring state land.
Massachusetts Department of Environmental Protection	Massachusetts Public Waterfront Act, M.G.L. ch. 91, 301 CMR 9.00	The Commonwealth's public trust statute, which seeks to (1) ensure that the waterfront and waterways are used primarily for water-dependent uses by (a) prevent encroachment by incompatible development, and (b) avoiding the disruption of existing maritime and waterway pursuits while promoting new water-dependent operations; and (2) provide public access for the use and enjoyment of waterway by (a) preserving and promoting the rights of safe pedestrian activities along the water's edge and its immediate environment and (b) securing public access benefits as compensation for nonwater-dependent development on private tidelands.	Structures (placement or construction), filling, dredging, change in use, structural alteration, demolition/removal of structures. Types of structures include: piers, wharves, floats, retaining walls, revetments, pilings, and waterfront buildings (if located on filled lands or over water).	(1) Flowed Tidelands—in, on, over, or under any tidal waters seaward of present MHW; (2) Filled Tidelands—(a) Outside DPAs, limit is the first public way or 250 feet from MHW, whichever is further landward, (b) Inside DPAs, limit is the historic MHW shoreline (i.e, all filled areas); (3) Great ponds; (4) Non-tidal rivers and streams.
Massachusetts Department of Environmental Protection	401 Water Quality Certification, 314 CMR 9.00	The regulations establish permitting requirements for dredging projects, as required by Section 401 of the federal Clean Water Act.	Discharge of dredged or fill material, dredging, and dredged material disposal activities	Waters of the United States within the Commonwealth which require federal licenses or permits and which are subject to state water quality certification under 33 U.S.C. 1251 (Clean Water Act).
Municipal Conservation Commissions implement the Act; Massachusetts Department of Environmental Protection oversees the administration of the law	Massachusetts Wetlands Protection Act, M.G.L. ch. 131, § 40, 310 CMR 10.00	Administered at the municipal level by conservation commissions, the Wetlands Protection Act requires a review of proposed work that may alter wetlands, land subject to flooding, riverfront areas, and land beneath waterbodies, waterways, salt ponds, fish runs, and the ocean. The regulations provide guidance on the types and extent of work allowed in the resource areas. Municipal conservation commissions review projects and issue Orders of Conditions that deny or approve the projects. Approval often includes special conditions that must be met to protect public interests. Written notice must be given to abutters of the project, and abutters have the opportunity to provide comments.	Activities involving removal, filling, dredging or alteration of wetlands, land subject to flooding, riverfront areas, and land beneath waterbodies, waterways, salt ponds, fish runs, and the ocean other than in the course of maintaining, repairing or replacing, but not substantially changing or enlarging, an existing and lawfully located structure or facility used in the service of the public and used to provide electric, gas, sewer, water, telephone, telegraph and other telecommunication services.	Massachusetts, any bank, riverfront area, fresh water wetland, coastal wetland, beach, dune, flat, marsh, meadow or swamp bordering on the ocean or on any estuary, creek, river, stream, pond, or lake, or any land under said waters or any land subject to tidal action, coastal storm flowage, or flooding. In addition, any work within the 100 foot "buffer zone" of a wetland resource area.

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
Massachusetts Department of Conservation and Recreation	Areas of Critical Environmental Concern (ACECs), 301 CMR 12.00	Describes the procedures for the nomination, review, and designation of ACECs. Directs the agencies of the Massachusetts Executive Office of Energy and Environmental Affairs (EOEEA) to take actions, administer programs, and revise regulations in order to (a) acquire useful scientific data on the ACEC, (b) preserve, restore, or enhance the natural and cultural resource of the ACEC, and (c) ensure that activities in or impacting on the area are carried out so as to minimize adverse effects on: (1) marine and aquatic productivity; (2) surface and groundwater quality or quantity; (3) habitat values and biodiversity; (4) storm damage prevention or flood control; (5) historic and archeological resources; (6) scenic and recreational resources; and (7) other natural resource values of the area.	Activities in or impacting any ACEC in Massachusetts, including a project undertaken directly by an agency, the granting of a permit by an agency, or the granting of financial assistance by an agency.	Within any ACEC in Massachusetts or within any area in which action taken could impact an ACEC.
Massachusetts Department of Conservation and Recreation (administration), Massachusetts Office of Coastal Zone Management (commenting on proposals through MEPA and Chapter 91 licensing)	Massachusetts Ocean Sanctuaries Act, M.G.L. ch. 132A, §§ 12A–16E, 18 (1970), 302 CMR 5.00	Designates 5 ocean sanctuaries to be protected from any exploitation, development, or activity that would seriously alter or otherwise endanger the ecology of the appearance of the ocean, the seabed or subsoil thereof, or the Cape Cod National Seashore.	Any activity that would seriously alter or endanger the ecology or appearance of the ocean, seabed, or subsoil of the Ocean Sanctuaries or the Cape Cod National Seashore. "Seriously alter" includes, but is not limited to, one or more of the following actions: (b) changing drainage or flushing characteristics, salinity distribution, sedimentation or flow patterns, flood storage areas or the water table, to more than a negligible extent; (d) driving pilings or erecting buildings, structures or obstructions of any kind of any significant size or quantity, whether or not they interfere with the flow of water.	Five Ocean Sanctuaries: North Shore Ocean Sanctuary, South Essex Ocean Sanctuary, Cape Cod Bay Ocean Sanctuary, Cape Cod Ocean Sanctuary, and Cape & Islands Ocean Sanctuary); and the Cape Cod National Seashore. The landward boundary is the mean low water mark and the seaward boundary is the limit of state waters.[4]
Massachusetts Office of Coastal Zone Management	Massachusetts Coastal Zone Management Program, M.G.L. ch. 21A, §§ 2, 4A and ch. 589, §30 of the Acts of 1983, 301 CMR 20, pursuant to the federal Coastal Zone Management Act of 1972 (16 U.S.C. 1451 et seq.), 15 CFR §§ 923 and 930	Implements the federal consistency review process in Massachusetts, which ensures federal projects meet state standards articulated in the MA coastal zone management plan.	Any project that (1) is or can reasonably be expected to affect a use or resource of the Massachusetts coastal zone, and/or (2) require federal licenses or permits, receive certain federal funds, are a direct action of a federal agency, or are part of outer continental shelf plans for exploration, development, and production.	The official Massachusetts coastal zone, which includes the lands and waters within an area defined by the seaward limit of the state's territorial sea, extending from the MA-NH border south to the MA-RI border, and landward to 100 feet inland of specified major roads, rail lines, other visible rights-of-way, or in the absence these, at the coordinates specified.[5]
Massachusetts Division of Fisheries and Wildlife	Massachusetts Endangered Species Act, M.G.L. Chapter 131A, §§ 1 et seq. (1990), 321 CMR 10.00	Protects rare species and their habitats by prohibiting the "take" of any plant or animal species listed as Endangered, Threatened, or Special Concern; Establishes procedures for the listing and protection of rare plants and animals; Outlines project review filing requirements for projects or activities that are located within a Priority Habitat of Rare Species; Provides clear review timelines and establishes an appeal process for agency actions.	The "take" of any plant or animal species listed as Endangered, Threatened, or Special Concern; Projects or activities that are located within a Priority Habitat of Rare Species.	Any area where an Endangered, Threatened, or Special Concern plant or animal species is located Massachusetts; Any Priority Habitat of Rare Species located in Massachusetts.

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
Massachusetts Executive Office of Energy and Environmental Affairs	Massachusetts Ocean Management Plan, under the authority of 2008 Mass. Acts 114 (Oceans Act), 301 CMR 28.00 et seq.	Oversight, coordination, and planning authority over the Commonwealth's ocean waters, resources, and development. All state agency authorizations for activities or projects in state waters must be consistent with the ocean plan.	Multi-Use Area: Uses, activities, and facilities allowed under the Ocean Sanctuaries Act, including but not limited to: community-scale wind energy facilities, wave and tidal energy facilities, offshore sand for beach nourishment, cables and pipelines, and aquaculture; Renewable Energy Areas: wind energy projects in two designated wind energy areas.	Water and submerged lands of the ocean, including the seabed and the soil, lying between a line designated as the "Nearshore Boundary of the Ocean Management Planning Area" and the seaward boundary of the Commonwealth.[6]
Massachusetts Board of Underwater Archaeological Resources	Underwater Archeology Act, M.G.L. ch. 6, §§ 179–180 and ch. 91 § 63 (amended 1996), 312 CMR 2.0-2.15	A permit from the Board of Underwater Archaeological Resources is required prior to conducting any activities that may disturb the site of a shipwreck or other underwater archeological resource.	Discovery of a shipwreck or other underwater archaeological resource.	Inland or coastal waters of the Commonwealth or the lands beneath such waters.
Massachusetts Historical Commission	Massachusetts Historical Commission, M.G.L ch. 9 §§26–27C, as amended by 1988 Mass. Acts 254, 950 CMR 70.00 -71.00	Any new construction projects or renovations to existing buildings that require funding, licenses, or permits from any state or federal governmental agencies must be reviewed by the Massachusetts Historical Commission (MHC) for impacts to historic and archaeological properties.	Any construction or renovation project that requires funding, licenses, or permits from any state or federal agency. It is the federal or state agency involvement that triggers MHC review, not listing in the National or State Registers of Historic Places. A listing in either register does not necessarily require review and likewise, lack of listing does not eliminate the need for review.	Any historical and archeological properties in Massachusetts.

4 The five designated ocean sanctuaries do not overlap with either the proposed Inner Harbor Barrier or the Outer Harbor Barrier. Nonetheless, impacts from the barrier project may affect the sanctuaries.

5 *https://www.mass.gov/service-details/massachusetts-coastal-zone-boundary*

6 The Nearshore Boundary of Ocean Management Planning Area appears to be seaward of both the proposed Inner Harbor and Outer Harbor Barrier options. As a result, this project is not included in the Ocean Management Planning Area. The Plan has been incorporated into the Massachusetts coastal zone management program, however, and therefore will guide interagency review of all relevant activities occurring in state waters.

TABLE APPENDIX F4

Review of Local Regulations Pertinent to the Construction of a Harbor Barrier

While the inner and outer barrier options would impact several different municipalities, actual construction would occur within the jurisdictions of a smaller number of municipalities, depending on the option selected. The following municipalities would be directly impacted by construction of the outer barrier as currently proposed: Revere, Winthrop, Boston, and Hull. Construction of the proposed inner barrier would directly impact Boston, Winthrop, and Revere. If berms and levees were constructed, each Conservation Commission (Revere, Winthrop, Boston, Milton, Quincy, Braintree, Weymouth, Hingham, and Hull) would review the project(s) within their jurisdictions. The primary review at the municipal level relates to protecting wetland resources. While some municipalities implement the state Wetlands Protection Act, other communities, such as Winthrop and Revere, have utilized the Home Rule Amendment of the Massachusetts Constitution to protect additional resource areas and public values. The following table describes both the state Wetlands Protection Act as well as the municipal ordinances and regulations, where those have been promulgated.

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
Municipal Conservation Commissions implement the Act (The Massachusetts Department of Environmental Protection oversees the administration of the law)	Massachusetts Wetlands Protection Act (M.G.L. Chapter 131, Section 40) and corresponding regulations (310 CMR 10.00)	Administered at the municipal level by conservation commissions, the Wetlands Protection Act requires a review of proposed work that may alter wetlands, land subject to flooding, riverfront areas, and land beneath waterbodies, waterways, salt ponds, fish runs, and the ocean. The regulations provide guidance on the types and extent of work allowed in the resource areas. Municipal conservation commissions review projects and issue Orders of Conditions that deny or approve the projects. Approval often includes special conditions that must be met to protect public interests. Written notice must be given to abutters of the project, and abutters have the opportunity to provide comments.	Activities involving removal, filling, dredging or alteration of wetlands, land subject to flooding, riverfront areas, and land beneath waterbodies, waterways, salt ponds, fish runs, and the ocean other than in the course of maintaining, repairing or replacing, but not substantially changing or enlarging, an existing and lawfully located structure or facility used in the service of the public and used to provide electric, gas, sewer, water, telephone, telegraph and other telecommunication services.	In Massachusetts, any bank, riverfront area, fresh water wetland, coastal wetland, beach, dune, flat, marsh, meadow or swamp bordering on the ocean or on any estuary, creek, river, stream, pond, or lake, or any land under said waters or any land subject to tidal action, coastal storm flowage, or flooding. In addition, any work within the 100 foot "buffer zone" of a wetland resource area.
City of Revere Conservation Commission	CH 16.04 —Wetlands Protection and City of Revere Wetlands by-law	The purpose of this chapter is to protect the wetlands of the city by controlling the activities deemed to have a significant effect upon wetland values, including but not limited to the following: public or private water supply, groundwater, flood control, erosion control, storm damage prevention, water pollution, fisheries, shellfish, wildlife, recreation and aesthetics.	Remove, fill, dredge, alter or build upon or within one hundred feet of any bank, fresh-water wetland, coastal wetland, beach, dune, flat, marsh, meadow, bog, swamp, or upon or within one hundred feet of lands bordering on the ocean or upon or within one hundred feet of any land under said waters or upon or within one hundred feet of any land subject to tidal action, coastal storm flowage, flooding or inundation, or within one hundred feet of the one-hundred-year storm line, other than in the course of maintaining, repairing or replacing, but not substantially changing or enlarging, an existing and lawfully located structure or facility used in the service of the public and used to provide electric, gas, water, telephone, telegraph and other telecommunication services.	Upon or within one hundred feet of any bank, fresh-water wetland, coastal wetland, beach, dune, flat, marsh, meadow, bog, swamp, or upon or within one hundred feet of lands bordering on the ocean or upon or within one hundred feet of any land under said waters or upon or within one hundred feet of any land subject to tidal action, coastal storm flowage, flooding or inundation, or within one hundred feet of the one-hundred-year storm line.

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
Town of Winthrop Conservation Commission	Chapter 12.40 Wetlands Protection	The purpose of this chapter is to protect the wetland, related water resources, and adjoining land areas in town by prior review and control of activities deemed by the conservation commission likely to have a significant or cumulatively adverse effect upon wetland values, including but not limited to public or private water supply, groundwater or surface water, flood control, erosion or sedimentation control, storm damage prevention, water quality, water pollution prevention, fisheries, land containing shellfish, wildlife habitat, recreation and aquaculture values.	Remove soil or vegetation, fill, dredge, build upon, discharge into, or alter coastal wetlands, freshwater wetlands, bank, beach, dune, marsh or flat bordering a water body, or land within 100 feet of these resources areas; or land under a waterbody; or land subject to flooding, tidal action, or coastal storm flowage or vernal pools within a wetland; or land within 100 feet of the marsh area of critical environmental concern.	Coastal wetlands, freshwater wetlands, bank, beach, dune, marsh or flat bordering a water body, or land within 100 feet of these resources areas; or land under a waterbody; or land subject to flooding, tidal action, or coastal storm flowage or vernal pools within a wetland; or land within 100 feet of the marsh area of critical environmental concern.
Town of Milton Conservation Commission	Wetlands Bylaws: Chapter 15 Wetlands; and Milton Conservation Commission Regulations —General wetland bylaw	The purpose of this Bylaw is to protect the wetlands of the Town of Milton by controlling activities deemed to have a significant effect upon wetland values, including but not limited to the following: public or private water supply; aquifer and groundwater protection; flood, erosion and sedimentation control; storm damage and water pollution prevention; the protection of fisheries, shellfish and wildlife; recreation and aesthetics.	Remove, fill, dredge, alter or build upon or within.	Within one hundred feet of any bank, freshwater wetland, vernal pool, coastal wetland, beach, dune, flat, marsh, meadow, bog, swamp, aquifer or upon or within one hundred feet of lands bordering on the ocean or upon or within one hundred feet of any estuary, creek, river, stream, pond or lake, or upon or within one hundred feet of any land under said waters or upon or within one hundred feet of any land subject to tidal action, coastal storm flowage, flood or inundation, or within one hundred feet of the 100-year storm line, or upon or within 200 feet of the mean annual high-water line of a perennial stream unless exempted by the Rivers Protection Act (st. 1996, c. 258). Also, a No Disturbance Zone that creates a boundary between the activity and the resource area to be protected, extends 25 feet from the edge of the resource area on or adjacent to any proposed to be altered except for vernal pools, where the zone is one hundred (100) feet. No activities within that zone can alter that zone or any land, water, animal life within the Zone.
City of Quincy Conservation Commission	Quincy Wetlands Protection Ordinance	The purpose of this chapter is to protect the wetlands, related water resources, and adjoining land areas in the city by prior review and control of activities deemed by the Quincy conservation commission likely to have a significant or cumulatively adverse effect upon wetland values; including, but not limited to, the following: Public or private water supply, groundwater, flood control, erosion and sedimentation control, storm damage prevention, water pollution, fisheries, shellfish, wildlife habitat, recreation, aesthetics (the visual quality and appearance of a project and/or quiet enjoyment of undisturbed resource areas), and aquaculture values.	Remove, fill, dredge, build upon or alter.	Any freshwater wetland including any marsh, wet meadow, bog or swamp; any saltwater wetland; any lake, river, pond, stream, drainageway, canal, estuary or the ocean; any bank, beach, dune or flat bordering on said water or wetlands; or any land subject to flooding or inundation by groundwater, surface water, tidal action or coastal storm flowage. In addition, the ordinance applies to land under said resources or land within one hundred feet of said resources.

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
Town of Braintree Conservation Commission	Wetlands Bylaw Chapter 12.20 and Wetlands Rules and Regulations	The purpose of the bylaw is to protect wetlands, water resources, groundwater quality, and adjoining areas in Braintree by regulating activities likely to have a significant or cumulative effect on public or private water supply, flood control, water quality, groundwater, storm damage prevention including coastal storm flowage, erosion and sedimentation control, water pollution control, fisheries, shellfish, wildlife habitat, rare species habitat, recreation and aesthetics.	Remove, fill, dredge, build upon, degrade, discharge into or otherwise alter.	Any freshwater wetland, coastal wetland, marsh, wet meadow, bog, swamp, bank, dune, beach, or land within 100 feet of these resources; land under a lake, pond, creek, river, stream (whether natural or manmade, intermittent or continuous), estuary, or ocean; land subject to flooding or inundation by groundwater or surface water; land subject to tidal action, coastal storm flowage or flooding; ;and which may case degradation or change to the physical characteristics of groundwater; alteration of land which requires the creation of detention or retention ponds or basins, 1000 sf in size or greater, which are required to control drainage for siltation or surface runoff; or riverfront area.
Town of Weymouth Conservation Commission	Wetlands Protection ordinance Chapter 7 Section 7-300	The purpose of this ordinance is to protect the wetlands, related water resources and adjoining land areas in the Town of Weymouth by prior review and control of activities deemed by the Conservation Commission likely to have a significant or cumulative effect upon resource area values deemed important to the community, including but not limited to the following: Public or private water supply, Groundwater, Flood control, Erosion and sedimentation control, Storm damage prevention, including coastal storm flowage, Water quality, Water pollution control, Fisheries, Shellfish, Wildlife habitat, Rare species habitat, including rare plant species, Aquaculture, Recreation, Aesthetics, Historical and archaeological preservation.	Remove, fill, dredge, build upon, degrade, discharge into or otherwise alter.	1. Any freshwater or coastal wetland, riverine wetland, marsh, wet meadow, bog, swamp or kettle hole, whether bordering on surface waters or isolated, or whether annual or seasonal; 2. Any bank, beach or dune; 3. Any ocean, bay or estuary; 4. Any reservoir, lake, pond of any size, vernal pool, river, stream or creek, whether intermittent or continuous, natural or manmade; 5. Any land under aforesaid waters; 6. Any land subject to flooding or inundation by groundwater or surface water; 7. Any land subject to tidal action, coastal storm flowage or flooding at or below the one hundred year storm line; 8. Any land within one hundred feet (100') of any of the aforesaid resource areas (the "buffer zone"); 9. Riverfront area.

Responsible Entities	Laws and Regulations	Description	Activities	Jurisdictions
Town of Hingham Conservation Commission	Hingham Wetland Regulations	The purpose of this bylaw is to protect the wetlands, related water resources and adjoining land areas of the Town of Hingham by controlling activities affecting Resource Areas. These regulations are promulgated in order to contribute to the following wetland values, including, but not limited to: (1) protection of public or private water supply; 2) protection of surface water and groundwater; 3) flood control; 4) erosion and sedimentation control; 5) storm damage prevention, including but not limited to coastal storm flowage; 6) prevention and abatement of water pollution; 7) protection of fisheries; 8) protection of shellfish; 9) protection of wildlife and wildlife habitat; 10) protection of rare species habitat, including rare plant and animal species; 11) protection of recreation and open space; and 12) protection of aesthetics.	Any activity proposed or undertaken within a Resource Area; Any activity deemed by the Commission as likely to have a significant or cumulative adverse effect upon Resource Areas; Any activity, including but not limited to, any and all of the following activities when undertaken to, upon, within or affecting Resource Areas or their wetland values: a) Removal, excavation, or dredging of soil, sand, gravel, or aggregate materials of any kind; b) Changing of preexisting drainage characteristics, flushing characteristics, salinity distribution, sedimentation patterns, flow patterns, or flood retention characteristics; c) Drainage, or other disturbance of water level or water table; d) Dumping, discharging, or filling with any material which may degrade water quality; e) Placing of fill, or removal of material; f) Driving of piles, construction or expansion or repair of buildings or structures or construction of any kind whether it be for industrial, commercial, residential, recreational or other purposes, regardless of its size; g) Placing of obstructions including, but not limited to, dams, or objects in water or the surface water or groundwater hydrology of any resource area; h) Destruction or removal of plant life, including, but not limited to, cutting or trimming of trees and shrubs; i) Changing temperature, biochemical oxygen demand, or other physical, biological, or chemical characteristics of any waters; j) Any activities, changes, or work which may cause or tend to contribute to pollution of any body of water or groundwater; and k) Incremental activities which cause, or may cause, or contribute to a cumulative adverse effect on the resource areas and interests protected by this Bylaw. Any activity proposed or undertaken outside the areas specified is not subject to regulation under the Bylaw, and does not require the filing of a Permit Application unless and until that activity actually alters a Resource Area. In the event that the Commission determines that such activity has in fact altered a Resource Area referenced in HWR 2.0(1) through (8), it shall impose such conditions on the activity or any portion thereof as it deems necessary to contribute to the protection of the wetland values.	The Bylaw and Regulations provide protection for Resource Areas and their wetland values. Resource Areas protected under the Bylaw are ANY of the following: (1) Any freshwater or coastal wetland, isolated wetland, beach, dune, flat, marsh, wet meadow, bog, swamp, vernal pool, creek, river, stream, pond, lake, estuary, or ocean; (2) Any bank bordering on a freshwater or coastal wetland or water body; (3) Land under water bodies, including but not limited to, land under the ocean, ponds, lakes, rivers, streams, creeks, any fresh water or coastal wetland, and estuaries; (4) Land bordering on the ocean, including but not limited to, beaches, dunes, tidal flats, coastal bank, salt marshes, salt meadows, and estuaries; (5) Land subject to flooding or inundation by groundwater or surface water, including but not limited to, fresh water wetlands, isolated wetlands, beaches, wet meadows, marsh, swamps, bogs, vernal pools, streams, rivers, ponds, lakes, or reservoirs; (6) Land within a minimum distance of 100 feet from any of the aforementioned Resource Areas (1-4 described above) (hereinafter referred to as the "Buffer Zone"); (7) Land subject to tidal action, coastal storm flowage, or flooding, including but not limited to, the coastal floodplain (FEMA Flood Zones AE, and VE, as shown on the Flood Insurance Rate (FIRM) maps for the Town of Hingham); or (8) Land within 200 feet of any river, stream, or creek (hereinafter referred to as the "Riverfront Area", refer to HWR 21.1 (c)) Resource Areas shall be protected whether or not they border surface water.

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