Preparing for the Rising Tide

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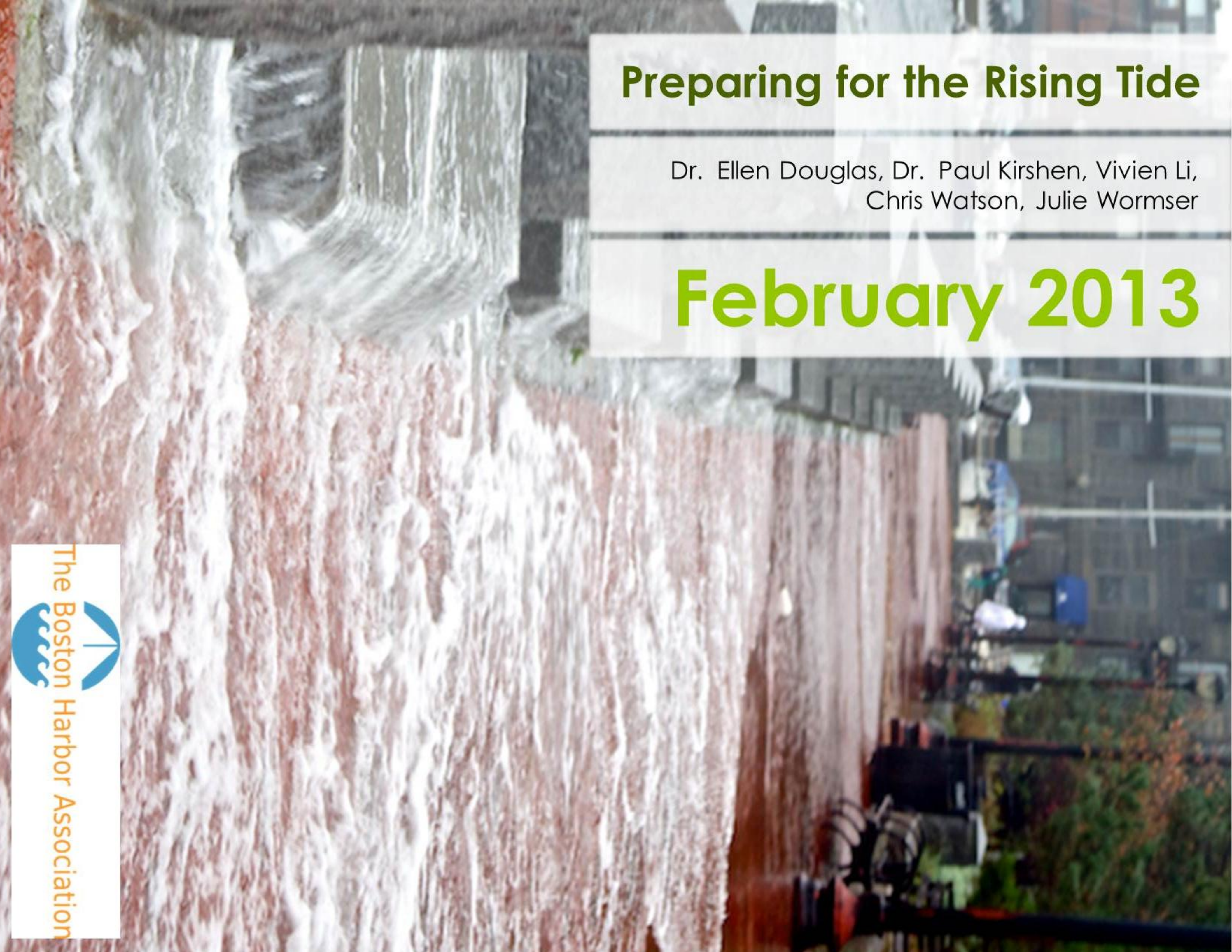

The Boston Harbor Association

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ABSTRACT: Current models predict that Boston will experience up to two feet of sea level rise by 2050 and up to six feet by 2100. Planning and preparing for this growing threat will save money and prevent disruption of people's lives and livelihoods. This report provides vulnerability analyses for Boston Harbor and time-phased preparedness plans for Boston's Long and Central Wharves and UMass Boston campus to increase their resilience to coastal flooding over time.

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Front cover: North End waterfront, Boston, October 29, 2012. Photo by Matt Conti

Glossary of Terms

100-year flood	More accurately, a flood that has a 1% likelihood of occurring or being exceeded in a given year
500-year flood	More accurately, a flood that has a 0.2% likelihood of occurring or being exceeded in a given year
Adaptation	Successful adjustment to new environmental conditions
Adaptive capacity	Ability of a system or population to adapt to a changing environment
Anthropogenic	Human-caused or produced
Co-benefit solutions	Solutions that also further other goals
Critical elevation	The lowest level at which a property potentially experiences flood damage
MHHW	Mean Higher High Water. The average level of the higher high water of each tidal day over the course of a 19-year reference period (the National Tidal Datum Epoch)
Mitigation	The effort to reduce the severity, in this case, of climate-change causing emissions such as carbon dioxide or methane
NAVD	North American Vertical Datum of 1988. A fixed vertical reference elevation. In 2012, Boston's Mean Higher High Water elevation is 4.8 feet relative to NAVD (4.8 ft. NAVD).
No-regret solutions	Solutions that provide benefits even without climate change
Resilience	The ability to recover quickly and relatively inexpensively from flooding or another stress
Resistance	The ability to prevent flooding
Storm surge	Higher-than-average sea level resulting from storm-related low air pressure and high winds
Storm tide	The water level rise during a storm due to the combination of storm surge and the astronomical tide (http://www.nhc.noaa.gov/prepare/hazards.php)
Subsidence	The gradual sinking of the earth's surface
Vulnerability	"The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes." (Intergovernmental Panel on Climate Change)

A Tale of Two Cities

On October 29, 2012, one of the largest Atlantic basin storms in recorded history hit the East Coast. Although Superstorm Sandy centered around New Jersey and New York when it made landfall, the massive storm system spanned 1,000 miles north to south, over three times the size of a typical hurricane.

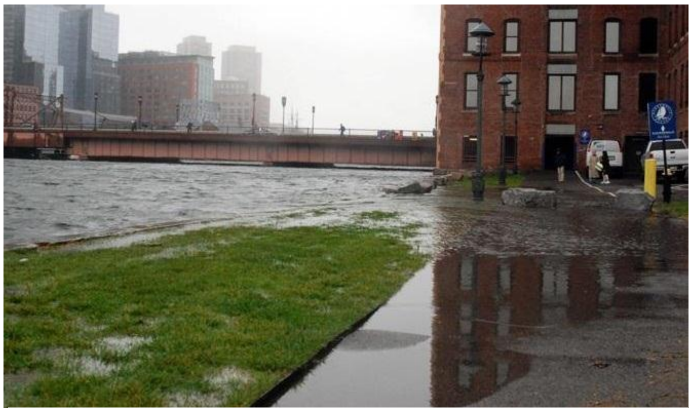

Figure 1. High tide October 29, 2012 overtops the Fort Point Channel seawall. Photo by Steve Hollinger.

This extreme storm event came one year after Tropical Storm Irene, which itself caused an estimated $15.8 billion in damage to Northeastern communities.[1] The confluence of Sandy's size, its concurrence with a full moon tide and a high pressure system to the east keeping the storm close to the coast resulted in substantial disruptions for over 60 million people.[2]

Luckily for Boston, Sandy's storm surge hit the city near low tide, causing relatively minor coastal flooding (see Figure 1). New York City fared far worse, where ocean levels nine feet above high tide flooded the streets of lower Manhattan and other boroughs (see Figure 2).[3]

Figure 2. Cars floating in seawater in New York City's Financial District. Photo by Andrew Burton, Getty Images.

The previously calculated likelihood of this level of flooding occurring in a given year was less than 0.1 percent (i.e., greater than a "1000-year storm"; see glossary).[4]

Over a million people were left without electricity, the largest power outage in the city's history. New York City's tunnels, subways, waterfront and financial district were flooded with corrosive seawater. Early estimates of Sandy's costs approached

[1] Rugaber, C, 2012
[2] Dutton, Liam, 2012
[3] For comparison, Boston's maximum storm surge from Hurricane Sandy was 4.6 ft, not 9.2 ft as it was in New York City, and the storm surge hit Boston near low tide, not at high tide.
[4] Kirshen et al., 2008

$50 billion, with $20 billion in insured property damages and $10 to $30 billion in lost productivity.[5]

Events such as Superstorm Sandy highlight the growing relevance of climate change to our everyday lives. They also draw attention to the importance of taking steps today to be prepared for the likely events of tomorrow. This report is designed to help Boston take these steps.

Figure 3. High tide October 29, 2012, downtown Boston. Photo by Jeremy Fox.

Introduction

Preparing for the Rising Tide provides policy makers, planners and property owners with site-specific examples of how to assess vulnerability and increase resilience to coastal flooding over time. Coastal flooding occurs due to extreme weather events, high tides, sea level rise, or a combination of all three. Coastal flooding is expected to increase in frequency and severity as climate change

[5] Associated Press, 2012.

increases both the average sea level and possibly the intensity of storm events over the coming decades.

Some neighborhoods in Boston are more susceptible to flooding than others. For example, portions of the downtown historic wharves and the neighborhood around Fort Point Channel already flood several times per year during extra-high full- and new-moon high tides. Other areas, notably areas of the city not filled in over the last three centuries, are on higher ground.

Our analysis found that up to 6 percent of Boston could have been flooded had Superstorm Sandy hit Boston at high tide on October 29, 2012, rather than at low tide, 5½ hours later (see Figure 8).

Add another 2.5 ft of sea level to that and our analysis predicts that it is possible that over 30 percent of Boston could be flooded (see Figure 9).

Climate change mitigation involves the cumulative impact of individual decisions on a global scale. But while carbon emissions from one source can be effectively offset by carbon mitigation elsewhere, climate change preparedness must be done at a local scale based on site-specific vulnerabilities. [6]

Conducting vulnerability assessments

One approach to conducting vulnerability assessments was outlined by ICF International (2009), briefly summarized below:

Step 1: Assess current vulnerabilities: Identify the system's current vulnerabilities to existing environmental, social and economic stressors (in this case coastal flooding and other considerations such as vulnerable populations). Use historical data and experience to identify which climate variables (e.g., sea level, precipitation) are most critical. We developed a limited collection of vulnerability indicators based on publically-available data.

Step 2: Estimate future conditions: Select target timeframes, model future climate change impacts and quantify how these impacts will affect current system stressors within a range of given uncertainties. This report uses scenarios of sea levels in 2050 and 2100 in our case studies.

Step 3: Analyze system sensitivity and resiliency to identified future impacts. A highly sensitive system means that a small change in an input (e.g., sea level) results in a large system response (e.g., failure of the power grid). System resiliency means that a system is prepared to accommodate some degree of

[6] Please note that the phrase "climate change adaptation" is being phased out in favor of "climate change preparedness" in the scientific and public policy literature. This report uses both terms interchangeably.

disruption. We looked at site specific systems vulnerable to flooding at these higher sea levels.

Vulnerability assessments focus action on highly sensitive populations, locations and infrastructure. Section 3 of this report provides a city-wide initial vulnerability assessment for Boston; Section 4 provides vulnerability assessments for specific properties for which we developed sample preparedness plans.

Preparedness planning over time and scale

Preparing for future increases in coastal flooding involves actions taken at multiple scales—from national down to individual buildings. Previous reports have described a range of large-scale adaptation strategies.[7] This report takes those recommendations and applies them to specific properties in Boston.

Building-specific preparedness actions might include initial resilient building design, sandbagging entrances, or flood proofing the basement and first floor. Neighborhoods might also or instead improve surrounding infrastructure, such as flood walls and well-drained open space. Cities could invest in large-scale infrastructure such as storm surge barriers, levee systems, or require that properties within flood zones prepare to "live with water" (see sidebar below).

Managing Risk in the Face of Uncertainty

*Managing risk for something so unpredictable, expensive and potentially destructive as coastal flooding requires effective preparedness plans that balance **robustness** (the ability to meet any future condition) and **flexibility** (the ability to change over time to meet needs as they arise).*

*To maximize private and public benefits, plans should include **"no-regret"** and **"co-benefit"** solutions that extend beyond flood control and across individual properties.*

In preparing these adaptation plans, we used estimates of the ranges of sea level rise projections for 2050 and 2100. Best available science predicts that, compared to the present water surface elevation, we can expect increases in sea level of one to two feet by 2050, and three to six feet by 2100.[8]

This means that, under the high-end scenarios, Boston will have to prepare for the following current and future scenarios over the coming century or soon after:

[7] E.g., MA EOEEA, 2011.

[8] Vermeer and Rahmstorf, 2009, Sriver, et al., 2012.

> ***Living with water***
>
> *Historically, cities seeking to prevent flooding have built walls and levees to keep water out. Repeated flooding and levee failures along the Mississippi River, however, have led to increased focus on flood "**resilience**" (recovering quickly and relatively inexpensively from flooding) over maximum "**resistance**" (keeping water out).*
>
> *Seattle, WA and Charleston, SC, for example, are developing "floodable zones" that preserve the city's access to its waterfront while minimizing damage when periodic flooding occurs. This concept of "living with water," is an option to consider for Boston as well.*

- Coastal floods presently with a 1% current likelihood of occurring in a given year (i.e., a "100-year storm surge,") could have a higher than 20% annual likelihood of occurring during coastal storms by the year 2050 and may occur as frequently as high tide sometime near or after year 2100.[9]

- Hurricane intensity appears to be linked to ocean temperature and as such, may also increase over time. It is uncertain what will happen to the intensity of extra-tropical storms or "Nor'easters" in the region.[10]

Preparedness plans involve one or more of four distinct options, depending on acceptable risk, timing and available resources:

1) No action,
2) Accommodate
3) Protect, and
4) Retreat.

Each of these involves public and private actions. Cost-effective plans will result in both "here and now" and "prepare and monitor" actions based on threshold triggers such as sea level rise. The sample preparedness plans we developed for Boston's Long and Central Wharves and the University of Massachusetts Boston (UMass Boston) are examples of such time-phased strategies.

We found that in all cases, property owners should start or continue taking feasible actions now and be prepared to undertake additional actions in the future in order for these buildings to continue to serve their present purposes in their present configurations.

Preparedness strategies presented in this report were generally proposed for 1) between now and mid-century, 2) around mid-century, and 3) between 2050 and 2100. More precise implementation will factor in observed sea level rise over time, building maintenance cycles and the vulnerability of desired property uses (e.g., hospitals versus parking garages).

[9] Kirshen et al, 2008
[10] IPCC, 2012

This report is divided into five sections.

Section 1 summarizes current scientific data on how climate change is likely to affect New England's exposure to coastal flooding.

Section 2 describes Boston's preparedness planning as of late 2012.

Section 3 provides an initial city-wide vulnerability assessment for Boston Harbor.

Section 4 presents site-specific vulnerability assessments and sample adaptation strategies for Boston's Long and Central Wharves area and the UMass Boston campus.

Section 5 offers findings and recommendations based on this research.

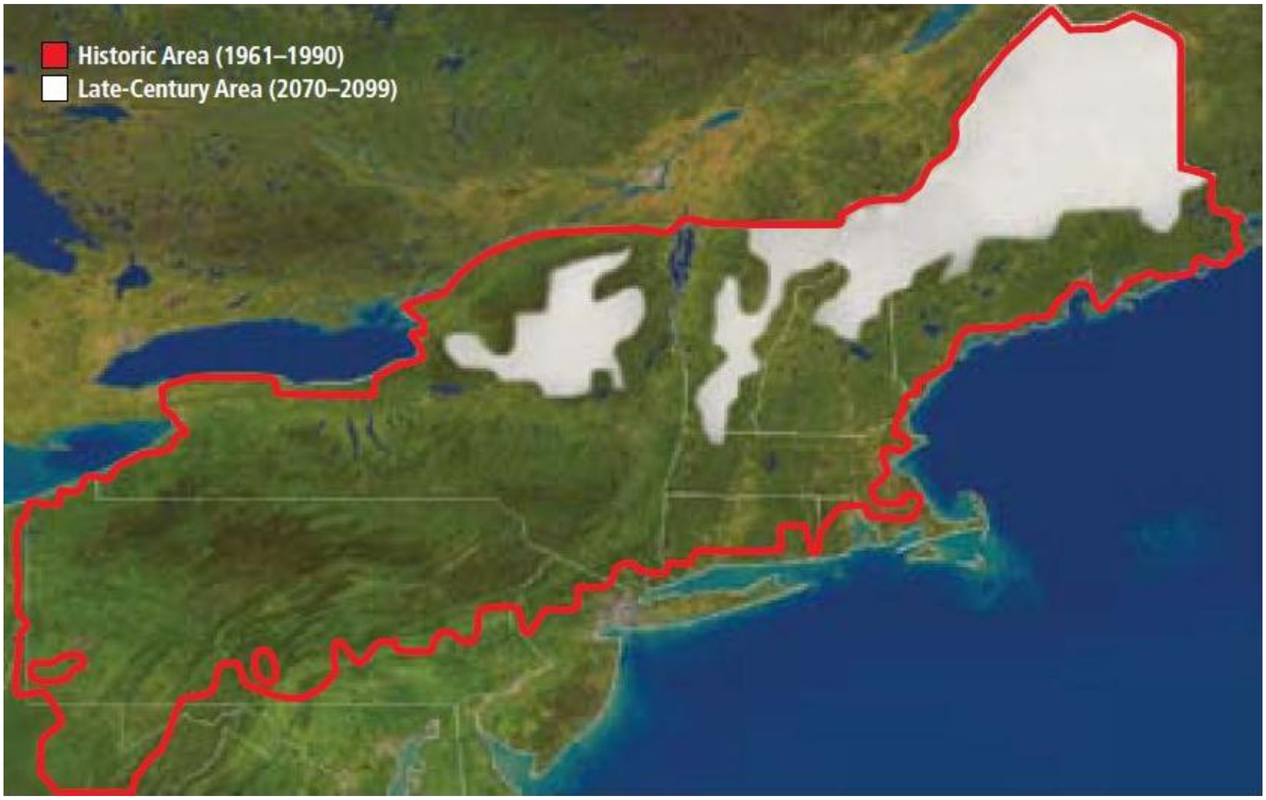

Figure 4. According to the Union of Concerned Scientists (2007), the area of the Northeast that has at least a dusting of snow on the ground for at least 30 days per year will shrink from its historic range given by the red line to higher elevations and latitudes by late century. See below for discussion.

Section 1. Climate Change in New England

The IPCC *Fourth Assessment Report* states that "most of the observed increase in globally-averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."[11] That is, the planet is warming faster than it should and the burning of fossil fuels such as coal, oil, gasoline and natural gas is mostly to blame.

Milder winters, hotter summers

As a result, temperature and precipitation patterns and storm tracks have been shifting across North America and these changes are expected to continue.[12] Here in New England, we have already seen increases in annual and seasonal temperatures,[13] decreases in snow pack and snow density,[14] and shifts in both

[11] IPCC, 2007.
[12] Hodkings et al., 2002; 2003; Collins, 2009.
[13] Hayhoe et al., 2007.
[14] Huntington et al., 2004; Hodgkins and Dudley, 2006.

lake ice-out dates and the timing and magnitude of river flood flows.[15] There is also evidence of increasing groundwater elevations over the last decade,[16] perhaps in response to observed increases in extreme precipitation events.[17]

Table 1. Changes in Massachusetts' climate

Parameter	Current Conditions (1961–1990)	Predicted Range of Change by 2050	Predicted Range of Change by 2100
Annual temperature[1] (°C/°F)	8/46	2 to 3 / 4 to 5	3 to 5/5 to 10**
Winter temperature[1] (°C/°F)	-5/23	1 to 3 / 2 to 5	2 to 5 / 4 to 10**
Summer temperature[1] (°C/°F)	20/68	2 to 3 / 4 to 5	2 to 6 / 4 to 10**
Over 90 °F (32.2 °C) temperature[2] (days/yr)	5 to 20	—	30 to 60
Over 100 °F (37.7° C) temperature[2] (days/yr)	0 to 2	—	3 to 28
Ocean pH[3,4]	7 to 8	—	-0.1 to -0.3[*]
Annual sea surface temperature (°C/°F)	12/53[5]	2/3 (in 2050)[5]	4/8
Annual precipitation[1]	103 cm/41 in.	5% to 8%	7% to 14%**
Winter precipitation[1]	21 cm/8 in.	6% to 16%	12% to 30%**
Summer precipitation[1]	28 cm/11 in.	-1% to –3%	-1% to 0%**
Streamflow—timing of spring peak flow[1] (number of calendar days following January 1)	85	-5 to -8	-11 to -13**
Droughts lasting 1–3 months[1] (#/30 yrs)	13	5 to 7	3 to 10**
Snow days (number of days/month)[1]	5	-2	-2 to –4**
Length of growing season[1] (days/year)	184	12 to 27	29 to 43

Table 1: ***Changes in Massachusetts' Climate***

Sources: 1-Hayhoe et al., 2006; 2-Frumhoff et al., 2007; 3-IPCC, 2007; 4-MWRA, unpublished; 5-Nixon et al., 2004
Note: All numbers have been rounded to the nearest whole number. Unless otherwise indicated, the predictions for the year listed as 2050 are for the period between 2035–2064. * *Global data; **Predictions for period between 2070-2099*

Table 1 was taken verbatim from the State of Massachusetts' *Climate Change Adaptation Report* and was used by the Commonwealth to summarize expected future conditions.[18] In Massachusetts (as across New England), average annual temperatures have already increased by 2 ^{0}F since the late 1800s with even higher increases in average winter temperatures.[19] Most of this warming has occurred within the last few decades.[20]

This has led to less snowfall and total area covered by snow, earlier springs and later winters, changes in river flows and a northward shift of both native species (e.g., spruce and maple trees) and exotic pests (e.g., hemlock wooly adelgid, Asian longhorn beetles; see Figure 4).

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[15] Hodkings et al., 2002; 2003; Collins, 2009.
[16] Weider and Boutt, 2010.
[17] Douglas and Fairbank, 2011; Speirre and Wake, 2010.
[18] Massachusetts EOEEA, 2011.
[19] National Climate Assessment and Development Advisory Committee, 2013.
[20] Northeast Climate Impacts Assessment, 2007.

We are also seeing an increased prevalence of disease carriers such as mosquitoes and ticks that carry Lyme disease, West Nile virus, and Eastern equine encephalitis that used to be held in check by colder winters. In short, climate change is affecting the very character of New England.

New England to see above-average sea level rise

For coastal communities, one of the most alarming impacts of accelerated warming has been an increase in sea levels and coastal flooding due to melting land-based ice and thermal expansion of the ocean. As a global average, we can expect approximately one to two feet of sea level rise by 2050 and three to six feet by 2100.[21]

The two main global factors that contribute to sea level rise are 1) warming water temperatures causing the oceans to expand, and 2) warming air temperatures causing accelerated melting of glaciers and ice sheets in Greenland and Antarctica. A third contributing factor is related to local land movement, which varies based on regional geologic processes. In some locations, land is sinking (subsiding), and in other locations the land is rising.

The combination of these three factors is called relative sea level rise (RSLR). Current rates of RSLR measured at tide gauges along the U.S. coastline range from 0.4 to 4 inches per decade.[22] Over the last century, RSLR has been approximately one foot in Boston with four inches of that due to land subsidence.

An additional factor predicted to cause New England to experience higher sea levels than the global average is related to the effect of warming waters on ocean currents such as the Gulf Stream. An ocean modeling study by Yin et al. (2009) suggested that a slowing of the Atlantic Ocean currents, including the Gulf Stream, could add six to nine inches of sea level rise along our coastline by 2100. This study was recently confirmed by Sallenger et al. (2012) who reported that the observed rate of sea level rise along the Northeast US coastline has been three to four times faster than the global average rate of sea level rise.

Increased vulnerability to coastal flooding

Climate change will increase coastal New England's vulnerability to flooding because higher sea levels will allow waves and storm surges to reach further inland than in the past. In addition, storm surge flooding may be compounded by increased rainfall and associated runoff in extreme events such as in a 20 year storm (IPCC, 2012). There also appears to be a link between hurricane

[21] Vermeer and Rahmstorf, 2009, Sriver et al., 2012
[22] NOAA, 2001.

intensity and ocean surface temperature suggesting that hurricane intensity may be increasing as well.[23]

As a result, coastal residents and business owners and their property and infrastructure are increasingly vulnerable to both intermittent (storm-related) and chronic (tidal) flooding. Planners also worry about the potential for storm events to cause massive disruption to transportation and other infrastructure—such as roads, tunnels, subways, water and sewer systems and the power grid—with consequent disruption of business activity and personal lives.

Identifying and protecting vulnerable populations.

Vulnerable populations such as the elderly, infirm, very young and low-income communities[24] may be disproportionately harmed by coastal flooding due to their reduced capacities to prepare for or recover from its damage.

East Boston is an example of a community that is the focus of environmental justice efforts. In our work with residents on the subject of climate change impacts and adaptive capacity, we found that the willingness to be involved in preparedness planning was there, but the financial resources for implementation were not.[25] Further discussion of these findings is provided in Section 3.

[23] The effect of climate change on hurricane frequency and intensity, however, is still the subject of debate.
[24] populations at disproportionately high risk from pollution and climate change, often low-income and/or people of color.
[25] Douglas et al., 2012.

Figure 5. Sandbagged New York City MTA station during Superstorm Sandy. Photo by Andrew Burton, Getty Images.

Section 2. Climate Change Preparedness in Boston

Boston, like many coastal cities, has a long history of adapting its environment, from the filling in of Mill Pond and Back Bay to the reshaping of East Boston and Spectacle Island. Responding specifically to sea level rise has been more recent. This section describes Boston's sea level rise preparedness activities just prior to Superstorm Sandy.[26]

1990s

The first step in contemporary responses to climate change occurred in the 1990s, when the Deer Island Sewage Treatment Plant was constructed two feet higher than originally designed.[27] This will allow treated water to continue to flow through the outfall pipe into Massachusetts Bay at higher sea levels. Around

[26] Such activities have accelerated in the wake of the storm.

[27] Accounts differ on whether this was done to prevent sea water from affecting the treatment process or to account for higher sea levels. Regardless, the positive co-benefit is the same.

the same time, Massport conducted an analysis of the potential for sea level rise to affect Logan Airport operations. [28]

2000s

The City of Boston's first climate actions were directed at reducing greenhouse gas emissions. In 2000, Mayor Thomas Menino enrolled Boston in the Cities for Climate Protection Campaign. In 2005, the mayor and others in the U.S. Conference of Mayors adopted the U.S. Mayors Climate Protection Agreement, committing Boston to "strive to meet or exceed Kyoto Protocol targets." As the City of Boston gained experience with energy efficiency and other climate mitigation actions, it also gave more attention to adaptation.

In 2004, the EPA-funded *Climate's Long-term Impacts on Metro Boston* (CLIMB) was published by researchers at Tufts and Boston University.[29] The Union of Concerned Scientists' published reports in 2006 and 2007 on the effects of climate change in the Northeast.[30]

Drawing on the latest data, including the work of the IPCC, these studies brought global projections of climate change down to a regional scale. They showed how increases in sea level, average temperatures, frequency of heat waves and intensity of storms could affect public health and safety, natural systems, major infrastructure, businesses, and property values in New England.

In 2007, Mayor Menino issued an executive order "Relative to Climate Action in Boston," directing municipal agencies to "prepare an integrated plan that outlines actions to reduce the risks from the likely effects of climate change and coordinates those actions with the City's plans for emergency response, homeland security, natural hazard mitigation, neighborhood planning and economic development."[31]

This was followed in 2009 by the appointment of the Climate Action Leadership Committee to prepare comprehensive recommendations on ways for the Boston community to move forward on climate change mitigation and adaptation. The Leadership Committee's 2010 adaptation recommendations can be summarized as:

- Climate adaptation is as important as climate mitigation.
- Information on the effects of climate change is sufficient to start planning now, but flexibility and openness to new information are essential.

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[28] Massport,1992.
[29] Kirshen et al., 2004.
[30] Union of Concerned Scientists, 2007.
[31] Menino, 2007.

- Climate adaptation must be thoroughly integrated into all planning and project review conducted by the City.[32]

The Leadership Committee also emphasized that climate adaptation is a responsibility of all members of the community and that special attention must be given to its most vulnerable members. In the City's 2011 climate plan update, Mayor Menino accepted the Leadership Committee's recommendations.[33]

Today

These broad policy statements set in motion multiple planning processes and other concrete actions across City agencies, including the following:

- The Boston Water and Sewer Commission is incorporating the effects of sea-level rise and more intense precipitation into its new 25-year capital plan for the storm and waste water system. The new plan is expected in 2014.

- The Boston Redevelopment Authority (BRA), which had been raising sea-level rise concerns on an *ad hoc* basis for waterfront development, approved in summer 2012 a broader preparedness questionnaire that all large projects under review will be required to complete beginning in 2013.

- The Office of Emergency Management included climate change concerns (coastal flooding, heat waves, more intense storms) in the City's natural hazards mitigation plan. This plan must be updated every five years; the next revision is due in spring 2013.

- The Boston Conservation Commission asks applicants to consider the effects of sea-level rise in their projects.

- The Parks and Recreation Department has expanded the Grow Boston Greener tree-planting program, which reduces the urban heat-island effect and stormwater run-off. Parks and Recreation will also analyze the effects of climate change on Boston's urban ecosystems in its updated Open Space Plan due in 2015.

- The Boston Transportation Department's Complete Streets Guidelines includes green infrastructure and other measures that anticipate increases in heat and precipitation.

- The Boston Public Health Commission has made climate change impacts a component of their Health-in-All approach to project and policy review.

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[32] City of Boston, 2010.
[33] City of Boston, 2011.

In addition, other municipal offices with policy or programmatic responsibilities not directly related to climate change are starting to examine the ways that increased flooding could affect their facilities and operations.[34] Important components of Boston's infrastructure such as energy and transportation lie outside the jurisdiction of Boston's municipal government, however, and must be managed in partnership with others.

Partnering with state and regional entities

Regional and state agencies are also giving increased attention to climate change issues. The Massachusetts Office of Coastal Zone Management developed the Stormsmart Coasts Program[35] to help "coastal communities address the challenges arising from storms, floods, sea level rise, and climate change, and provide a menu of tools for successful coastal floodplain management."[36]

City of Boston staff is engaged in multiple regional and national partnerships—such as the Urban Sustainability Directors Network and its regional affiliate, the New England Municipal Sustainability Network—to share lessons learned on climate change adaptation.

The City of Boston was represented on the Commonwealth's Climate Change Adaptation Advisory Committee, whose 2011 report delivered an analysis of potential climate adaptation strategies. The City is also currently engaged in the advisory committee for the Metropolitan Area Planning Council's development of a regional adaptation strategy and works closely with many local universities and non-profits that have already produced useful research and proposals regarding adaptation.

Partnering with the Private and Nonprofit Sectors

While City government has understandably taken the lead in Boston's climate preparedness efforts, Boston's private and non-profit sectors have also taken important steps. The Boston community has, on the whole, strongly supported the green building movement, formalized in the Boston zoning code's reference to the U.S. Green Building Council's LEED (Leadership in Energy and Environmental Design) standards, which incorporate a variety of preparedness measures.

The Mayor's Climate Action Leadership Committee, which included a major focus on adaptation, was comprised of representatives of all sectors of the Boston community. These representatives are now engaged in the Green

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[34] Personal communication with City of Boston staff, November 2012.
[35] http://www.mass.gov/czm/stormsmart/
[36] Ibid.

Ribbon Commission, set up to help support the implementation of Boston's Climate Action Plan.

Business leaders have additionally engaged in a variety of public events to examine adaptation issues, including those sponsored by The Boston Harbor Association (TBHA), the Urban Land Institute, and Ceres. Individual projects such as the new Spaulding Rehabilitation Hospital in Charlestown have set examples of how to incorporate adaptation "from the ground up."

Finally, Boston residents have shown an increasing desire to address climate change. Public workshops led by the City, non-profits and researchers have had strong attendance. Superstorm Sandy has substantially raised awareness and political discourse about the risks of flooding to Northeastern coastal cities.

Next Steps

Although Boston is recognized as one of the country's more climate-aware cities, there is more work to be done to prepare this historic city for current and future risks of coastal flooding. For example, many of the existing and proposed policies address new projects and construction of large public systems. These policies need to be integrated with each other and expanded to include existing buildings and infrastructure.[37]

City planners, property owners and local residents generally know which neighborhoods in Boston are prone to flooding. This general knowledge needs to be taken a step further to prioritize specific actions over time based on:

- Identifying the elevations at which flood-prone buildings and infrastructure are at risk,
- Identifying property-specific vulnerabilities to flooding,
- Developing cost-effective measures to increase vulnerable properties' resilience, and
- Pursuing an integrated strategy to maximize the resilience of Boston's most sensitive populations, neighborhoods and infrastructure.

Increasing Boston's resilience to coastal flooding will take a strong public-private partnership that optimizes the resources and expertise of all sectors.

[37] Personal communication with City of Boston staff, November 2012.

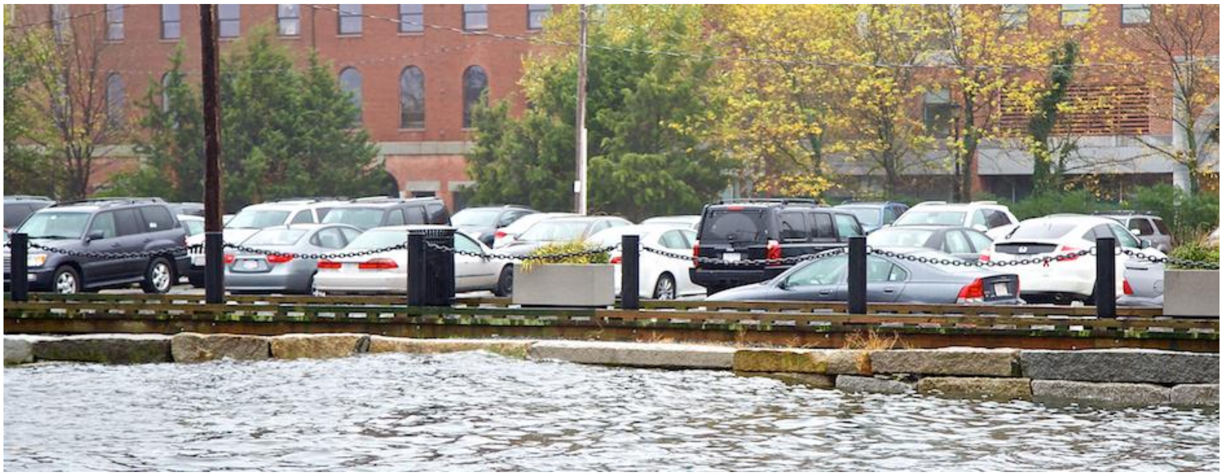

Figure 6. High sea levels in Boston's North End during Superstorm Sandy. Photo by Matt Conti.

Section 3. Assessing Boston's Vulnerability to Coastal Flooding

We examined Boston's vulnerability to coastal flooding at two sea levels: five feet above current average high tide (MHHW+5, equivalent to 9.8 ft NAVD) and 7.5 feet above current average high tide (MHHW+7.5, equivalent to 12.3 ft NAVD).[38] We identified and mapped Boston's total footprint (in millions of square ft) and ten largest properties that would experience flooding at these two flood levels, and analyzed these results by land use, neighborhood, historical district and presence of known hazardous waste sites.[39]

Methods

Appendix 3 includes a fuller discussion of methods used in our analysis. Flood impacts were limited to an analysis of "flooded" or "not flooded" for each parcel, based on the 2009 digital elevation model (DEM) developed by the BRA. Properties were considered to be "flooded" only if the geographic center of the building(s) on the parcel was flooded.

We used the City of Boston Assessing Department database of city-wide property parcel data to identify, map and analyze the total footprint (in millions of square ft) of properties within Boston city limits vulnerable to coastal flooding for the following three scenarios:[40]

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[38] See Appendix A for additional discussion of the reference elevations used in this report.

[39] The impact of coastal flooding on the City of Boston could additionally be quantified in a variety of ways such as property damage, displaced residents, lost productivity, and/or impact on public health. This analysis is by no means comprehensive.

[40] Unfortunately, it would have taken not-insignificant additional resources to modify these data to directly calculate total economic value of affected properties. This is primarily due to the methods with which the assessor maintains information related to condominiums; using the

Scenario 1: Mean Higher High Water + 2.5 ft (MHHW+2.5 or 7.3 ft NAVD). See Figure 7. A vulnerability analysis was not performed for this scenario as it is currently limited to minor flooding of streets, buildings and infrastructure near the waterfront. This scenario approximates the flooding that occurred at the mid-day high tide on October 29, 2012 (i.e., 5½ hours before Superstorm Sandy's maximum storm surge hit).

Scenario 2: Mean Higher High Water + 5 ft (MHHW+5 or 9.8 ft NAVD). See Figure 8. This approximates the current 100-year coastal storm surge at high tide, or the flooding that could have happened had Superstorm Sandy's maximum storm surge hit at the mid-day high tide on October 29, 2012, instead of near low tide. It also approximates the projected high tide mark sometime around 2100 if sea level were to rise by 5 feet by that time.

Scenario 3: Mean Higher High Water + 7.5 ft (MHHW+7.5 or 12.3 ft NAVD). See Figure 9. This approximates the 100-year coastal storm surge at high tide when sea levels are 2.5 ft higher. According to current projections, this sea level could happen as soon as just after 2050. As can be seen on Figure 9, there is considerably more and deeper flooding due to the overtopping the Charles River Dam and associated flooding around it.[41]

These maps probably underestimate the extent of flooding from higher sea levels because they do not include wave heights and other effects.

Also not included in the analysis is the likelihood of subsurface structures (e.g., subway tunnels and utility conduits) flooding. Finally, with most storm drain outlets at or only slightly above the level of current high tides, rising sea levels and storm surges could block flows from these outlets, causing storm water to back up into streets and buildings and further exacerbate expected flooding.

For each of these three coastal flooding scenarios, we calculated the square footage of land affected by flooding, considering only parcel size. We then categorized the amount of flooded area by land use—commercial, industrial, residential,[42] mixed use[43] and tax exempt[44]--and by historic district and

existing dataset for these purposes would potentially have led to substantial multiple-counting of appraised values.

[41] Depending on the cause (e.g., chronic sea level versus temporary storm event) and duration of the flooding. Pumps currently installed at the Charles River Dam may be able to lessen its upstream impacts.

[42] For the purposes of this study, we considered only the parcel size of the condominium as a whole, and assigned land use to each master condominium parcel based on the uses of its constituent units. Master condominiums parcels for which there was a combination of land uses for its constituent units were assigned to the Mixed Use category

[43] Residential and commercial

[44] I.e., tax exempt—non-profit and public facilities

neighborhood. We also used this analysis to identify the ten largest properties affected by coastal flooding in each scenario.

Results

Tables 2 through 4 rank the total area flooded at MHHW+5 and MHHW+7.5 (i.e., 9.8 ft NAVD and 12.3 ft NAVD) by land use, neighborhood and historic district.

Table 2. Area of Boston flooded at MHHW+5 ft and MHHW+7.5 ft, by land use

Land Use Category	All Boston		Flooded at MHHW+5 ft			Flooded at MHHW+7.5 ft		
	Total Area (in million sq. ft.)	% Total Area By Category	Flooded Area (in million sq. ft.)	% of City Area	% of Category Area	Flooded Area (in million sq. ft.)	% of City Area	% of Category Area
Exempt[45]	646.4	51.9%	62.4	5.0%	9.7%	273.2	21.9%	42.3%
Residential	385.6	31.0%	2.17	0.02%	0.6%	26.1	2.1%	6.8%
Commercial	101.4	8.1%	8.57	0.7%	8.5%	41.0	3.3%	40.4%
Vacant Land[46]	64.1	5.1%	6.25	0.5%	9.7%	16.4	1.3%	25.6%
Mixed Use	28.6	2.3%	0.84	0.07%	3.0%	10.0	0.8%	35.0%
Industrial	18.9	1.5%	2.49	0.2%	13.2%	7.6	0.6%	40.4%
Totals								
Flooded	0	0%	82.8	6.6%		374.4	30.1%	
Not flooded	1,244.9	100%	1,162.2	93.4%		870.6	69.9%	
Citywide	1.244.9	100%	1,244.9	100%		1,244.9	100%	

45 Eighty percent of tax exempt lands in Boston are owned by the state and city, four percent are owned by hospitals and universities, and 16 percent are owned by other tax-exempt landowners (Boston Redevelopment Authority, 2011).
46 Includes not only agricultural and park areas but also any other properties without buildings (e.g., highway overpasses).

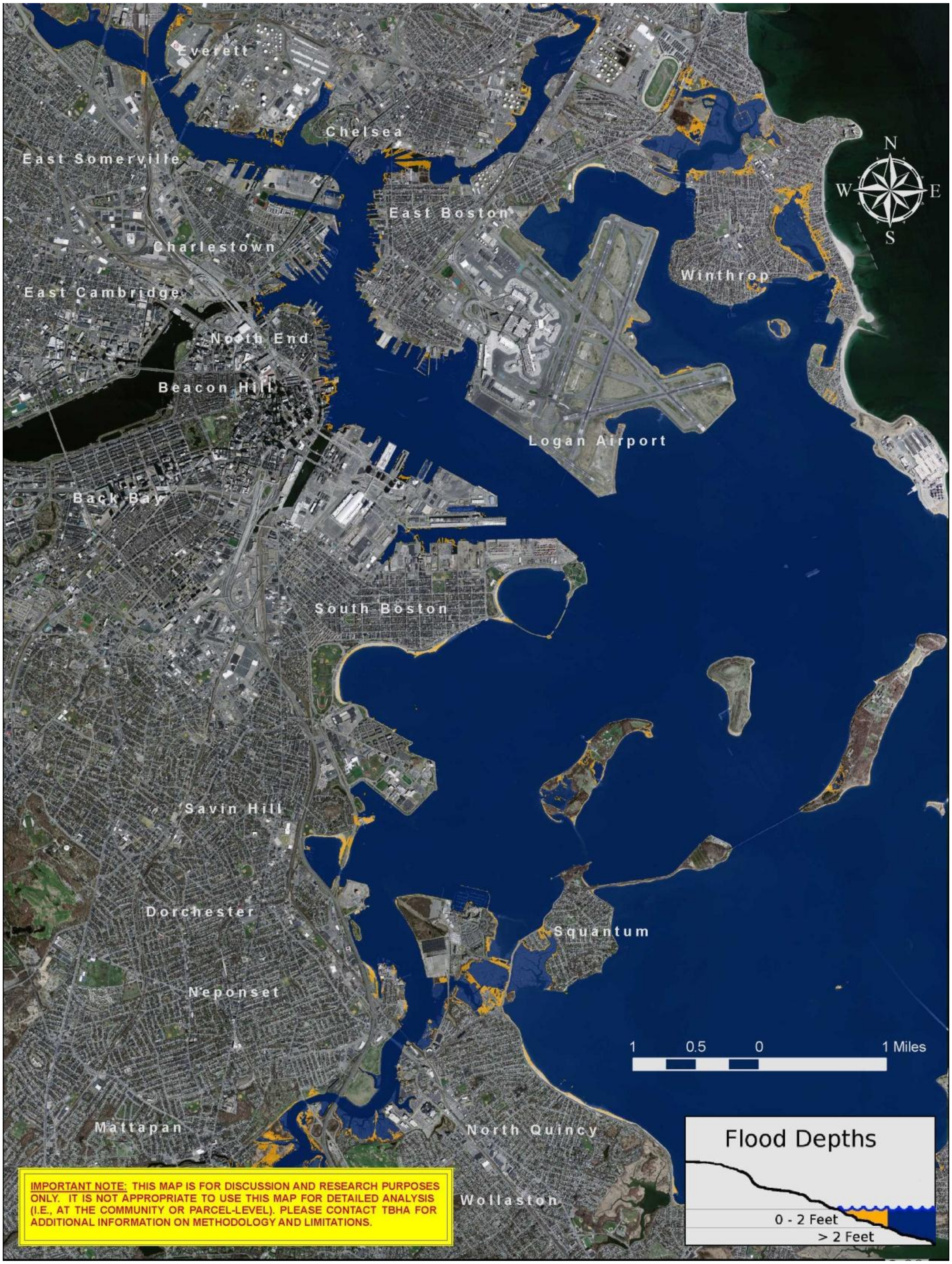

Figure 7. Estimated flooding in Boston at MHHW+2.5/7.3 ft NAVD (TBHA, 2010).

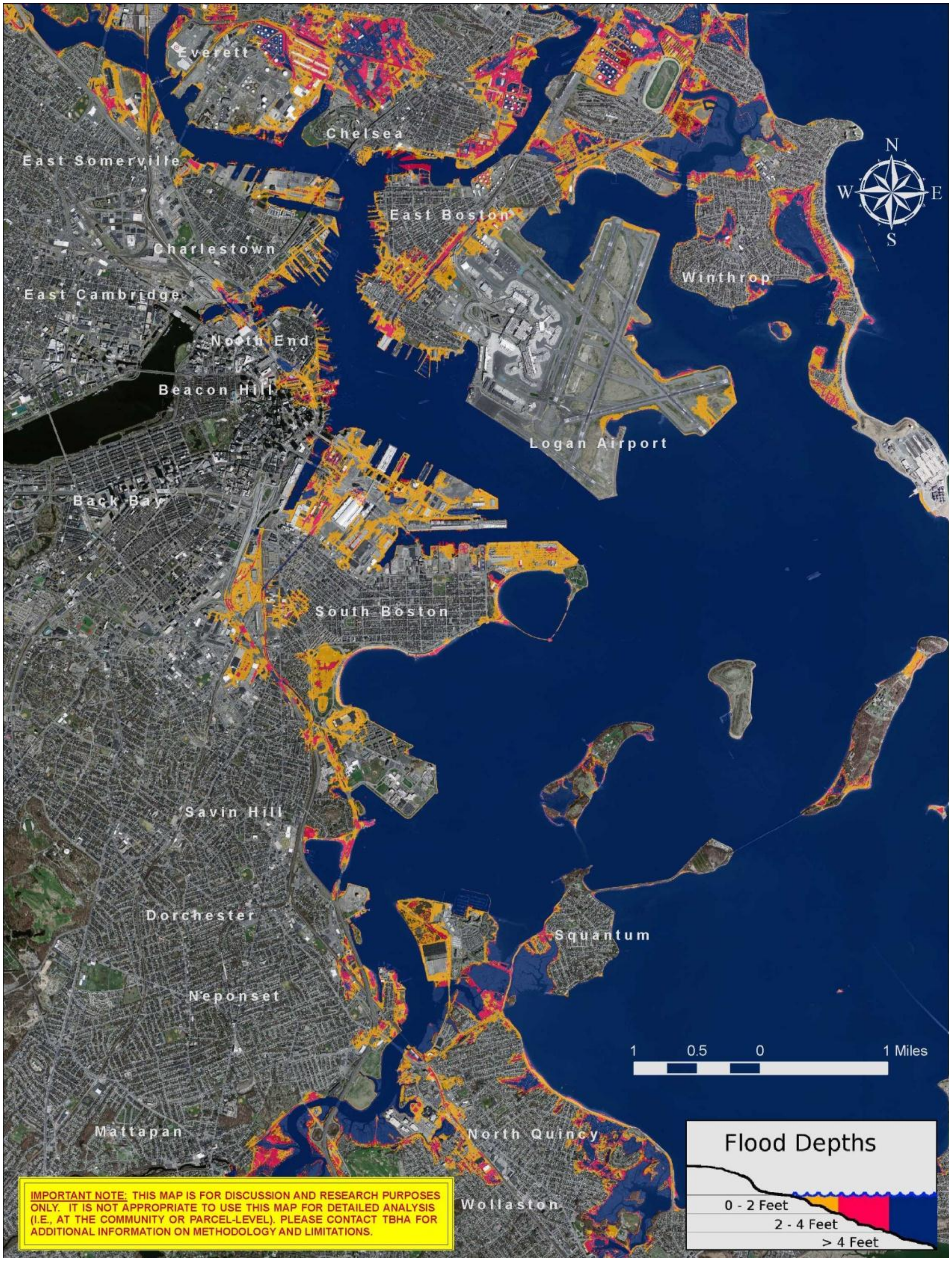

Figure 8. Expected flooding in Boston at a sea level of MHHW+5/9.8 ft NAVD (TBHA, 2010).

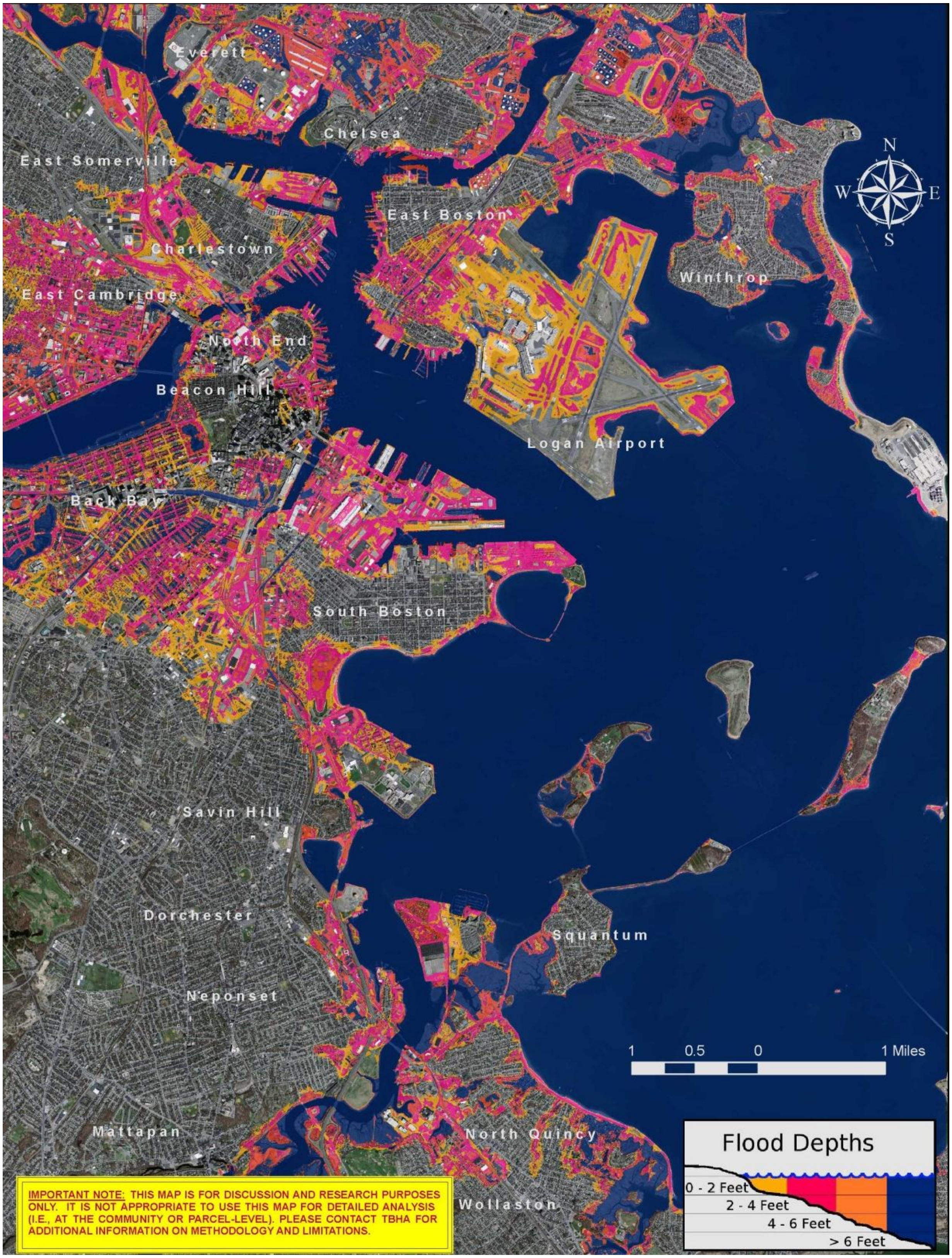

Figure 9. Plausible flooding in Boston at a sea level of MHHW+7.5/12.3 ft NAVD (TBHA, 2010).

Land Use

Overall, 6.6 percent of Boston could be flooded at a sea level of MHHW+5 (9.8 ft NAVD). At a sea level of MHHW+7.5 (12.3 ft NAVD), the Charles River Dam and other land surfaces would be overtopped, causing floodwaters to enter the surrounding area and flood large portions of Boston and Cambridge upstream of the dam. Our analysis predicts that just over 30 percent of Boston could be flooded at MHHW+7.5 (12.3 ft NAVD).[47]

Some land use categories are affected more than others. In both cases, the majority of the parcels most vulnerable to coastal flooding are exempt parcels, or parcels owned by public agencies and non-profits, though some properties include many commercial and residential tenants. The next most affected land use type at MHHW+5 (9.8 ft NAVD) is commercial, followed by "vacant land" (i.e., properties lacking buildings). At MHHW+7.5 (12.3 ft NAVD), 35 to 42 percent of all exempt, industrial, commercial, and mixed use parcels and 26 percent of vacant land would be flooded.

Commercial and industrial facilities comprise less than 10 percent of Boston's total land area. They warrant special attention, however, because flooding may lead to hazardous contamination of surrounding areas as well as affect residents' livelihoods and commercial activities.

Neighborhoods

All of Boston's coastal neighborhoods plus the Harbor Islands (shown below in bold and underline) are flooded to various extents at MHHW+5 (9.8 ft NAVD). Flooding spreads to 14 additional neighborhoods (shown below in bold) at MHHW+7.5 (12.3 ft NAVD).

The neighborhood most affected by flooding at MHHW+7.5 (12.3 ft NAVD) is East Boston, with over 140 million square feet of land submerged. Twelve neighborhoods would be more than 50 percent flooded at MHHW+7.5 (12.3 ft NAVD). Only five neighborhoods would not be flooded at either flooding scenario: Hyde Park, Jamaica Plain, Mattapan, Roslindale, and West Roxbury.

[47] This analysis relies on data accurate only to +/- 1 foot. Property owners should use site-specific information to more precisely assess their actual vulnerability to flooding.

Table 3. Area of Boston flooded at MHHW+5 ft and MHHW+7.5 ft, by neighborhood

Neighborhood	All Boston		Flooded at MHHW+5 ft			Flooded at MHHW+7.5 ft		
	Total Area (million sq. ft.)	% Total Area by Neighbor-hood	Flooded Area (million sq. ft.)	% of City Area	% of Neighbor-hood Area	Flooded Area (million sq. ft.)	% of City Area	% of Neighbor-hood Area
Dorchester	180.8	14.5%	22.6	1.8%	12.5%	39.9	3.2%	22.1%
East Boston	171.8	13.8%	24.3	2.0%	14.1%	141.8	11.4%	82.6%
West Roxbury	124.6	10.0%						
Hyde Park	14.0	9.2%						
Jamaica Plain	90.0	7.2%						
Roxbury	75.4	6.1%				7.8	0.6%	10.3%
Brighton	65.2	5.2%				3.5	0.3%	5.4%
South Boston	60.9	4.9%	10.4	0.8%	17.1%	37.9	3.0%	62.3%
Roslindale	59.6	4.8%						
Mattapan	48.7	3.9%						
Allston	38.6	3.1%				15.2	1.2%	39.5%
Harbor Islands	34.9	2.8%	6.9	0.6%	19.8%	6.9	0.6%	19.8%
Charlestown	34.4	2.8%	5.3	0.4%	15.4%	19.9	1.6%	57.9%
South Boston Waterfront	33.1	2.7%	10.2	0.8%	30.7%	30.5	2.5%	92.2%
Downtown	22.1	1.8%	2.2	0.2%	9.9%	11.6	0.9%	52.8%
Fenway	19.9	1.6%				17.5	1.4%	88.3%
South End	15.8	1.3%				14.8	1.2%	93.8%
Back Bay	13.8	1.1%				12.0	1.0%	87.2%
Mission Hill	12.3	1.0%				0.6	0.1%	5.1%
Beacon Hill	7.3	0.6%				3.1	0.2%	41.7%
Longwood Medical Area	7.1	0.6%				2.7	0.2%	37.6%
North End	5.4	0.4%	0.8	0.1%	15.6%	3.1	0.3%	58.1%
West End	4.0	0.3%				1.7	0.1%	42.1%
Chinatown	3.8	0.3%				2.6	0.2%	67.2%
Bay Village	0.8	0.1%				0.6	0.0%	73.2%
Leather District	0.5	0.04%				0.5	0.0%	93.2%
Totals								
Flooded	0	0%	82.8	6.6%		374.4	30.1%	
Not flooded	1,244.9	100%	1,162.2	93.4%		870.6	69.9%	
Citywide	1,244.9	100%	1,244.9	100%		1,244.9	100%	

Table 4. Area of Boston flooded at MHHW+5 ft and MHHW+7.5 ft, by historic district

Historic District	All Boston		Flooded at MHHW+5 ft			Flooded at MHHW+7.5 ft		
	Total Area (million sq. ft.)	% Total Area By District	Flooded Area (million sq. ft.)	% of City Area	% of District Area	Flooded Area (million sq. ft.)	% of City Area	% of District Area
South End	16.6					15.7	1.3%	94.9%
Back Bay	5.6	1.3%				5.2	0.4%	92.4%
Beacon Hill	3.1	0.4%				0.8	0.1%	26.2%
Fort Point	1.6	0.2%	1.2	0.09%	70.8%	1.5	0.1%	92.1%
Bay State Road - Back Bay West	1.5	0.1%				0.9	0.1%	63.8%
Saint Botolph Street Area	0.9	0.1%				0.8	0.1%	82.5%
Bay Village	0.4	0.03%				0.3	0.02%	78.4%
Blackstone Block (undesignated)	0.1	0.01%	0.06	0.005%	65.5%	0.1	0.01%	90.1%
Historic districts not flooded	5.4	0.4%	33.9	2.7%		9.8	0.8%	
Rest of Boston								
Flooded	0	0%	81.5	6.6%		349.1	28.0%	
Not flooded	1,209.8	97.2%	1,128.2	90.6%		860.7	69.1%	
Totals								
Flooded	0	0%	8.28	6.6%		374.4	30.1%	
Not flooded	1,244.9	100%	1,162.2	93.4%		870.6	69.9%	
Citywide	1,244.9	100%	1,244.9	100%		1,244.9	100%	

Historic Districts

We examined historic districts both because they represent areas of irreplaceable cultural value to the city and because we hypothesized that the age of their buildings may make them more difficult to floodproof.

More than 65 percent of the Fort Point historic district and the proposed Blackstone Block district would be flooded at MHHW+5 (9.8 ft NAVD). Historic districts that experience more than 75% flooding at MHHW+7.5 (12.3 ft NAVD) include the South End, Back Bay, Fort Point, St. Botolph Street Area, Bay Village, and the Blackstone Block. Also flooded at MHHW+7.5 (12.3 ft NAVD) are the Bay State Road – Back Bay West district (64%) and a limited amount of Beacon Hill (26%).

Tables 5 and 6 list the ten largest developed properties at risk of flooding at MHHW+5 (9.8 ft NAVD) and MHHW+7.5 (12.3 ft NAVD).[48] Please note that some parcels located near the water's edge include large areas of open water because of Massachusetts' law governing "Commonwealth tidelands." We omitted parcels that appeared on aerial photographs to be entirely open water, roadways, beaches, parks and greenways.

Table 5. Ownership of ten largest properties flooded at MHHW+5 (9.8 ft NAVD)

Land Use Category	Total Area (in million sq. ft.)	Site Name	Owner	Address
Industrial	1.0	Boston Generating Station	Exelon New Boston LLC	776-834 Summer Street
Exempt	1.0	Charlestown Navy Yard	US Government	93 Chelsea Street
Exempt	0.8	Bayside Expo Center	UMass Boston	160-234 Mt Vernon Street
Industrial	0.7	World Shaving Headquarters	P&G/Gillette	20 Gillette Park
Exempt	0.7	Charlestown Navy Yard	Boston Redevelopment Authority	Eighth Street
Land	0.6	Boston Marine Works	Boston Marine Works	218-260 Marginal Street
Commercial	0.6	commercial building	Bulgroup Colorado LLC	144 Addison Street
Exempt	0.6	Boston Fish Pier	Massport	212 Northern Avenue
Commercial	0.5	South Bay Shopping Area	E&A Northeast LP	1-8 Allstate Road
Commercial	0.5	Savin Hill Yacht Club	Savin Hill Yacht Club Inc.	400 Morrissey Boulevard

Known hazardous waste facilities and remediation sites that would be flooded at each of these sea levels have the potential to release hazardous materials that could impact other adjacent and distant properties, based on the type of

[48] These parcels were identified using USGS topographic maps, 2012 USDA aerial photographs, Google Maps and Google Street View.

material and flood intensity. Our analysis found that twenty-two sites would flood at MHHW+5 (9.8 ft NAVD) and 87 sites would flood at MHHW+7.5 (12.3 ft NAVD). Detailed analysis of the impacts from these facilities is beyond the scope of this study.

Table 6. Ownership of ten largest parcels flooded at MHHW+7.5 (12.3 ft NAVD)

Land Use Category	Total Area (in million sq. ft.)	Site Name	Owner	Address
Exempt	101.6	Logan Airport	Massport	Maverick Street
Exempt	7.2	Marine Industrial Park	Economic Development and Industrial Corporation	600 Summer Street
Exempt	4.5	Conley Terminal	Massport	20 Farragut Road
Exempt	2.7	Harvard Stadium	Harvard University	69-79 N. Harvard Street
Residential	1.9	Harbor Point Apartments	Harbor Point Apts. Co Lessee	400-260 Mt Vernon Street
Exempt	1.6	Black Falcon Cruise Terminal	Massport	666R Summer Street
Exempt	1.3	Curley Community Center	City of Boston	William J Day Boulevard
Exempt	1.3	Boston Autoport	Massport	Terminal Street
Exempt	1.2	MBTA Maintenance Facility – Orient Point	MBTA	1023-1081A Bennington Street
Exempt	1.1	Boston Convention and Exhibition Center	Mass. Convention Center Authority	Summer Street

Assessing socioeconomic vulnerabilities

Qualitative assessments such as surveys, focus groups and other forms of community outreach augment more quantitative assessments with cultural knowledge and local priorities to help secure support for and engagement in effective preparedness strategies.[49]

Since 2008, the National Oceanic and Atmospheric Administration (NOAA) has funded the research team of Douglas, Kirshen and Watson and others to work with East Boston residents on climate change vulnerability and preparedness capacity related to future sea level rise.

East Boston is essentially a peninsula bordered by tidal portions of Chelsea Creek, the Mystic River and Boston Harbor. Large portions of the neighborhood were created by filling in the area among several islands during the 19th century. Logan International Airport comprises the entire southeastern half of East Boston.

Originally a center of shipbuilding, East Boston is now predominantly a residential area with some industrial and commercial activities, particularly along the coastal fringe. Buildings are a mixture of old and new. Since 1840, East Boston has been a gateway for working class immigrants, "by turns, largely Irish, Jewish, and Italian… [and now] a growing Latino population."[50]

Our research team has been working with lower-income, Spanish-speaking Latino residents, city officials and community organizations to gain a better understanding of current vulnerabilities within the residential areas of the community. We held three community workshops to identify their adaptation incentives and obstacles and are currently involved in a follow up study to capitalize on incentives and address obstacles to preparedness planning. [51]

Existing housing concerns include frequent electrical fires, a shortage of subsidized housing and aging infrastructure. Residents also described flooding caused by outdated and poorly maintained drainage systems.[52] Residents believed they had little power over the management of their community. They were generally renters with very limited economic, political or social resources.

All flood preparedness options included disincentives for residents such as high financial costs and loss of access to the harbor. Participants preferred options that enhance their present environment and that do not require temporary or permanent evacuation. Their least-favored option was to permanently leave

[49] Kirshen et al., 2012; Douglas et al., 2012.
[50] BRA, 2003.
[51] Participants were solicited by the Neighborhood of Affordable Housing , a non-profit multi-service community development corporation headquartered in East Boston. These workshops complemented a community workshop our team led in 2010 as part of TBHA's Barr-funded Boston Harbor Sea-Level Rise Forum.
[52] Participants from the City of Boston expressed a commitment to improving drainage infrastructure where possible, while also wanting to better understand East Boston's chronic and acute vulnerabilities to climate change-related flooding.

the area. Residents were committed to their communities, both out of choice and a lack of other options, while recognizing that waterfront living presented special risks.

The many reports on climate change have not reached this community.[53] Participants believe they need more information on climate change, how it will impact them, and what resources are available to assist them. After these community members became educated and engaged in the issue, they wanted to become a part of the decision making process. While residents were eager to be involved in adaptation planning, financial resources to plan and implement adaptation measures have not yet been identified.

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[53] For example, IPCC 2007; USCCSP 2009; NRC 2010.

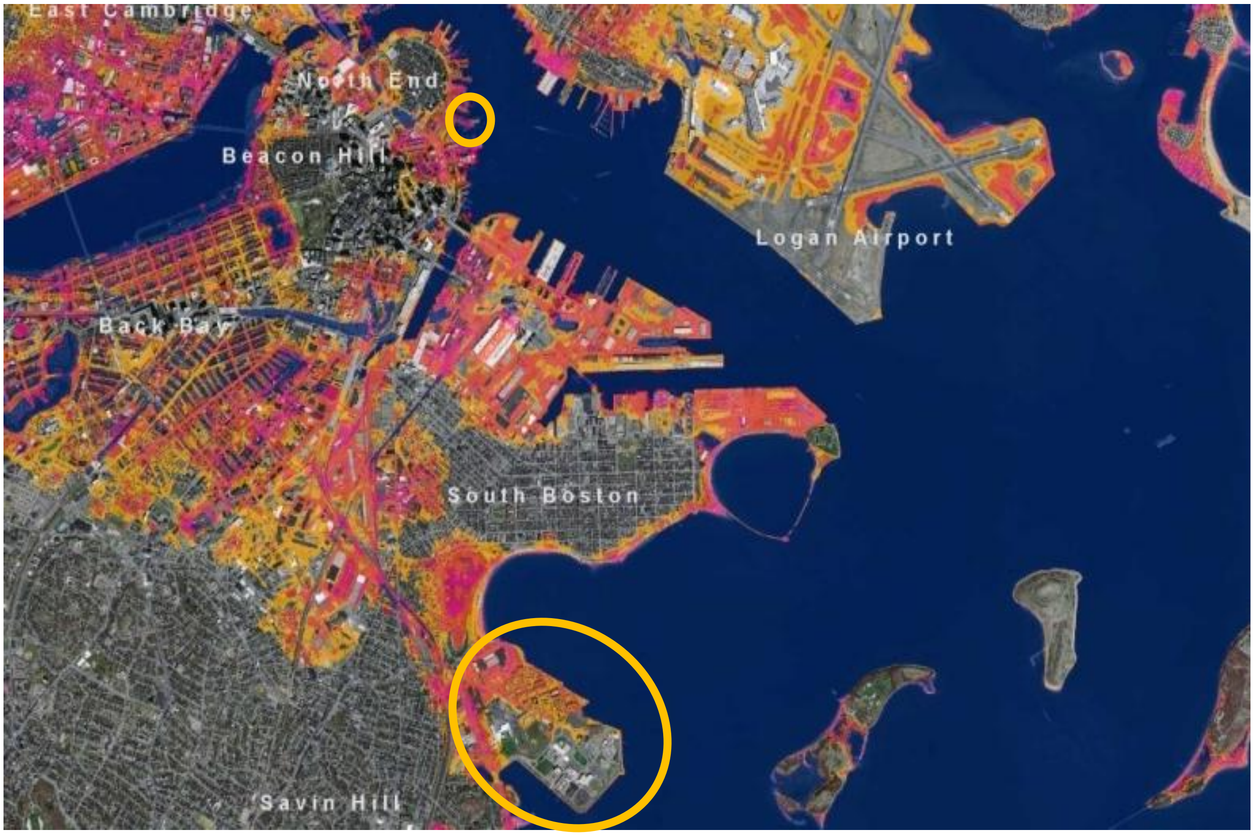


Figure 12. Location of case studies: Downtown historic wharves and UMass Boston

Section 4. Case Studies

This section provides the results of vulnerability analyses and sample preparedness plans for two sites in Boston: Long and Central Wharves, located in downtown Boston, and UMass Boston, located on Columbia Point in Dorchester.[54]

The preparedness plans we developed are designed to be implemented over time as sea level increases. Such phased plans are linked to sea level elevation thresholds and future ranges of time to manage future uncertainty. This makes on-going monitoring of sea level elevation essential. Also critical to successful implementation of such plans are periodic emergency preparedness drills to ensure that equipment and personnel are ready at short notice to deal with flooding from extreme storm events.

[54] We are in the process of completing a third case study involving East Boston residences described in Section 3.

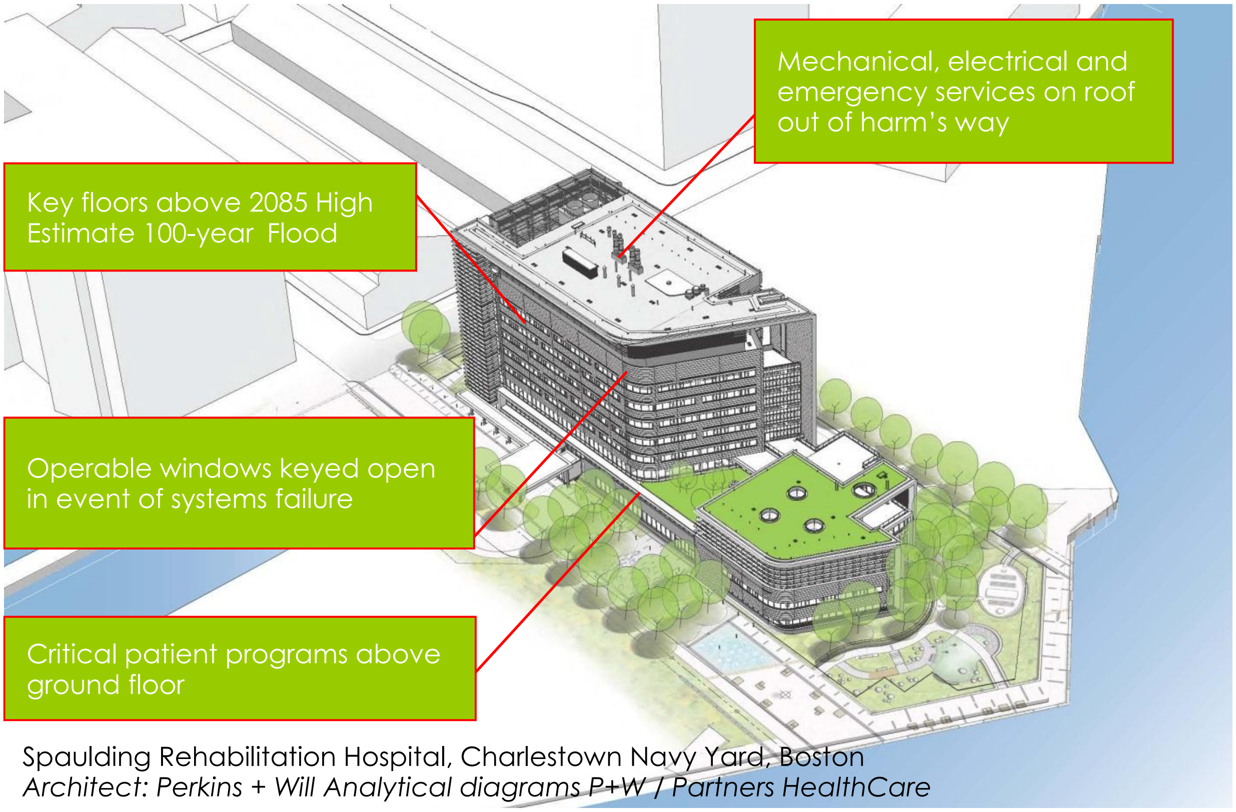


Figure 10. Flood preparedness design features included in the new Spaulding Rehab Hospital.

Preparedness actions were generally proposed for 1) up to 2050, 2) around 2050, and 3) up to 2100. Plan implementation will be based on observed sea level rise over time and building maintenance cycles and uses. Economies of scale would support some sets of actions being taken as a neighborhood. Once buildings start becoming more regularly flooded by high tides, more significant actions will need to be employed.

The newly-constructed Spaulding Rehabilitation Hospital (see Figure 10) in Charlestown is a local example of flood-preparedness design which incorporates a number of these strategies. Appendix 2 provides additional examples of a range of possible preparedness tools relevant to other cities (New York City and San Francisco).

Long and Central Wharves, Downtown Boston

This case study focused on four buildings on Long and Central Wharves expected to flood at MHHW+5 (9.8 ft NAVD; see Figure 11).[55] This area is slightly larger than the current FEMA 100-year floodplain (see Figure 12) due to differences in how the areas were calculated.

[55] Kirshen et al., 2008. Again, this is similar to the current "100-year" flood zone, or the area with a current one percent likelihood of flooding in a given year.

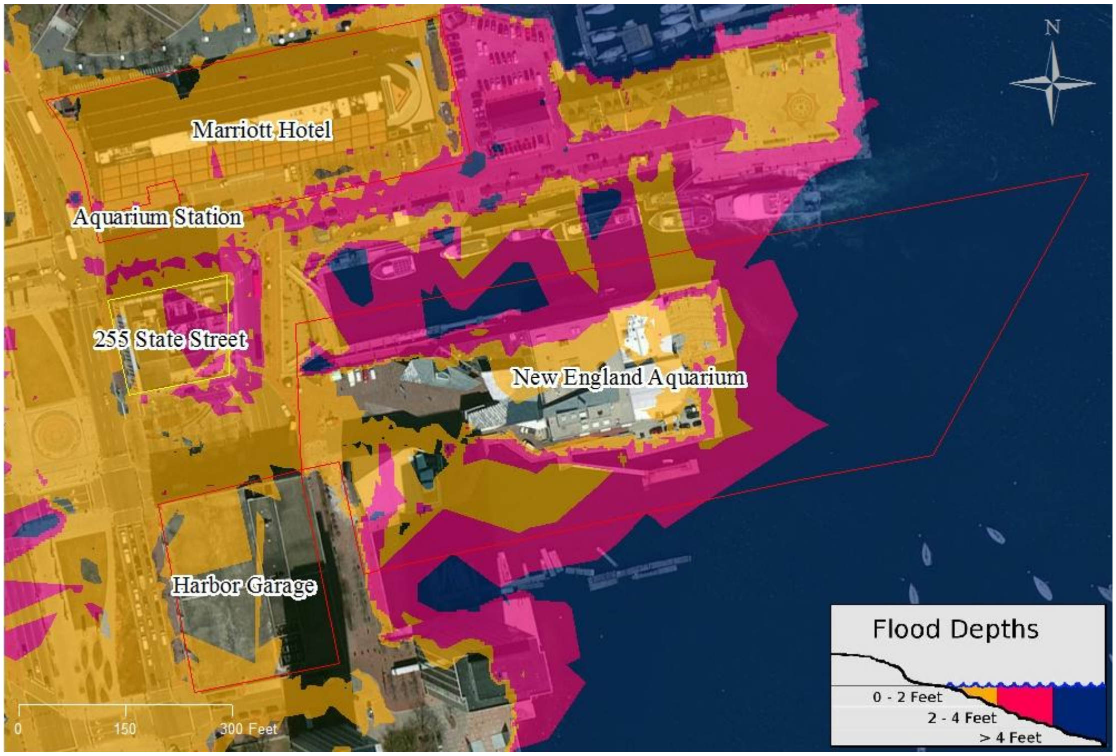


Figure 11. Estimated current 100-year flood zone (Kirshen et al., 2008; MHHW + 5/9.8 ft NAVD)

Figure 12. Estimated current 100-year flood zone (Federal Emergency Management Agency)

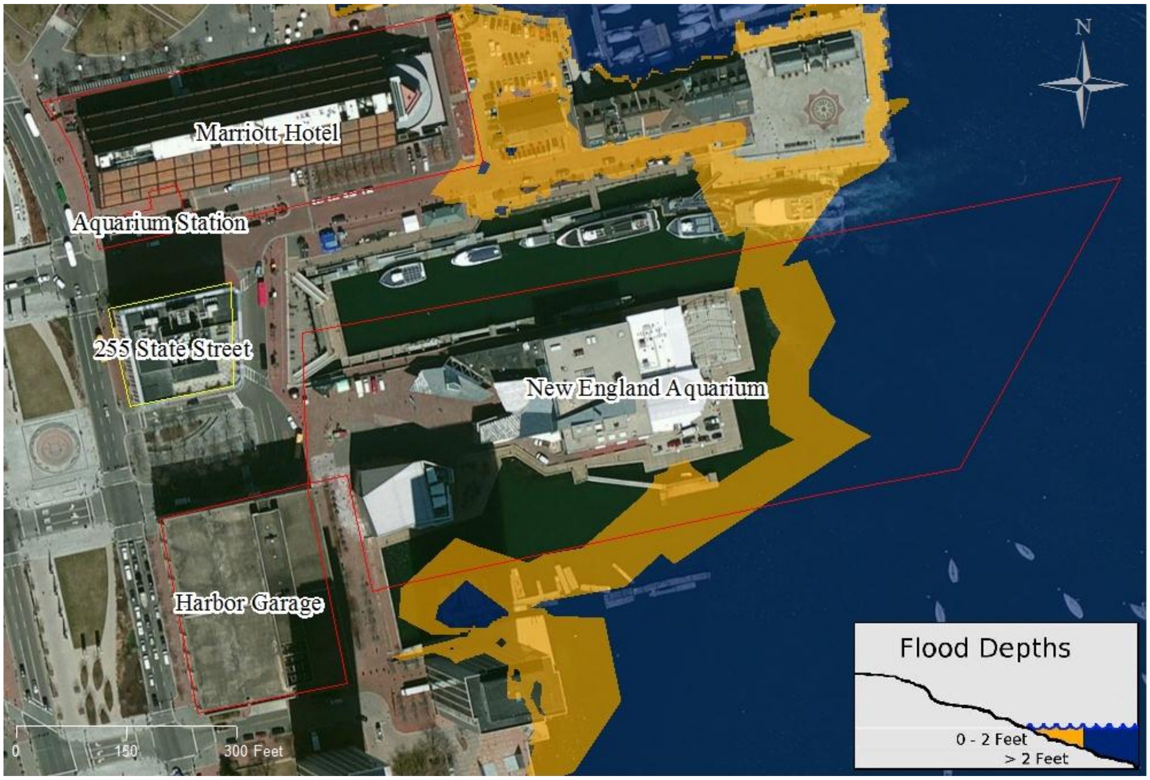


Figure 13. Estimated area of tidal flooding by mid- to late-century (Kirshen et al.; MHHW+2.5/7.3 ft NAVD)

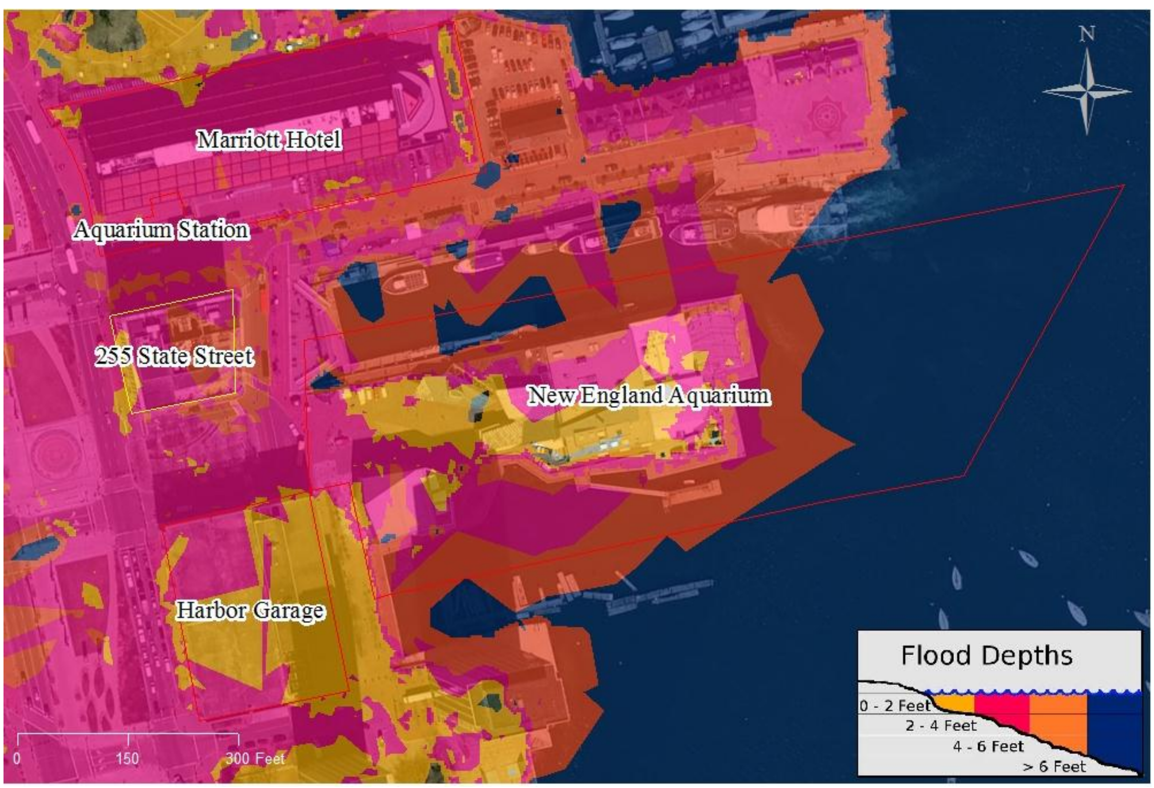


Figure 14. Predicted 100-year flood around or after 2100(Kirshen et al.; MHHW+7.5/12.3 ft NAVD)

Our team met with owners and managers of buildings located on Long and Central Wharves to better understand their vulnerability to and current preparations for coastal flooding. Our preparedness plans were based on present and future threats to the buildings from both tidal and storm surge flooding at various future sea levels. We calculated these threats based on both visual surveys and modeled elevations.

It was notable that all of the owners and managers were eager to talk to us about climate change. None doubted the future threat, though some were surprised by the extent of potential flooding even today.

Results

Vulnerability assessments and preparedness plans for four properties on Long and Central Wharves are provided below. The preparedness plan for the Marriott Long Wharf Hotel is discussed in the text and in Table 7; the others are provided in Tables 8 through 11.

Marriott Long Wharf Hotel and Aquarium MBTA Station

Vulnerability Assessment. The hotel was built in 1982 and takes up the entire building structure except for the ground-floor where a restaurant and coffee stand are located. The lobby is located on the second story. There is a parking garage with sump pumps in the basement. The critical elevation is the entrance to the below-ground garage located at 7.5 ft NAVD (MHHW+2.7). All utilities are on the penthouse level.

The hotel is prepared for flooding with a Bobcat tractor and sandbags on site; neither have been used in recent memory. Exhaust ducts can be blocked off if necessary and the hotel is equipped with a backup generator and emergency food and water onsite for guests.

The Marriott Hotel has its lobby on the second floor. Although this was done to decrease pedestrian traffic through the lobby, it has the added advantage (a co-benefit solution) of increasing the facility's resilience to flooding.

The entrance to the Aquarium MBTA subway station is above ground, though all but the small entrance foyer is both underground and below sea level. The critical elevation is 7.5 ft NAVD (MHHW+2.7), leaving the station vulnerable to flooding during a 100-year storm surge. Were significant seawater to enter the station and flood the subway line, the Blue Line from East Boston through Revere would be cut off from the rest of the MBTA subway system.

The MBTA has pumps at all its stations designed to keep water off of the tracks under non-extreme storm conditions. The Aquarium station has a backup generator. The emergency exit located seaward (east) of the Marriott Hotel is for passenger escape from Aquarium station. The critical elevation for this escape structure is 11 ft NAVD (MHHW+6.2). Although there is not yet a flood management plan for this station, MBTA personnel indicated to our team that they were well aware of the need to prepare for potential flooding.

Sample preparedness plan. The Marriott will need to undertake additional actions to protect against the current 100-year flood (MHHW+5/9.8 ft NAVD) when the Long and Central wharves area floods up to two feet (see Figure 11).[56] By mid-century or beyond, a similar-strength storm would cause flooding of 2 to 4 ft because of predicted sea level rise.

Figure 15. Example of parapet wall

- Short-term, the Marriott could undertake a purely site-specific response action to protect the building, even as the area around it temporarily floods.
- To protect against the 100-year flood sometime after mid-century when sea level will be at least 2 ft higher, we recommend considering a multi-property approach such as construction of an adjustable parapet wall (see Figure 15) around Long and Central Wharves.
- With a possible six or more feet of sea level rise by the end of the century, there could be tidal flooding approximately covering the area of the present 100-year flood (see Figure 11). Although a parapet wall would provide protection against tidal flooding, it would also create new rainfall drainage problems. These could be handled by drainage pumping facilities.

If the building owners on Long and Central Wharves desire regional protection against the present 100-year surge flood of 9.8 ft NAVD (MHHW+5), then adjustable parapet walls should be installed soon. As noted above, this only provides protection to 12.3 ft NAVD (MHHW+7.5) as a flood above that level would enter the area from locations beyond the wharves.

Additional Vulnerability Assessments

56 Perhaps more importantly, to provide protection against a 100-year flood to at least mid-century when it could be up to MHHW+7.5 (12.3 ft NAVD).

How to read the sample preparedness plans:

These plans recommend actions to take over time to deal with flooding from 1)twice-daily high tides, 2) average annual storms and 3) a "100-year" flood event.

For example, Table 7 notes that the entrance to the Aquarium MBTA station floods at 7.5 ft NAVD. At today's sea level, the station would be high and dry at high tide, barely flooded by the annual storm surge and 2.5 feet under water during a "100-year" flood.

In 2050, the station entrance is likely to still be dry at high tide, but flooded during annual and 100-year storm surges. By 2100, the station entrance could be flooded at high tide.

Thus, while the MBTA today does not have to do anything in the near term to prepare for tidal flooding, it does need plan today to manage both today's severe storms and increased flooding over time.

255 State Street. This building was constructed in 1916. It has a ten-foot high basement in which there are switch gear, telephone equipment, and storage. They have two sump pumps which they have only occasionally used. Elevator machinery and emergency generator are on the roof. The building is entirely comprised of office and retail space with no parking.

The critical elevation is 9.5 ft NAVD (MHHW+4.7) at the street level entrances. Building managers are prepared for flooding with sandbags; they had not been used in recent memory. Managers believed that many of the office occupants could work offsite for some time if necessary. The owners expect to redevelop the building before 2050. At this time, they would incorporate climate change preparedness considerations.

Harbor Garage. The Harbor Garage was built in 1969 as part of Harbor Towers. It has two basement levels—one for parking and one for mechanical and oil tanks. The basement also contains the boilers for adjacent residential condominiums that have their cooling towers on the roof of the Harbor Garage. The first floor of the Harbor Garage contains multiple retail tenants; the upper floors are parking. There is some groundwater seepage in the basement that is handled by pumps.

The critical elevation is the entrance to the below-ground garage located at 9.5 ft NAVD (MHHW+4.7). They have never had flooding from either precipitation or storm surges in the basement. The site will be part of the new Municipal Harbor Plan, and the building owner anticipates that a new building will replace the existing structure. Climate adaptation will be incorporated into the new building.

New England Aquarium. Buildings include the Aquarium exhibit building, and the IMAX Theatre. The Aquarium also rents office space on the first floor of the Harbor Garage. The critical elevation for the Aquarium is the first floor elevation at 15 NAVD (MHHW+10.2). The switching station for incoming electricity is on the second floor. Backup power is supplied by two diesel generators (one for safety, one for the fish tanks), both located at 11.5 NAVD (MHHW+6.7). The Aquarium basement is damp at present high tides, managed by two sump pumps.

The IMAX Theater has no basement or backup power. Its main door is at 11 NAVD (MHHW+6.2). During extreme precipitation events, the Aquarium experiences backups in their sanitary drain system due to excess flows in the Boston sewer system. During storm surges, some low lying areas around the Aquarium and the IMAX Theater are flooded. During these flood events, the Aquarium employs various measures to reduce water penetration at exposed building openings, such as vents.

The Aquarium has already increased the height of the HarborWalk on the south side of the building by two ft. Implementation of the Aquarium's exterior master plan in 3-5 years will incorporate climate change into its design.

Table 7. Sample adaptation plan for Long Wharf Marriott/Aquarium MBTA

Long and Central Wharves - Coastal Climate Change Adaptation Planning	Marriott Hotel and MBTA Aquarium Station
General Description	The Boston Marriott parcel, residing at the landward end of Long Wharf, becomes flooded when the stillwater elevations exceed approximately 9.5 ft NAVD. Stillwater elevations less than 9.5 ft NAVD do create access issues, as areas around the Marriott parcel become flooded. The MBTA station entrance, west of the Marriot, floods at 7.5 Ft NAVD.

Mean Higher High Water (MHHW) Timeline	Annual (1-year) Storm Surge Timeline	100-year Storm Surge Timeline	Approximate Maximum Water Surface Elevation (ft, NAVD88)	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*
2010			4.0			
			5.0			
2050			6.0	No Flooding Expected	No Action Required	N/A
	2010		7.0			
	2050		8.0	Flooding of surrounding area and 7.5 ft NAVD entrances to below-ground garage and MBTA station.	Develop alternate access route plans. Minor flood proofing.	Minimal
2100			9.0			
		2010	10.0	Flooding of Marriott infrastructure and entire Long Wharf region.	See Regional Adaptations	See Regional Adaptations
		2050	11.0			
	2100		12.0			
			13.0	Widespread flooding of entire area during storm events. Water arriving into Long Wharf area from other regional sources in addition to local flooding.	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	*Capital Cost: $20 per square foot of building for wet flood proofing
		2100	14.0			
			15.0			
			16.0			

* = Initial Capital Costs and Operational and Maintenance costs provided are estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction. Estimated costs are based on 2010 dollar value.

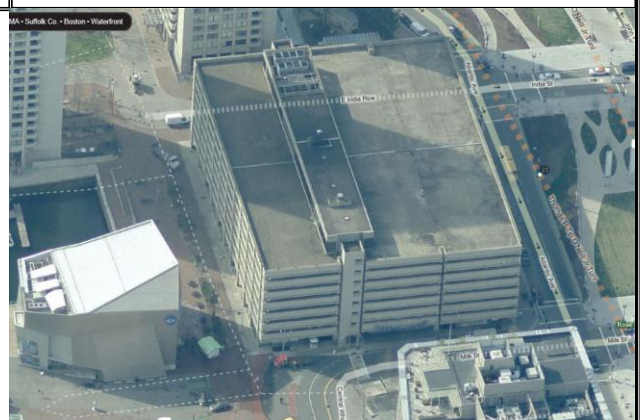
Table 8. Sample adaptation plan for 255 State Street

Long and Central Wharves - Coastal Climate Change Adaptation Planning				Two Fifty Five State Street		
General Description				The Two-Fifty Five State Street parcel resides landward of Long Wharf. The parcel initially becomes vulnerable at 8.5 ft NAVD, when water floods State and Central Streets around the parcel. This water floods the street from overtopping at the seaward end of Long Wharf. During these initial flooding stages, site-specific solutions (such as local flood proofing) can be effective. However, as the stillwater elevation continues to rise, and exceeds approximately 10.0-10.5 feet, regional solutions become more important to reduce flooding potential at this location.		
						
Mean Higher High Water (MHHW) Timeline	Annual (1-year) Storm Surge Timeline	100-year Storm Surge Timeline	Approximate Maximum Water Surface Elevation (ft, NAVD88)	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*
			4.0			
2010						
			5.0			
2050			6.0	No Flooding Expected	No Action Required	N/A
	2010		7.0			
			8.0			
	2050					
			9.0			
2100				Flooding of State Street and Central Wharf Street	Dry flood proofing (membrane) on lower levels; or Long Wharf adaptations	*Cost: \$5 /ft² for waterproof membrane
		2010	10.0			
			11.0	Flooding of Parcel and surrounding areas	See Regional Adaptations	See Regional Adaptations
	2100	2050				
			12.0			
			13.0			
		2100	14.0	Widespread flooding of entire area during storm events. Water arriving into Long Wharf area from other regional sources in addition to local flooding.	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	*Capital Cost: \$20 per square foot of building for wet flood proofing
			15.0			
			16.0			

* = Initial Capital Costs and Operational and Maintenance costs provided are estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction. Estimated costs are based on 2010 dollar value.

Table 9. Sample adaptation plan for Harbor Garage

Long and Central Wharves - Coastal Climate Change Adaptation Planning	Harbor Garage
General Description	This parcel resides landward of Central Wharf (New England Aquarium). Flooding of the surrounding streets occurs approximately at 9.5 feet NAVD, and the parcel does not fully flood until approximately 11.0 feet NAVD, when waters arrive from flooding over both Central and Long Wharf pathways. Site-specific adaptations focus on elevating critical utilities and flood proofing of lower levels under these initial flood stages. However, as the stillwater elevation continues to rise, and exceeds approximately 11.0 feet, regional solutions become more important to reduce flooding potential at this location.



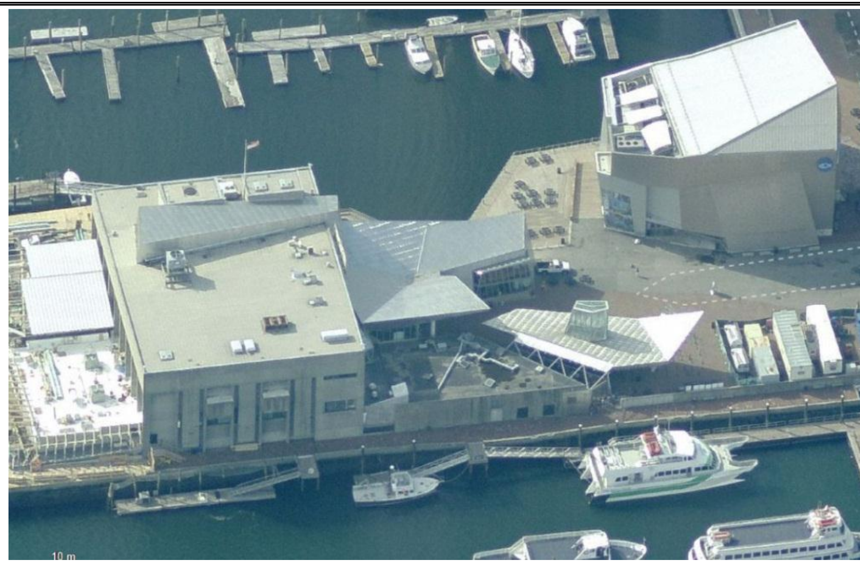
Mean Higher High Water (MHHW) Timeline	Annual (1-year) Storm Surge Timeline	100-year Storm Surge Timeline	Approximate Maximum Water Surface Elevation (ft, NAVD88)
			4.0
2010			
			5.0
2050 ↑			
2050			6.0
2050 ↓			
	2010		7.0
2100 ↑			
2100	2050 ↑		8.0
2100	2050		
2100	2050 ↓		9.0
2100			
2100	2100 ↑	2010	10.0
2100 ↓	2100		
	2100	2050 ↑	11.0
	2100	2050 ↓	
	2100	2100 ↑	12.0
	2100	2100	
	2100	2100	13.0
	2100 ↓	2100	
		2100	14.0
		2100	
		2100	15.0
		2100	
		2100 ↓	16.0

Approximate Maximum Water Surface Elevation (ft, NAVD88)	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*
4.0 – 9.0	No Flooding Expected	No Action Required	N/A
9.5 – 10.5	Flooding of Milk Street, Atlantic Ave., and East India Row	Elevate or relocate utilities and electrical equipment in basement. Dry flood proofing on lower levels.	$5 /ft^2 for waterproof membrane plus elevation of critical utility costs
11.0 – 11.5	Flooding of Parcel and surrounding areas	See Regional Adaptations	See Regional Adaptations
12.0 – 16.0	Widespread flooding of entire area during storm events. Water arriving into Long Wharf area from other regional sources in addition to local flooding.	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	*Capital Cost: $20 per square foot of building for wet flood proofing

* = Initial Capital Costs and Operational and Maintenance costs provided are estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction. Estimated costs are based on 2010 dollar value.

Table 10. Sample adaptation plan for New England Aquarium

Long and Central Wharves - Coastal Climate Change Adaptation Planning	Site-Specific Solutions New England Aquarium
General Description	Compared to the rest of the region, the New England Aquarium parcel and buildings are less vulnerable to potential flooding due to sea level rise and/or storm surge. For example, Long Wharf begins experiencing significant flooding when the stillwater elevation reaches approximately 8.0 ft NAVD, while Central Wharf does not significantly flood until approximately 10 ft NAVD and is primarily flooded due to regional flooding pathways. The higher elevation of the NEAQ main building first floor at 15 feet NAVD and its relatively flood resistant design reduces its vulnerability. The entrance to the IMAX Theater, on the other hand, is at 11 feet NAVD and thus more vulnerable than the main building. The Exhibit Hall's emergency generators are vulnerable to flooding at 12 feet NAVD.

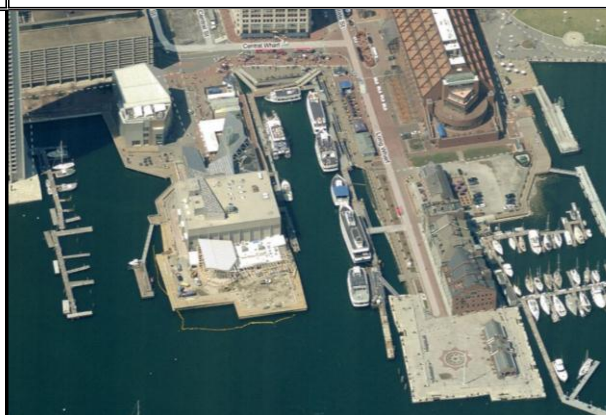


Mean Higher High Water (MHHW) Timeline	Annual (1-year) Storm Surge Timeline	100-year Storm Surge Timeline	Approximate Maximum Water Surface Elevation (ft, NAVD88)	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*
			4.0	No Flooding Expected	No Action Required	N/A
2010						
			5.0			
2050			6.0			
	2010		7.0	Minor flooding on north and south side of aquarium walkway and approaches	Minor flood proofing, covering of open vents on northern side, etc.	Minimal
2100	2050		8.0			
			9.0			
	2100	2010	10.0	Flooding of NEAQ parcel from region. Water overtopping all sides of wharf and surrounding the exhibit hall, which is isolated at 15 feet NAVD. IMAX Theater main door is flooded at 11 feet NAVD.	See Regional Adaptations	See Regional Adaptations
		2050	11.0			
			12.0	Widespread flooding of entire area during storm events. Water arriving into Central Wharf area from other regional sources in addition to local flooding. NEAQ exhibit hall entrance flooded at 15 feet NAVD. The main building emergency generators flood at 12 feet NAVD.	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	To be estimated separately given the uniqueness of the Aquarium buildings.
		2100	13.0			
			14.0			
			15.0			
			16.0			

* = Initial Capital Costs and Operational and Maintenance costs provided are estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction. Estimated costs are based on 2010 dollar value.

Table 11. Sample adaptation plan for Long and Central Wharves, Boston

Long and Central Wharves - Coastal Climate Change Adaptation Planning	Regional Adaptations
General Description	Overtopping of Long Wharf, and to a lesser extent Central Wharf, create flooding pathways for upland areas landward of the wharf region. Significant flooding starts to occur when the stillwater elevation is approximately 8.0 ft NAVD. When the stillwater elevation reaches 9.0 ft NAVD, water has completely flooded Long Wharf and advanced landward via State Street and Central Street. At a stillwater elevation of approximately 10.0 ft NAVD, Central Wharf is also overtopped and contributes additional water to lower lying upland areas. Due to the relatively wide scale flooding potential from Long Wharf, there are limited regional solutions that can function without protecting the entire wharf region.



Mean Higher High Water (MHHW) Timeline	Annual (1-year) Storm Surge Timeline	100-year Storm Surge Timeline	Approximate Maximum Water Surface Elevation (ft, NAVD88)	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*
			4.0			
2010						
			5.0			
2050			6.0	Insignificant to minimal flooding	No Action Required	N/A
	2010		7.0			
			8.0			
2100	2050		9.0			
		2010	10.0	Flooding of Long Wharf creating pathways of water that flood upland, landward areas.	Design and construction of a adjustable parapet wall installed around the edge of Long and Central Wharfs. Elevation could be adjusted as a function of time as necessary. A modular seawall could also be considered.	#Capital Cost: $2.5-3.5 Million Annual Maintenance Costs: $20,000
			11.0			
	2100	2050	12.0			
			13.0			
		2100	14.0	Widespread flooding of entire area during storm events. Water arriving into Long Wharf area from other regional sources in addition to local flooding.	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	*Capital Cost: $20 per square foot of building for wet flood proofing
			15.0			
			16.0			

* = Initial Capital Costs and Operational and Maintenance costs provided are estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction. Estimated costs are based on 2010 dollar value.

- Depends on height of parapet installed.

UMass Boston, Dorchester

This case study focused on the University of Massachusetts (UMass) Boston, a nationally recognized model of excellence for urban public universities and the second-largest campus in the UMass system. The student body has grown recently to nearly 16,000 undergraduate and graduate students. The university's eight colleges offer more than 100 undergraduate programs and 50 graduate programs.

Current challenges

Surrounded by Boston Harbor and Dorchester Bay, UMass Boston has little to obscure its external visibility or protect the campus from the sun, wind, waves, corrosive salt air and noise from airplanes accessing nearby Logan Airport.

Figure 16. UMass Boston 25-year campus master plan framework with primary campus entrances.

The UMass Boston campus was originally constructed in the 1970s. The campus buildings were designed to sit on top of, and be interconnected by, a plaza that covered a two-level substructure. The original campus plan envisioned the substructure garage as the central "mother ship to which college building modules dock along its edges and above it."[57] The substructure extended to each corner of the campus, including under each academic building and was designed and primarily used for parking. Years of exposure to road salt and the elements have caused widespread corrosion damage to the two substructure levels, including mechanical, electrical, plumbing and architectural features.

In 2005, concerns about the structural integrity of key campus buildings led UMass Boston to close the parking garage and to commission the "Study for Structural Repair of Plaza and Upper and Lower Levels at UMass Boston Harbor Campus."[58] This study proposed comprehensive long-term repairs with an estimated total project cost of $160 million.

In 2010, UMass Boston purchased the adjacent 20-acre Bayside Expo Center. In the short term, this property will be used for parking and staging areas for construction of new campus buildings. Longer term, the university will engage in a multi-stakeholder planning process to determine future uses of this site.[59]

A 25-year master plan, completed in 2010, envisions the demolition of the substructure and the construction of a number of new buildings to address academic and housing needs of students. Buildings will become free-standing and independent structures, with improved circulation, better access to the HarborWalk, and numerous infrastructure improvements.[60]

Figure 16 shows the campus layout envisioned by the 25-year campus master plan. Currently, the main access to campus is via the entrance at the intersection of Bianculli and Morrissey Boulevards. As part of the master plan, the secondary entrance from Mt. Vernon Street will become a second primary entrance to the campus (both entrances are circled in blue).

Methods

In the Master Plan document there is little mention of potential vulnerabilities to climate change impacts or future strategies for dealing with climate change. As with our other case studies, we evaluated the vulnerability of UMass Boston property at MHHW+5 (9.8 ft NAVD) and MHHW+7.5 (12.3 ft NAVD). Figures 17 and 19, respectively illustrate potential flooding from these scenarios.

In order to assess the source of surface flooding, we performed a GIS analysis in which digital representation of flood heights increased incrementally by 0.5 ft, starting at 0 ft NAVD. This allowed us to identify locations where flood water first

[57] UMass Boston, 2009.
[58] Massachusetts State Project No. UMB0502
[59] http://www.umb.edu/the_university/bayside/
[60] Ibid.

begins to affect UMass Boston property and to visualize flow paths as the water extends from these locations.

This exercise was useful in designing flood prevention and preparedness strategies for the UMass Boston property. For example, Figure 19 shows that flooding of Morrissey Boulevard (Blvd) begins at 8.0 ft NAVD (MHHW+3.2).

Results

Vulnerability Assessment. For the most part, the campus itself is not particularly vulnerable to surface flooding, even during the higher flooding scenario shown in Figure 18 (MHHW+7.5 or 12.3 NAVD).

The base elevation for new buildings on campus has already been established at 5 ft above the current 100-year flood elevation (approximately 15 ft NAVD (MHHW+10.2). Our preliminary analysis indicates that the new campus buildings will not be immediately vulnerable to surface flooding from a coastal storm.

The major vulnerabilities for the UMass Boston campus include flooding of campus entrances (both Morrissey Blvd and Mt. Vernon Street (St) and flooding of the Bayside Expo property (see Figures 17 and 18).

Flooding along both Morrissey Blvd and Mt. Vernon St currently impedes travel through both entrances during extreme coastal storm events and would likely completely block access to or egress from the campus during a similar storm event under higher sea levels. In addition, flood waters could impact the Bayside Expo property, located within the current 100-year floodplain.

The fact that Morrissey Blvd is occasionally flooded during high tide suggests that our incremental GIS analysis (see Figure 19) may underestimate actual flood risks, possibly due to the error in the DEM which is accurate only to ±1 ft. Flooding of the Bayside Expo property and Columbia Point begins at locations along the northern shoreline at 9.6 ft NAVD (MHHW+4.8; Figure 20).

Parts of the Bayside Expo property regularly flood after relatively minor rainstorms. Shortly after the Bayside Expo property was purchased, the catch basins and storm drains were cleaned out, allowing stormwater to drain more readily from the property and decreasing stormwater flooding impacts.

One concern we were not able to address during this initial assessment is the effectiveness of the campus and Bayside property storm drain system during a combined rainstorm and storm surge event. Most drain outlets are at or slightly above the high tide level. However, because of tide gates and large in-system storage capacity, the storm drainage system is not expected to back up during high tides in the near future.[61]

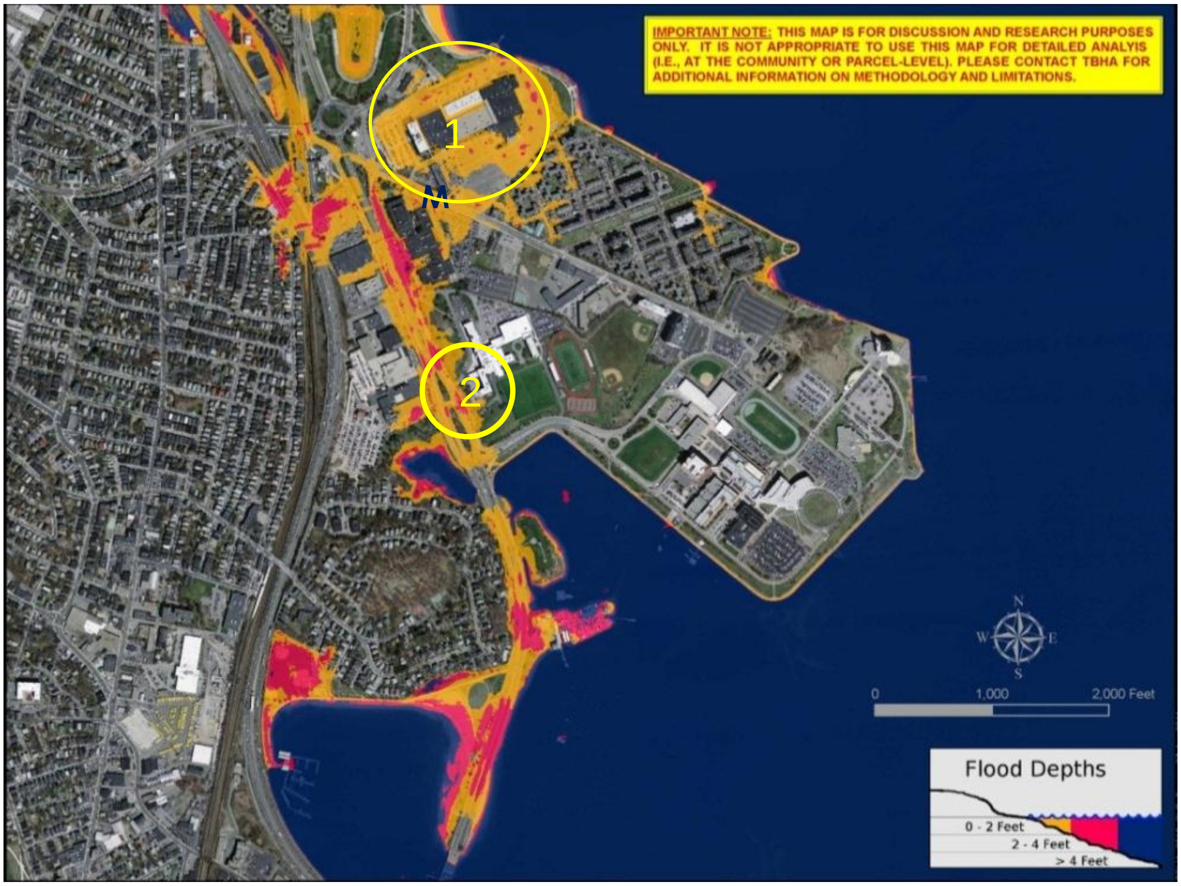


Figure 17. Projected surface flooding from a 5-ft storm surge (MHHW+5/9.8 ft NAVD). Vulnerable areas at UMass Boston are circled in yellow and include the Bayside Expo property (1) and Morrissey Blvd (2).

[61] The Boston Water and Sewage Commission notes that there is a lot of additional storage capacity within the stormwater system to prevent stormwater from flooding streets and property. In addition, storm drain outlets have gates that prevent seawater from entering the system.

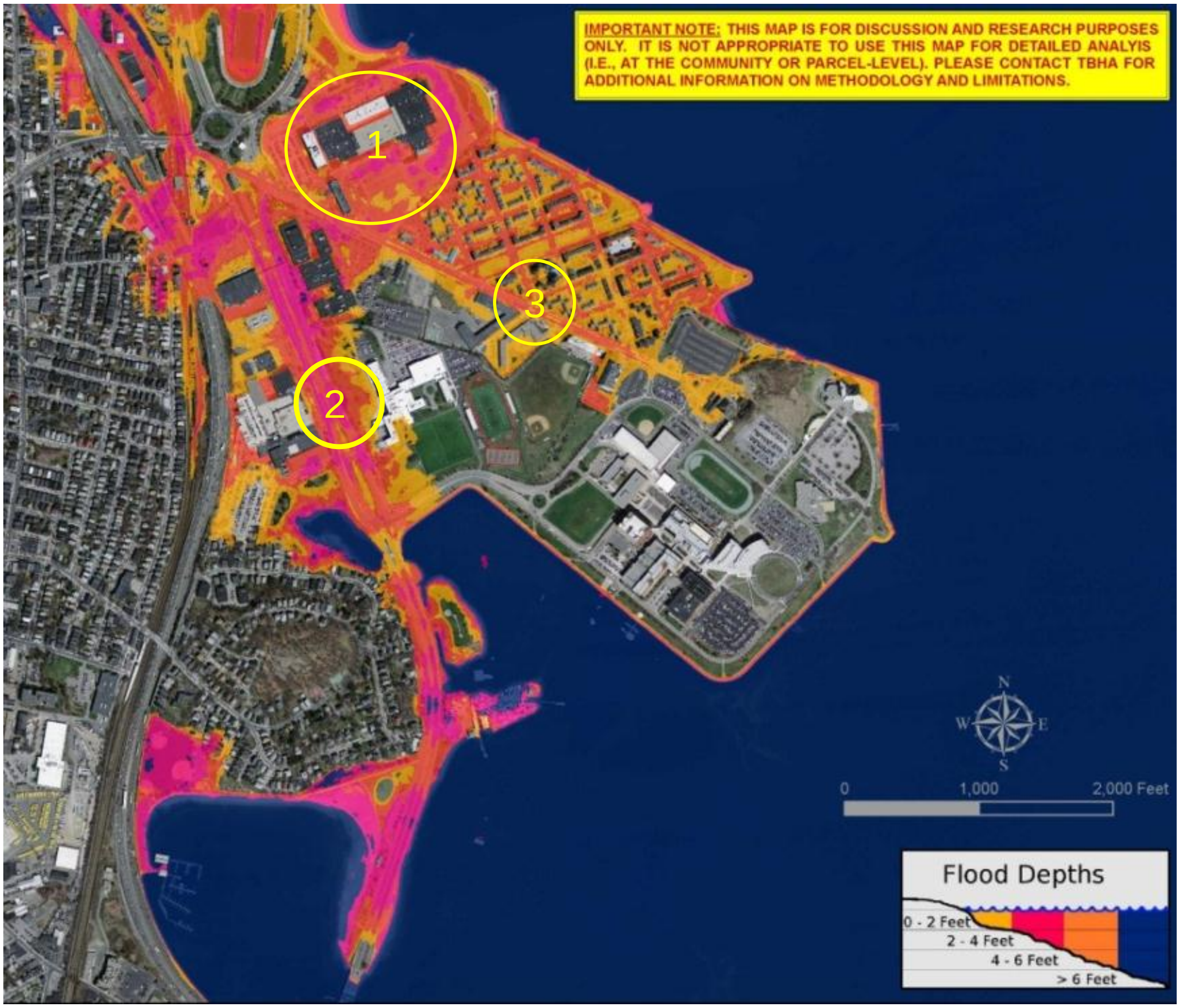


Figure 18. Projected surface flooding at UMass Boston due to future 2.5 ft of sea level rise plus 5 ft storm surge (MHHW+7.5/12.3 ft NAVD). Vulnerable areas include Bayside Expo (1), Morrissey Blvd (2) and Mt. Vernon St (3).

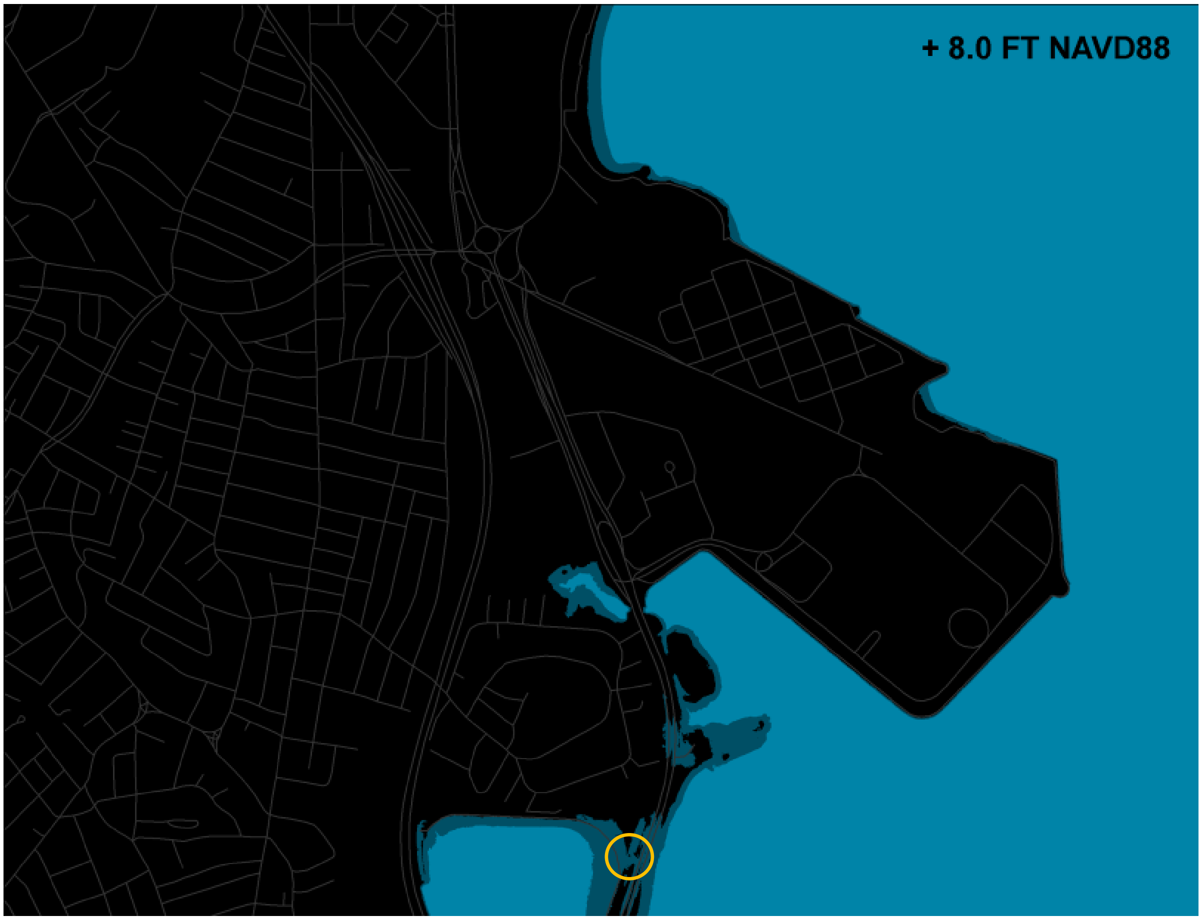


Figure 19. Source location for flooding: Morrissey Blvd. floods at 8.0 ft NAVD (MHHW+3.2).

Sample Preparedness Plans. Model preparedness plans in Tables 12 and 13 below address three types of impacts: flooding at high tide; a mild to moderate annual storm surge; and a 100-year storm surge. Timeframes for action and cost estimates associated with each impact are also provided.

Morrissey Blvd entrance: No action is required through mid-century to manage for tidal flooding. However, for coastal storm events, tidal control structures and soft engineering solutions will likely need to be employed to prevent flooding of the campus entrance, as early as mid-century for common (e.g., one or more times each year) storm surges and even sooner for 100-year storm surges. Along Savin Hill Cove, for example, due to the lower wave energy environment, soft engineering solutions could include beach nourishment, enhanced grading and elevation increases with supportive planting, or coir logs or other biodegradable protection measures to keep the roadway from being overtopped.[62]

[62] Bosma, 2012.

Figure 20. The Bayside Expo and three other locations along the northern shore of Columbia Point begin flooding at 9.6 ft NAVD (MHHW+4.8 ft). Flood water approaches the Morrissey Blvd. entrance.

Capital costs would range from $500,000 to $750,000 with $10,000 for annual maintenance. By late century, widespread flooding of Morrissey Blvd as well as portions of the campus is likely under both typical and extreme storm scenarios and more aggressive interventions will be required. The cost to wet floodproof existing buildings is currently about $20/sq. ft. This technique involves using flood-resistant construction and finishing materials so that flooded areas are minimally damaged by sea water intrusion.

Bayside Expo property: Flooding of this property is already occurring during heavy rain events; mitigation will require a solution such as a pump-based drainage system, a $2 million capital investment. Alternatively, future design of this site could include a "living with water" component that provides healthy open space during dry periods and engineered flood management areas during storm events.

Table 12. Sample preparedness strategies for Morrissey Blvd and Bayside Expo.

UMASS BOSTON - Coastal Climate Change Adaptation Planning	Vulnerable Flood Risk Areas: Morrissey Blvd. Entrance	Vulnerable Flood Risk Areas: Bayside Expo Center
General Description	The Morrissey Blvd. Entrance is currently the primary entrance to the UMASS-Boston campus. A significant portion of this street, especially south of the campus entrance, is low-lying and is prone to flooding even under present day conditions (storm surge or heavy rainfall events). Once the water surface elevation overtops higher elevations along the coastline, most of Morrissey Blvd. will become flooded. At the campus entrance specifically, as shown in the aerial view, storm surge flooding initially may occur from the Patten's Cove side and subsequently the Savin Hill Cove side when water surface elevations reach between approximately 9.5-10.0 feet NAVD88.	Bayside Expo center region, recently purchased by UMASS-Boston, is slated to undergo redevelopment. Currently, the area is prone to potential flooding, especially the low-lying parking lot regions (one of the lowest elevations in the region). There is potential for poor drainage and flooding of this area (approximately 30 acres) even during contemporary rainfall storm events. As sea level increases, there are also lower areas along the Dorchester Bay shoreline that will become susceptible to the higher water surface elevations during storm events, resulting in significant overtopping and widespread flooding of the area. Specifically, areas along the Harbor walk area shown in aerial view.
		

Mean Higher High Water (MHHW) Timeline	Annual (1-year) Storm Surge Timeline	100-year Storm Surge Timeline	Approximate Maximum Water Surface Elevation (ft, NAVD88)	Morrissey Blvd. Entrance: Upland Flooding Potential	Morrissey Blvd. Entrance: Engineering Adaptations	Morrissey Blvd. Entrance: Estimated Adaptation Cost*	Bayside Expo Center: Upland Flooding Potential	Bayside Expo Center: Engineering Adaptations	Bayside Expo Center: Estimated Adaptation Cost*
			4.0						
2010			5.0	No Flooding Expected	No Action Required	N/A	Poor Drainage of Bayside Expo Parking areas during heavy rainfall events. No Flooding of areas from Dorchester Bay waters.	Minor flood proofing of structures Installation of a pump house and pumped based-drainage system for parking area[+]	Capital Cost: $ 2.0 Million Annual Maintenance Costs: $ 10,000
2050			6.0						
	2010		7.0	Flooding of Morrissey Blvd. approx 1/4 mile south of campus entrance. No flooding of campus entrance or facilities					
	2050		8.0						
2100			9.0						
		2010	10.0	Flooding of campus entrance. Initially from Patten's Cove (tidal pond to the west of entrance), and subsequently from Savin Hill Cove.	Tidal control structure at entrance to Patten's Cove. Soft solution (beach nourishment and vegetation enhancement) along Savin Hill Cove.	Capital Cost: $500-750,000 Annual Maintenance Costs: $10,000	Flooding of Bayside Expo areas from Dorchester Bay. Water overtops harbor walk in places.	Modular seawall installation at critical locations along Harbor walk. Seawall extension along Harbor walk as needed.	Capital Cost[#]: $1.0-1.5 million (1,000 foot length) Annual Maintenance Costs: $15,000
		2050	11.0						
	2100		12.0						
			13.0	Widespread flooding of UMASS Boston Campus, Morrisey Blvd. and surrounding areas	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	Capital Cost: $20 per square foot of building for wet flood proofing.	Widespread flooding of UMASS Boston Campus, Morrisey Blvd. and surrounding areas	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	Capital Cost: $20 per square foot of building for wet flood proofing.
		2100	14.0						
			15.0						
			16.0						

* = Initial Capital Costs and Operational and Maintenance costs provided are estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction. Estimated costs are based on 2010 dollar value.

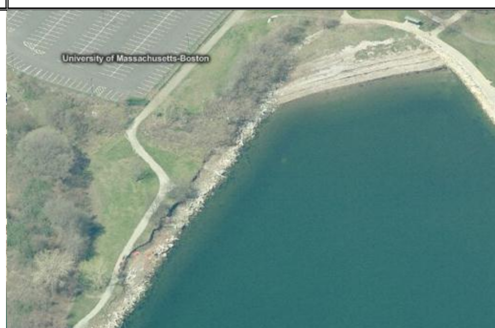
- Depends on length of seawall installed.

+ = Based on a 30 acre area with a peak intensity rainfall of 5 in/hr (average of 0.3 inches/hr over a 24 hour period)

In addition, the current 100-year storm surge is expected to overtop the HarborWalk and protective berm. Sometime after 2050, annual coastal storms will likely overtop the HarborWalk as well. Improving the seawall would require an additional $1-1.5 million investment to install a modular sea wall at critical locations along the HarborWalk, with an additional $15,000 annual maintenance cost.

Table 13. Sample preparedness plans for Mt. Vernon St and Ocean View Drive.

UMASS BOSTON - Coastal Climate Change Adaptation Planning	Vulnerable Flood Risk Areas: Mt. Vernon Street	Vulnerable Flood Risk Areas: Ocean View Drive
General Description	The southeastern end of Mt. Vernon Street is under consideration as a potential location for a secondary entrance to the UMASS-BOSTON campus. This areas currently experiences storm water drainage delays and issues. The current storm water drain lines from this area discharge into Dorchester Bay with an invert elevation at approximately Mean Higher High Water. As sea level rises, this will further impede storm water drainage ability from this region. There is also some susceptible low lying areas to the east of the Mt. Vernon Street terminus, as shown in the aerial below. Potential upland flooding may occur along some lower elevation access points in this region.	The Ocean View Drive region has potential for flooding during storm surge events, especially as sea level continues to rise. Once water overtops the harbor walk area, water quickly floods many of the Ocean View Drive and many of the connecting streets, specifically near the region shown in the aerial below.



Mean Higher High Water (MHHW) Timeline	Annual (1-year) Storm Surge Timeline	100-year Storm Surge Timeline	Approximate Maximum Water Surface Elevation (ft, NAVD88)	Mt. Vernon Street: Upland Flooding Potential	Mt. Vernon Street: Recommended Engineering Adaptations	Mt. Vernon Street: Estimated Adaptation Cost*	Ocean View Drive: Upland Flooding Potential	Ocean View Drive: Recommended Engineering Adaptations	Ocean View Drive: Estimated Adaptation Cost*
			4.0	No Flooding Expected.	No Action Required	N/A	No Flooding Expected.	No Action Required	N/A
2010			5.0						
2050			6.0						
2100	2010		7.0	Area has experienced poor storm water drainage. Storm water outfall at 2010 MHHW elevation may not adequately drain in future.	Improve storm water removal and drainage lines. Modify storm water outfall or add pump house.	Capital Cost: $ 250,000 Annual Maintenance Costs: $ 2,000			
	2050		8.0						
			9.0						
	2100	2010	10.0		Provide clean fill in low lying areas or increase storm protection with soft coastal engineering solutions.	Capital: $300-500,000 Annual Maintenance: $5,000	Flooding of streets around Ocean View Drive, expanding to buildings around the region.	Flood proofing of structures. Increasing crest height of revetment along Harbor walk or installation of a modular seawall.	Capital Cost#: $2.0-2.5 million (2,300 foot length) Annual Maintenance Costs: $20,000
		2050	11.0	Flooding from Dorchester Bay via low-lying pathways to the east of Mt. Vernon Ave.					
			12.0						
		2100	13.0	Widespread flooding of UMASS Boston Campus, Morrisey Blvd. and surrounding areas.	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	Capital Cost: $20 per square foot of building for wet flood proofing.	Widespread flooding of UMASS Boston Campus, Morrisey Blvd. and surrounding areas.	In addition to adaptations above, additional flood proofing and elevation of critical infrastructure. Evacuate during storm event and return.	Capital Cost: $20 per square foot of building for wet flood proofing.
			14.0						
			15.0						
			16.0						

* = Initial Capital Costs and Operational and Maintenance costs provided are estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction. Estimated costs are based on 2010 dollar value.

- Depends on length of seawall installed.

+ = Based on a 30 acre area with a peak intensity rainfall of 5 in/hr (average of 0.3 inches/hr over a 24 hour period)

Mount Vernon Street entrance: This area is unlikely to currently be affected by flooding at full- and new-moon high tides. The stormwater drainage system outlet, however, is at or just slightly above MHHW, and would require upgrading to maintain proper drainage capacity, even without higher sea levels. This would require a capital investment of $250,000 with a $2,000 annual maintenance cost.

Low-lying areas in the vicinity of this intersection should be filled or soft engineering structures installed to reduce flooding from Dorchester Bay under current and future extreme (100-year) storm events. This would require a $300,000 to $500,000 capital investment and $5,000 in annual maintenance costs. Improving the drainage and reducing the risk of flooding of this intersection is important because it will be designated as a second primary entrance to the UMass Boston campus.

Ocean View Drive: This area within the Harbor Point complex provides housing for UMass Boston students and other local residents. Flooding of buildings in this area from the current 100-year storm surge as well as the annual storm surge by late-century will require flood proofing of existing buildings. This would require $2-2.5 million in capital costs and $20,000 in annual maintenance costs.

Figure 21. Sea water flooding in New York City at Ground Zero during Superstorm Sandy. Photo by John Minchilo, AP

Section 5. Findings and Recommendations

Findings

Expected Future Conditions

1. Climate change will increase coastal New England's vulnerability to flooding in at least two ways. Higher sea levels will cause waves and storm surges to reach further inland and deeper than in the past. Hurricane intensity may also increase. In addition, changes in the magnitude and intensity of extreme precipitation will affect stormwater management and exacerbate flooding.

2. Best available science predicts that, compared to the present water surface elevation, global average sea levels will increase one to two feet by 2050, and three to six feet by 2100. New England's local sea level is expected to rise even faster.

3. This means that, under the high-end scenarios, Boston will have to prepare for the current "100-year storm surge" (with a 1% likelihood of occurring in a given year) increasing to at least a 20% likelihood of occurring in a given year around 2050 and possibly as frequently as high tide around 2100.

Boston's Preparedness Planning as of Late 2012

4. Boston's climate change preparedness activities accelerated after 2009, when Mayor Thomas M. Menino appointed the Climate Action Leadership Committee. Their recommendations can be summarized as:
    - Climate adaptation is as important as climate mitigation.
    - Information on the effects of climate change is sufficient to start planning now, but flexibility and openness to new information are essential.
    - Climate adaptation must be thoroughly integrated into all planning and project review conducted by the City.

5. These broad policy statements set in motion multiple planning processes and other concrete actions across City agencies and in partnership with other governmental, private sector and non-profit entities.

Boston's Vulnerability to Coastal Flooding

6. Vulnerability assessments involve three steps: identifying a system's current vulnerabilities, estimating future conditions, and analyzing system sensitivity and resilience to identified future impacts.

7. Our analysis found that 6.6 percent of Boston could be flooded at a sea level five feet higher than MHHW (MHHW+5 or 9.8 ft NAVD). This approximates the current 100-year coastal storm surge at high tide. This potentially flooded area includes all of Boston's coastal neighborhoods and the Harbor Islands, along with over 65% of the Fort Point historic district and the proposed Blackstone Block district.

8. At a sea level 7.5 feet higher than MHHW (MHHW+7.5 or 12.3 ft NAVD), just over 30 percent of Boston could be flooded. This approximates the 100-year coastal storm surge at high tide when sea levels are 2.5 ft higher, sometime after mid-century. This represents 35 to 40 percent of all exempt, industrial, commercial and mixed use parcels in Boston. More than 50 percent of 12 Boston neighborhoods is included in this vulnerable area; East Boston would have the largest flooded area (>140 million sq. ft.)

Preparedness planning

9. Climate change preparedness plans involve multiple activities from building-specific through regional scales and can be phased in over time as sea level rises. They need to be robust enough to handle any future condition, and/or flexible enough change over time to meet needs as they arise. Best is to identify "no-regret" and co-benefit" solutions that extend beyond flood control goals.

10. Some cities such as Seattle, WA and Charleston, SC are developing "floodable zones" that preserve the city's access to its waterfront while minimizing damage when periodic flooding occurs. This concept of "living with water" is an option to consider in Boston as well, as suggested for the Bayside Expo property.

Case Studies

11. Property owners, residents and agency staff in our case studies were keen to talk to us about climate change. None doubted the increased future threat from climate change, though some were surprised by the degree and speed of future sea level rise. City agencies were very open to working with each other and with the private and non-profit sectors.

12. The buildings considered on Long and Central Wharves already have individual plans in place to manage current flooding threats, but will have to take action on a wharf-wide basis to protect against future flood levels.

13. The entrances to UMass Boston are not yet adequately protected from current 100-year floods. Effective short term adaptation plans can be developed for these areas; adaptation activities for 2100 will require significant new planning and investment.

14. We found that in all cases, property owners should start or continue taking feasible actions now and be prepared to undertake additional actions in the future in order for these properties to continue to serve their present purposes.

15. Low-income, Spanish-speaking Latino renters in East Boston preferred preparedness actions that enhance their present environment and that do not require temporary or permanent evacuation. They wanted more information on climate change, how it will impact them, and what resources are available to assist them. Once engaged in the issue, community members wanted to become a part of the decision making process.

Recommendations

Preparing for the climate of the future will require coordinated efforts among all sectors of the Boston community, because no one entity has the resources, knowledge, and authority to complete the task. The City of Boston's existing Climate Action Plan establishes a framework for climate change preparedness. Now, using this framework, the Boston community needs to accelerate the development of concrete actions such as creating a robust public-private partnership to prepare Boston's waterfront and neighborhoods for the expected rise in sea level.

Private Sector Actions

1. All property owners in Boston on or near the coastal floodplain should take cost-effective action to reduce their vulnerability to higher and more frequent flooding. In particular, they should:

- Ensure that existing and proposed properties and the people who use them are adequately prepared for the current 100-year flood.
- Determine how levels of future flooding will affect their properties, by, for example, comparing existing site plans to maps of projected flooding depths.
- Identify critical elevations, such as door or vent openings, that indicate levels at which flooding could cause significant damage.
- Evaluate ways to make properties more flood-resistant or resilient.
- Based on potential damages, cost of action, and financial needs, take or plan actions that correspond to change in the actual sea level over time.

2. Because adjacent properties are likely to face similar risks from sea-level rise, property owners should look for opportunities to collaborate with their neighbors on preparedness projects. This may help to reduce costs or reduce vulnerabilities that could not be addressed individually.

3. Property owners should identify the obstacles to and limits of private action such as restricted resources, lack of technical knowledge, market disincentives, or overwhelming scale. They should also evaluate how the flooding of major infrastructure (transportation, energy) could affect their properties, and communicate both sets of information to public officials.

4. Property owners should participate in city, regional, state, and other planning processes addressing climate preparedness to ensure that their concerns are included.

Public Sector Actions

1. As outlined above, the City of Boston should also take cost-effective actions to reduce the vulnerability to higher and more frequent flooding of municipally owned facilities on or near the coastal floodplain.

2. The City should establish a range of planning levels for different future time periods for all public and private property owners to use when evaluating the risks of sea-level rise for existing and proposed buildings and other projects. Once the ranges are initially set, they should be periodically re-evaluated to incorporate new scientific understanding.

3. Because sea-level rise will increase the vulnerability of most neighborhoods of Boston, the City should strengthen its efforts to involve all segments of the Boston community in the climate planning process.

4. The City should host a robust discussion of the concept of "living with water" and its potential applicability to Boston.

5. The City, other levels of government, and the private sector should work together to identify and remove obstacles and disincentives to preparedness action by private property owners. They should further work together to identify and implement reasonable steps to encourage, incentivize, and, if necessary, mandate such action. Measures could involve, for example, building, public health, and zoning codes and insurance requirements.

6. Because the City lacks jurisdiction over important elements of Boston's infrastructure (e.g., public transit, the electrical grid, and highway tunnels), the City should work closely with state, regional, and federal agencies to protect these critical components.

7. Notwithstanding this report's focus on sea-level rise and coastal flooding, the City of Boston should ensure that other important effects of climate change, particularly increasing frequency and intensity of heat waves and storms, are included in climate preparedness plans.

Research Needs

Although there is much knowledge and many tools available to use in evaluating and preparing for the risks of climate change and sea-level rise, more is needed. Boston's academic community, as well as government agencies and private companies, are playing important roles in filling this need. We have identified the following areas as needing attention:

1. Flood preparedness strategies. Property owners and government agencies need a readily available—and expanding—toolkit of cost-effective ways to identify and reduce the vulnerability of buildings, neighborhoods, and infrastructure to sea-level rise and other consequences of climate change.

2. Complexity. Boston needs climate vulnerability assessments that examine the dense interconnectedness of the urban environment, and include consideration of the full economic, environmental, cultural, and public health impacts, and their interaction. Such assessments should compare the costs of doing nothing versus preparing for future flood events.

3. Flood models. Boston needs better, dynamic flood projections that combine the effects of relative sea-level rise with the effects of storm surges, waves, river discharges, precipitation, and the details of local topography.

Conclusion

We hope that readers of this report will take away the following lessons learned. First, that climate change-related coastal flooding is already a reality we need to manage for, and that such flooding is predicted to increase over time, possibly reaching 6 feet by 2100 and continuing past that for centuries.

Second, that preparing for increased coastal flooding involves implementing phased plans over time. Assessing a property's vulnerability to flooding is relatively straightforward and inexpensive, and preparedness actions may be integrated into maintenance plans to lower overall costs.

Finally, neither the public sector nor the private sector alone has the resources and influence necessary to prepare Boston for increased coastal flooding over time. We need a robust public-private partnership with clear benchmarks and engagement from all sectors to prepare this extraordinary historic city for the rising tide.

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Appendix 1. Reference Sea Level Elevations as of February 2013

This report uses reference elevations for sea level: the North American Vertical Datum of 1988 (NAVD) and Mean Higher High Water (MHHW). NAVD is the more precise, generally accepted vertical reference elevation (datum). We also used MHHW in describing more general future predictions in order to provide a more intuitive measure. Below is a chart providing reference elevations for several key sites in Boston.

Reference Elevation MHHW[1,2] Plus	Elevations Relative to Datum in Boston							
	MDC[3]	BCB[4]	MLLW[1,5]	NGVD[1,6]	MSL[1,7]	NAVD[1,8]		
ft[9]	ft[9]						meters[9]	Comments
0	111.2	11.2	10.3	5.6	5.1	4.8	1.45	Contemporary MHHW[1,2]
2.2	113.4	13.4	12.4	7.7	7.2	6.9	2.11	1998 King Tide (Predicted)[1,10]
2.5	113.7	13.7	12.8	8.1	7.6	7.3	2.22	MHHW+2.5 ft
4.1	115.3	15.4	14.4	9.7	9.2	8.9	2.71	Baker Dam (Neponset River)[11]
4.6	115.8	15.9	14.9	10.2	9.7	9.4	2.87	FEMA 100-Year Flood[12]
4.8	116.0	16.1	15.1	10.4	9.9	9.6	2.92	Highest Observed Water Level[1,13]
5	116.2	16.2	15.3	10.6	10.1	9.8	2.98	MHHW+5 ft
5.4	116.6	16.6	15.7	11.0	10.5	10.2	3.10	Historical Flood April 1851[14]
6.8	118.0	18.0	17.1	12.4	11.9	11.6	3.53	Charles[14,15] & Earhart[16] Dams
7.5	118.7	18.7	17.8	13.1	12.6	12.3	3.74	MHHW+7.5 ft
10	121.2	21.2	20.3	15.6	15.1	14.8	4.50	MHHW+10 ft
12.5	123.7	23.7	22.8	18.1	17.6	17.3	5.26	MHHW+12.5 ft

Notes: 1) Reference: NOAA Tides and Currents website (www.tidesandcurrents.noaa.gov) Elevations are relative to the 1983 - 2001 Boston Tidal Epoch
2) Mean Higher High Water
3) Metropolitan District Commission Vertical Datum
4) Boston City Base
5) Mean Lower Low Water
6) National Geodetic Vertical Datum of 1929
7) Mean Sea Level
8) North American Vertical Datum of 1988
9) Elevation shown may not equal total of components due to rounding
10) HAT: Highest Astronomical Tide (5-Nov-1998); predicted; observed elevation ~3 inches lower
11) Reference: Personal Correspondence, need to confirm
12) Reference: FEMA Boston Preliminary Flood Information Study (FIS), October 2008
13) HOWL: Highest Observed Water Level (7-Feb-1978)
14) Reference: "Charles River Dam, Design Memorandum No. 2", The Department of the Army New England Division Corps of Engineers, 1972
15) FEMA Boston FIS states Charles River Dam is 12.5 ft above MSL (=MHHW+7.4 ft)
16) Reference: Personal Correspondence, Mike Misslin (DCR Engineering)

Appendix 2. Sample Climate Change Adaptation Strategies.

POTENTIAL IMPACTS AND ADAPTATIONS SUMMARY | 5

DRAINAGE AND WASTEWATER MANAGEMENT

POTENTIAL CLIMATE CHANGE EFFECT	POTENTIAL IMPACT TO DEP
Increased temperature of harbor waters	■ Water quality impairment due to thermal stratification, reduced dissolved oxygen concentrations, and increased ammonia toxicity
More frequent intense rainfalls	■ More street and basement flooding ■ Sewer flood ■ Capacity exceedances for sewers and treatment facilities ■ Need to manage more CSOs to prevent water quality standards non-compliance
Sea level rise	■ More coastal flooding ■ More street and basement flooding ■ Increased inflow of seawater to sewers and WPCPs ■ Reduced ability to discharge CSOs and WPCP effluent by gravity ■ Rise in groundwater levels could cause basement flooding and sewer infiltration
More frequent coastal storms	■ More damage to coastal infrastructure

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POTENTIAL ADAPTATIONS

WATER SUPPLY

POTENTIAL IMPACT TO DEP	POTENTIAL ADAPTATION
Decrease quantity of supplies	■ Further diversify the water supply system: ▪ Bank surface water in aquifers ▪ Desalinate Hudson or Harbor waters ▪ Expand groundwater system ▪ Interconnect systems with other municipalities ■ Implement conservation and water use restrictions ■ Increase system redundancy (e.g., additional tunnels and new pumps for transferring water between systems) ■ In addition to enhancing flood works at select DEP reservoirs and other non-mandated DEP measures for assisting with flood mitigation in and downstream of the watershed, require operators of other (non-NYC) impoundments to mitigate reservoir spills ■ Require jurisdictions potentially impacted by flooding to restrict development in flood plains
Decreased quality of supplies	■ Increase and improve water supply quality protection measures such as the Stream Management Program in the Catskill Watershed and the Waterfowl Management Program ■ Acquire additional land and enhance land-use management ■ Increase operational flexibility (e.g., rely more heavily on the filtered Croton system during turbidity events and drought) ■ Apply alum and sodium hydroxide when necessary to reduce peak levels of turbidity ■ Apply structural and non-structural controls to reduce turbidity as necessary ■ Balance water supply needs with maintenance
Increased water demand	■ Reduce demand through conservation programs: ▪ Address illegal opening of fire hydrants ▪ Develop programs for City and non-City seasonal use reductions ▪ Increase in-City conservation programs

DRAINAGE AND WASTEWATER MANAGEMENT

POTENTIAL IMPACT TO DEP	POTENTIAL ADAPTATION
Street, basement flooding, and sewer flood	■ Augment collection system ▪ Increase sewer cleaning ▪ Build "high level" storm sewers ▪ Implement stormwater controls at the source ▪ Retain stormwater using rooftop or off-line storage and reuse it for ecologically productive purposes ▪ Pump stormwater ▪ Increase WPCP wet weather capacity ▪ Build larger sewers ■ Revise drainage design criteria ■ Enhance natural landscape and drainage features for runoff control ■ Manage flooding unconventionally (e.g., plan for controlled flooding in designated areas during storms)
Coastal flooding	■ Raise elevations of key infrastructure components ■ Construct watertight containment for critical equipment and control rooms ■ Use submersible pumps ■ Have additional backup emergency management equipment in reserve ■ Install local protective barriers ■ Construct large harbor-wide storm surge barriers ■ Develop plans allowing for coastal inundation in defined areas ■ Gradually retreat from the most at-risk areas or use these areas differently, such as for parkland that could flood with minimal damage
Wastewater treatment process disruptions	■ Discuss with regulators the possibility of water quality variances for severe weather conditions ■ Increase blower capacities or use redundant equipment for high temperature events ■ Increase backup power capacity ■ Clean interceptors and catch basins to reduce grit and sediment loads during wet weather ■ Improve main sewage pumps and screening for wet weather ■ Relocate vulnerable equipment and construct watertight containment for critical equipment ■ Raise freeboard for flooding ■ Revise design criteria for flood protection ■ Pump effluent
Receiving water quality impairment	■ Aerate critical water bodies ■ Upgrade WPCP processes to improve effluent quality ■ Enlarge or supplement CSO control facilities ■ Reduce runoff into the stormwater and combined sewer systems

Strategies for managing sea level rise

Waterfront communities around the world use both ancient and experimental flood-protection strategies. In the Bay Area, we rely on innumerable levees, and some wetlands, for flood protection.

Barrier or tidal barrage

A large dam, gate or lock—or a series of them—that manages tidal flows in and out of San Francisco Bay.

Advantages
Protects a huge area of land from flooding with one project
Protects everyone; no social equity issues

Disadvantages
Expensive
Ecologically transformative and damaging

Unknowns
Might not work where significant two-way flow exists

Coastal armoring

Linear protection, such as levees and seawalls, that fix the shoreline in its current place.

Advantages
Well-known, widely used tool
Can be designed to accommodate new development or protect threatened habitat

Disadvantages
Short-term
Expensive, with costly annual maintenance
Can fail in extreme events
Increases erosion

Elevated development

Raising the height of land or existing development and protecting it with coastal armoring.

Advantages
Allows structures to be built in a vulnerable area with low risk of flooding
Useful for critical infrastructure, such as airports

Disadvantages
Short-term
Expensive

Unknowns
Might not support high-density development and a transit orientation

Source: SPUR, 2009, http://www.spur.org/publications/library/report/strategiesformanagingsealevelrise_110109

Floating development

Structures that float on the surface of the water, or may be floated occasionally during a flood, making them largely invulnerable to changing tides.

Advantages
Manages the uncertainty of high tides
Seismically safe

Disadvantages
Works only in protected areas (no wind or waves)

Unknowns
Might not support high-density development and a transit orientation

Floodable development

Structures that are designed to withstand flooding or to retain storm water.

Advantages
Could store and retain flood water at the site scale

Disadvantages
Could result in hazardous conditions

Unknowns
Untested
Scalability

Living shorelines or wetlands

Wetlands are the natural form of our shoreline, absorbing floods, slowing erosion and providing habitat.

Advantages
Reduces pollution, provides open space and critical habitat for diverse species, stores carbon

Disadvantages
Require more land than linear protection strategies
Expensive to construct/restore
Require management, monitoring and time to become established

Unknowns
May not naturally adapt to sea level rise
Alone, may not be sufficient flood protection

Managed retreat

The planned abandonment of threatened and unprotectable areas near the shoreline, including banning new development in areas likely to be inundated.

Advantages
Minimizes human suffering from severe events
Less expensive than armoring strategies in very low-density or uninhabited areas
Can allow for ecological restoration

Disadvantages
More expensive than armoring strategies in high-density areas
Loss of communities and private property values
Political quagmire, with legal and equity issues

SPUR's recommendations for sea level rise planning

1. Undertake a shoreline risk assessment and prepare coastal inundation maps.

Planning departments, in consultation with BCDC, the Coastal Commission and the Federal Emergency Management Agency, should prepare maps based on the estimated 100-year flood elevations that take into account the best available scientific estimates of future sea level rise (currently about 55 inches) and current or planned flood protection. The maps and risk assessment should include a range of sea level rise projections for the middle and end of the century. Inundation maps should be prepared under the direction of a coastal engineer and updated every five years.

2. Revise the Safety Element within General Plans to include policies relating to climate change hazards, including sea level rise.

Safety Elements of city and county General Plans describe seismic, flooding, fire and other hazards, and planned approaches to reducing their potential damage. Local governments are required to monitor their Safety Elements to assure that they remain pertinent to local conditions; sea level rise is clearly a change to existing flooding hazards that has rarely been addressed. Local governments should update their Safety Elements to include a new section on climate change impacts, using information revealed in shoreline risk assessments, coastal inundation maps and other sources.

3. Do not permit new development in areas identified by local risk assessment and inundation maps as vulnerable to projected end-of-century sea level rise, unless certain criteria are met.

This strategy should be included in revised Safety Elements to mitigate future sea level rise and coastal flooding hazards. BCDC, planning departments, redevelopment agencies and other local agencies within their areas or jurisdiction should only permit new development that is:

a. A small or temporary project, especially if it can be removed or relocated;
b. A park or natural-resource restoration project;
c. An infill project on underutilized land within an existing urbanized area served by transit and other supporting infrastructure, or within an existing or potential ABAG Priority Development Area;
d. Critical infrastructure, necessary for the viability of existing development;
e. A project that can demonstrate it will protect public safety even under projected end-of-century sea levels, through its design or financial strategies.

4. Develop sea level rise flood-protection plans.

Planning departments, redevelopment agencies and other local agencies should utilize local risk assessment and inundation maps to plan flood protection from sea level rise, and where applicable, include these strategies in their Safety Element revisions. Existing development generally should be protected from flooding as long as the costs of publicly financed protection do not significantly exceed the costs of managed retreat to invulnerable areas, through such tools as voluntary buyouts, purchasing development rights or rolling easements. Eminent domain should not be used except where public safety is imminently and permanently threatened. Wherever feasible, non-structural measures such as wetlands should be used for flood protection.

5. Formulate a cross-agency regional sea level rise adaptation strategy to prioritize flood-protection resources and include it in the Senate Bill 375 Sustainable Communities Strategy.

The MTC and ABAG, in collaboration with the Joint Policy Committee, BCDC, other regional, state and federal agencies, and local governments, should identify financial and engineering strategies to protect regionally significant infrastructure, Priority Development Areas and other infill locations, and to protect the health, ecosystem and adaptive capacity of the Bay. The MTC and partners should prepare this regional strategy as an element of the Senate Bill 375 Sustainable Communities Strategy, and these two strategies should be consistent.

6. Require that public access to the Bay be viable for the long term.

BCDC should require that public Bay access that is a condition of new development be constructed to remain viable under future sea level rise, such as through elevated pathways. BCDC should also consider requiring that new public access be provided to the Bay if existing access areas are permanently inundated, or allow in-lieu fees to create access or mitigate loss of accessible area from sea level rise.

7. Update local coastal plans every five years.

The Coastal Act, the law that regulates development along the coast of California, does not require local governments to update their coastal plans, most of which are decades old. The California legislature should change this law to require updates every 5 years, and local governments should specifically denote climate change hazards of sea level rise, erosion and wildfire, and include local adaptation plans and strategies for existing coastal resources. Local coastal management officials should consult risk assessments and inundation maps prepared by local planning departments in their plans.

8. Include projected sea level rise scenarios in National Flood Insurance Program rate maps to help participating communities understand future risks of developing in low-elevation coastal areas.

The National Flood Insurance Program, within FEMA, maps flood-hazard areas and offers flood insurance to property owners within communities that adopt flood-protective building codes and other measures. While attempting to reduce risk, this practice can also increase it by encouraging building in areas that will only become more vulnerable in the future. Current NFIP mapping standards do not account for potential sea level rise, or the risk that rising seas pose to flood hazard defenses such as levees. The NFIP should also make federal flood insurance availability and pricing more risk and actuarially based to reflect repetitive losses in the most hazardous areas as well as the future risk posed by sea level rise. FEMA should also include projected sea level rise scenarios in its flood hazard maps.

NASA

CONCLUSION

Climate change is one of the greatest challenges the world has ever faced. At once, we need to begin reducing greenhouse-gas emissions to stave off its worst effects. But we also need a plan to respond, because some climate change will occur regardless, as the result of historic and ongoing emissions.

Climate change adaptation will need to be dealt with at all levels of government. Yet it is at the local and regional levels where vulnerability can best be understood and addressed. In the Bay Area, we are lucky to have institutions that are increasingly aware of these vulnerabilities and are beginning to plan ahead. But there is much more we need to do within specific areas of planning and governance to consider long-term impacts and, as much as possible, prevent foreseeable damage, loss and misery. Local government agencies in particular need a starting place. This SPUR report looks across planning areas to recommend ways to do just that.

Appendix 3. Property size analysis—methodology and data issues

Based on initial analysis of the City of Boston Assessing Department's publicly-available city-wide property parcel data (both attribute database and GIS parcel polygons), and on feedback provided by BRA staff, we determined that this database would need to be modified to accurately calculate the value of properties potentially affected by coastal flooding.

Data constraints: assessor's database

We were constrained by the fact that the assessor's database is not a normalized relational database. For example, significant additional analysis would be required to avoid double-counting of various values (e.g., assessed value) related to condominiums. Based on substantial discussions with BRA staff, we determined that adjusting the assessor's database to eliminate double-counting of assessed values was a non-trivial task and, therefore, beyond the scope of this study.

BRA PID dataset

To compensate for some of the known constraints associated with the assessor's database, BRA staff maintains its own GIS dataset based on this database. We used this dataset, called the Parcel Identification Number (PID) dataset.

The PID dataset is a "point feature class" that was developed by the BRA to facilitate a logical join with the assessor's parcel polygon feature class (parcel polygons) based on a unique 10-digit parcel identification number (PID).

The PID dataset point features each represent a single geo-located record from the assessor's database, and incorporates, as attributes, the data available in that database. The configuration of this dataset significantly facilitated our spatial analysis of estimated flooding impacts.

Methodology

Building-level flood impacts can be estimated using generic depth-damage algorithms developed by the United States Army Corps of Engineers. Input parameters for these algorithms include assessed value, construction, type of use, building contents and flood depth.

For this study, we initially planned to perform a screening-level analysis by aggregating and estimating several of these parameters, and by approximating both the depth and location of flooding. As discussed above, assessed value was not available for this analysis. However, the location of flooding, with respect to a particular parcel, was still critical to evaluating the parcels.

Location and level of flooding

The location of flooding was to be based on a point that approximated the vulnerable portion of the building as determined through GIS analysis of the parcel polygons. However, due to the ready availability of the PID point feature class, the PID dataset points were used to approximate the location of each parcel.

Flood impacts were limited to a binary analysis—flooded/not flooded—for each PID point feature, based on the flood datasets developed for the 2010 TBHA Sea Level Rise forum (TBHA, 2010). Flood dataset for two scenarios, MHHW+5 (9.8 ft NAVD) and MHHW+7.5 (12.3 ft NAVD), developed using the BRA's 2009 DEM were evaluated.

Additionally, based on the methodology developed by Kirshen et al (2008), areas upstream of the Charles River Dam that were identified as flooded at MHHW+5 (9.8 ft NAVD) were eliminated as a coastal flood of this magnitude would not overtop the dam.

Categorization by neighborhood and historical district was performed using related datasets provided by the BRA.

Land Use

Categorization by land use was performed by aggregating the land-use (LU) attribute values into the following categories:

- Commercial
- Industrial
- Mixed Use
- Residential
- Exempt
- Vacant Land (including Agricultural/Horticultural)

Parcel size

Parcel size for most of the LU categories was readily available. However, determining parcel size and associated LU for condos required additional analysis due both to the repetitive counting issues described above, and because many condos have both commercial and residential uses. The process, by which the parcel size was determined for the condos, as well as additional issues encountered, is described below.

Working Definition

The following definition of condo attributes was developed based on both conversations with BRA staff and our analysis of the database:

1. For each condo, there is at least one record, known as the condo main (CM) record and zero, one or more associated condo records for each of the individual condo units.
    a. Each CM record has a unique identifier, the CM_ID.

2. Each condo record has a unique PID, and a non-unique CM_ID.
   a. For the CM record, the CM_ID is equal to the PID and, except as described below, the last three digits of both the CM_ID and the PID are zeros.
      i. Some CMs are located on land that was sub-divided from earlier larger parcels; for these types of CMs, the last three digits may not be all zeros
   b. For the associated condo records, the first seven digits of the CM_ID match the first seven digits of the PID.
   c. For each CM record, LU = "CM".
3. All other condo records should have one of the following four LU values:
   - CC: Commercial Condominium
   - CD: Residential Condominium
   - RC: Mixed Use (residential and commercial)
   - E: Tax Exempt
   - CP: Condominium Parking
4. Total area in square ft (total sq. ft.) for the entire condo parcel is provided in the CM record.

Resolution of database issues

We resolved database issue based on conversations with BRA staff and our own analysis as follows:

1. Total sq. ft for each condo was categorized by the LU values listed above based on the following:
   - Condo parking records were ignored as not relevant to the LU categorization process.
   - For CM records where the LU values for all associated condo records were identical, total sq. ft was categorized by that LU value.
   - For CM records where the LU values for the associated condos were not identical, total sq. ft was categorized as Mixed Use.
2. Two database records were found that did not meet the criterion that the CM_ID is equal to the PID for the condo main record (and thus only for the condo main record).
   a. For **100 Cambridge Street**, CM_ID was missing for one record. The last three digits of the PID for that record were zeros, suggesting that this was likely a CM record. The LU value was Exempt. All associated records having a street address of 100 Cambridge Street had CM_IDs equal to the PID for the record presumed to be the CM record. The LU values for all associated records were Commercial Condominium. The record presumed to be the CM record was assigned a CM_ID equal to its PID. The LU value was changed to "CM"
   b. For **35 Cannel Center Street**, the CM_ID for one record did not match the PID. The last three digits of the CM_ID were not three zeros,

suggesting that this might not be a CM record. A CM record was found for 35 Cannel Center Street. All other associated records having a street address of 35 Cannel Center Street had CM_IDs equal to the CM_ID for the CM record. The CM_ID for this one record (Unit 102) was edited to match the CM_ID for the CM record for 35 Cannel Center Street.

3. Six records were found where CM_ID = PID, but LU = "R3". For each of these six records, there was no associated condo owner record. These six parcels were presumed to actually be R3. Therefore, the CM_ID was removed (set to null) for the following six parcels:
   - 5 Marion Street East Boston
   - 7 Condor Street East Boston
   - 39 Maywood Street Roxbury
   - 12 Wheatland Avenue South Dorchester
   - 28 Stellman Road Roslindale
   - 41 Seymor Street Roslindale
4. One record, PID = 1301323000 Contained an Unknown LU = "XX". Owner = Pilgrim Church. LU was changed to Exempt.
5. Fifty-five CM records were found for which there were no associated condo records. These 55 condos are presumed to contain no buildings and were, therefore, categorized as Land. A list of these 55 condos is provided below for reference
6. Four CM records were found for which all associated condo records were Parking. The following four CM records are presumed to contain no buildings and , therefore, all associated condo records were re-categorized as Land
   - 5 Jefferson Avenue Charlestown
   - 76 110R Gainsborough Street Fenway
   - 70 Brimmer Street Beacon Hill
   - 168R Camden Street Roxbury
7. Values of zero for LAND_SF were found in 340 parcel records, amongst all categories. These parcels, therefore, were not included in, and so may have biased, the analysis.
   - A total of 8,188 condos were identified: 7,606 Residential, 433 Mixed Use, 79 Commercial, 10 Exempt, 60 Land (including Parking Only Parcels)
8. Final counts for condominiums were:
   - 162,148 Records (PIDs)
   - 61,423 Individual Condo Records
   - 558 Condo Parking Records w/out CM_ID
9. The final count of records analyzed was 100,167 Records for all CMs and all others records not associated with condos

10. Additional analysis was not performed; therefore other undiscovered issues present in the attribute database may also affect the accuracy of this analysis.

CM records with no associated condo records (55 total)

PID	CM_ID	LU	ST_NUM	ST_NAME	ST_NAME_SU	PD
0102627000	0102627000	CM	4 2	TRENTON	ST	East Boston
0103947000	0103947000	CM	54	FRANKFORT	ST	East Boston
0200813000	0200813000	CM		AUBURN	TE	Charlestown
0200814000	0200814000	CM		AUBURN	TE	Charlestown
0200815000	0200815000	CM		AUBURN	TE	Charlestown
0203145000	0203145000	CM	30	CEDAR	ST	Charlestown
0302952010	0302952010	CM	520 540	ATLANTIC	AV	Central
0302952016	0302952016	CM	280-294	CONGRESS	ST	
0302953010	0302953010	CM	500	ATLANTIC	AV	Central
0303041000	0303041000	CM	2 - 5	BATTERY WHARF	ST	Central
0303740000	0303740000	CM		CHATHAM	ST	Central
0304832010	0304832010	CM	1 -3	AVERY	ST	Central
0304870010	0304870010	CM	2 -16	AVERY	ST	Central
0304965010	0304965010	CM	660	WASHINGTON	ST	Central
0305112010	0305112010	CM		TYLER	ST	Central
0305424020	0305424020	CM	1	NASSAU	ST	Central
0306377000	0306377000	CM		FAY	ST	South End
0400837100	0400837100	CM	230 -232	W NEWTON	ST	Back Bay/Beacon Hill
0402245000	0402245000	CM	316	HUNTINGTON	AV	Fenway/Kenmore
0500075020	0500075020	CM	100	STUART	ST	Central
0500200000	0500200000	CM	95 97	BROADWAY	ST	Central
0501158000	0501158000	CM	412 406	BOYLSTON	ST	Back Bay/Beacon Hill
0501389000	0501389000	CM	647	BOYLSTON	ST	Back Bay/Beacon Hill
0600332000	0600332000	CM		BAXTER	ST	South Boston
0601281000	0601281000	CM		W SECOND	ST	South Boston
0601302000	0601302000	CM	70	BOLTON	ST	South Boston
0602039000	0602039000	CM		E FOURTH	ST	South Boston
0602680250	0602680250	CM	1	PARK	LA	South Boston
0602684000	0602684000	CM	355 359	CONGRESS	ST	South Boston
0702416010	0702416010	CM	400R- 404R	K	ST	South Boston
0702505000	0702505000	CM	207	M	ST	South Boston
0702719000	0702719000	CM	750	DORCHESTER	AV	North Dorchester
0702902000	0702902000	CM	889 897	DORCHESTER	AV	North Dorchester
0801391020	0801391020	CM	45	E NEWTON	ST	South End
0801840010	0801840010	CM	1	E LENOX	ST	South End
0901323500	0901323500	CM	650	COLUMBUS	AV	South End
1002038010	1002038010	CM	353 365	CENTRE	ST	Jamaica Plain
1102105000	1102105000	CM	70	BROOKSIDE	AV	Roxbury
1103243000	1103243000	CM		SOUTH	ST	Jamaica Plain
1600077000	1600077000	CM	2	ASHLAND	ST	South Dorchester
1602694003	1602694003	CM		FRANKLIN	ST	South Dorchester
1604854010	1604854010	CM	1906 -1918	DORCHESTER	AV	South Dorchester
1701495000	1701495000	CM	22 24	FERNDALE	ST	South Dorchester
1704781100	1704781100	CM	380 -390	TALBOT	AV	South Dorchester
1809290000	1809290000	CM	1391 1395	HYDE PARK	AV	Hyde Park
1809298000	1809298000	CM	1392	HYDE PARK	AV	Hyde Park
1812152010	1812152010	CM	1	WESTINGHOUSE	PZ	Hyde Park
1900313000	1900313000	CM		OAKVIEW	TE	Jamaica Plain
1903160001	1903160001	CM	4144	WASHINGTON	ST	Roslindale
2100638000	2100638000	CM	139 143	BRIGHTON	AV	Allston/Brighton
2203685000	2203685000	CM	700	WASHINGTON	ST	Allston/Brighton
2203718000	2203718000	CM	7	PLAYSTEAD	RD	Allston/Brighton
2203940000	2203940000	CM		BIGELOW	CI	Allston/Brighton
2205268075	2205268075	CM	127	LAKE	ST	Allston/Brighton
2205652000	2205652000	CM	50	UNDINE	RD	Allston/Brighton

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